

VIBRATION AND NOISE IDENTIFICATION OF A COMMERCIAL REFRIGERATOR

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Abstract. The vibration transmission to the cooled goods within a refrigerator is a usually neglected field of interest. Previous studies however show that biochemical properties can be affected by continuous exposure to vibration. Optimal storage conditions necessitate protection against UV light and vibration to prevent the cooled good's quality being degraded by outside factors. Using operational transfer path analysis, we investigate different excitation sources that affect a commercial refrigerator and quantify the spectral input-distributions for all potential sources. Environmental influences, operational conditions and human interactions with both the refrigerator directly as well as indirectly via the environment were considered. Based on previous works, we developed a robust algorithm for the estimation of the varying transmission paths within the refrigerator and the close environment. Utilizing the measured and calculated data we investigate optimizations in design. We identified and characterized the impact of different vibration-sources and used deflection shapes of the system and the results from the TPA to identify areas of interest. Finally, we investigate measures to shift resonance frequencies into spectral ranges with less excitation and to introduce additional damping.

1 Introduction

Cooling devices have been the subject of numerous studies. The vibroacoustic analysis usually [1, 2, 3, 4] focusses on the psychoacoustics and the impact of engineering on the emission of vibrations in the audible frequency ranges. While the propagation of vibrations is also considered [5, 6], these studies tend to narrowly focus on the surrounding of one active component, e.g., a compressor or a fan.

Continuous exposure to vibration was shown [7] to affect the biochemical properties of stored wine and the changes became more significant at higher vibration levels. Optimal storage conditions necessitate [8] protection against UV light and vibration to prevent the reduction of aromatic components and the formation of undesirable flavor and taste. While some goods [9] tend to be robust against these outside factors others [10] 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 the commercial refrigerator

shown in figure 1 and propose improvements to reduce the exposure of the cooled goods within.



Figure 1: The investigated device is a Liebherr WTes 5872 Vinidor. This multi-temperature wine cabinet has a frame made of stainless steel, a glazed door and wooden grid shelves. Up to 178 bottles can be stored in 13 storage shelves.

Table 1: Technical data for the WTes 5872 Vinidor

Product dimensions (H/W/D)	192.0 / 70.0 / 74.2 cm
Weight (without packaging)	134.00 kg
Net capacity, total	496 l
Maximum number of 0.75 l Bordeaux bottles	178
Noise level	38 dB
Energy consumption per year	180 kWh/a

2 Measurements and data analysis

In order to accurately identify the vibrations we placed acceleration sensors at 47 sensitive locations. All sensors were current-fed piezoelectric transducers (IEPE/ICP). Places with non-trivial directions of movement, e.g., corners of the frame, the shell of the compressor or the cooled goods inside, were measured using triaxial sensors. To better utilize our limited measurement channels locations enclosed by two triaxially measured points were measured with uniaxial sensors. The surrounding temperature was recorded during each measurement cycle to catch 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.

Several different actuation variants were used:

- During normal operation, the refrigerator autonomously regulates its components. The compressor and the fans operate to keep a steady 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.

2.1 Processing of measurement data

We focus our investigation on vibrations with frequencies up to 200 Hz. The measurement acquisition system was set to use a low-pass Bessel filter with a cut-off frequency of 1000 Hz and a measurement frequency of 5000 Hz. The measured vibrations are low in amplitude. Therefore, all measurement cycles were conducted with a vacated laboratory to avoid measuring the influence of uncontrolled additional vibrations from the surroundings.

Due to the limited number of channels of the acquisition system and the limited number of sensors not all measurement points can be recorded simultaneously. However, independent measurements can be affected by different environmental effects. A noise-peak that is present in one measurement but not the other can lead to estimation error. 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 noise can be greatly reduced. The H_4 -estimator [11, 12] was shown to improve the performance of TPA estimations and leads to robust results.

Two noisy signals $x(t)$ and $y(t)$ have the Fourier transforms $X(\Omega)$ and $Y(\Omega)$. The auto power spectral density $S_{xx}(\Omega)$ and the cross power spectral density $S_{xy}(\Omega)$ are defined as

$$\begin{aligned} S_{xx}(\Omega) &= \lim_{T \rightarrow \infty} \frac{1}{2T} \{X_T^*(\Omega)X_T(\Omega)\} \\ S_{xy}(\Omega) &= \lim_{T \rightarrow \infty} \frac{1}{2T} \{X_T^*(\Omega)Y_T(\Omega)\} \end{aligned} \quad (1)$$

where Ω is the Fourier frequency, T is the time interval of the measurement and the index of the Fourier transforms indicates that X_T and Y_T are calculated from the measurement data within this time interval T . Multiple intervals of time T each can be averaged to get smoother estimates of the frequency spectra. The H_x -estimators are thus calculated as follows:

$$\begin{aligned}
 H_1(\Omega) &= \frac{S_{xy}(\Omega)}{S_{xx}(\Omega)} \approx \frac{\sum_i [X_i^*(\Omega)Y_i(\Omega)]}{\sum_i [X_i^*(\Omega)X_i(\Omega)]} \\
 H_2(\Omega) &= \frac{S_{yy}(\Omega)}{S_{yx}(\Omega)} \approx \frac{\sum_i [Y_i^*(\Omega)Y_i(\Omega)]}{\sum_i [Y_i^*(\Omega)X_i(\Omega)]} \\
 H_3(\Omega) &= \frac{1}{2} [H_1(\Omega) + H_2(\Omega)] \\
 \kappa(\Omega) &= \frac{|H_3(\Omega)|}{\max_{\Omega} \{|H_3(\Omega)|\}} \\
 H_4(\Omega) &= [1 - \kappa(\Omega)]H_1(\Omega) + \kappa(\Omega)H_2(\Omega)
 \end{aligned} \tag{2}$$

These estimations are done for each measurement point with the selected point being set as the y -channel and the reference point always being set as the x -channel.

2.2 Transfer path analysis

The most important part of conducting 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 mathematic workflow for a TPA as described in [13] 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}

$$\mathbf{X}\mathbf{T}^T = \mathbf{Y}. \tag{3}$$

The input \mathbf{X} has m channels whereas the output \mathbf{Y} has n channels, the width of both matrices is dependent on the number of measurement cycles or redundancies that are to be used in the calculations. Utilizing the singular value decomposition (SVD) on \mathbf{X} , we can obtain the parameters σ_j , \mathbf{u}_j and \mathbf{v}_j

$$\mathbf{X} = \mathbf{U}\Sigma\mathbf{V}^T = \sum_{j=1}^m \sigma_j \mathbf{u}_j \mathbf{v}_j^T. \tag{4}$$

The generalized cross validation (GCV) can then be used to select optimal parameters λ for Tikhonov regularization

$$\text{GCV}(\lambda) = \min_{\lambda} \left\{ \frac{\|\mathbf{X}\mathbf{T}_{\lambda}^T - \mathbf{Y}\|^2}{m - n + \sum_{j=1}^m \left(\frac{\lambda^2}{\lambda^2 + \sigma_j^2} \right)} \right\}. \quad (5)$$

These optimal values of λ can then be inserted into

$$\mathbf{T}_{\lambda}^T = \sum_{j=1}^n \frac{\sigma_j^2}{\lambda^2 + \sigma_j^2} \frac{\mathbf{u}_j^T \mathbf{Y}}{\sigma_j} \mathbf{v}_j \quad (6)$$

and with our previously calculated SVD-parameters, the estimate of the transmissibility function matrix \mathbf{T}_{λ}^T is fully defined. These calculations then have to be applied in iteration for every considered frequency in the frequency range. The input matrix \mathbf{X} and the output matrix \mathbf{Y} are varied according to the previously determined pathways and are filled with the respective sensor data to calculate all necessary transmissibility functions. Finally, the results are visualized in false color plots as seen in figure 2.

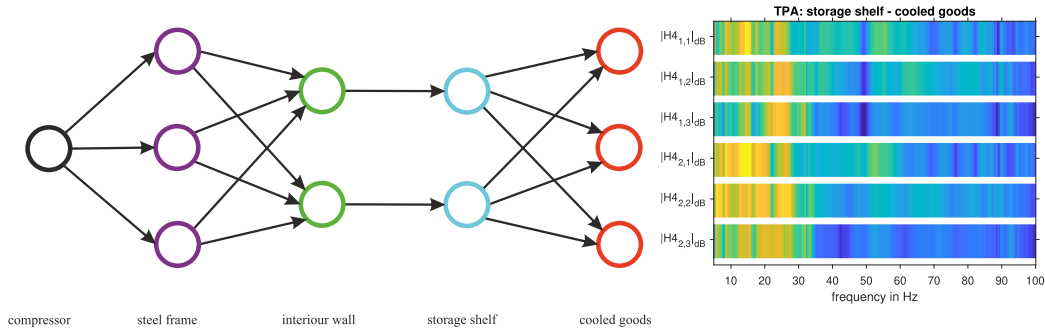


Figure 2: A possible pathway for a TPA (left) and an exemplary result of the calculations (right) that visualizes the transfer paths between the wooden storage shelf and the cooled goods. The yellow colored areas in the plot indicate frequencies that are only weakly damped within this sub-path.

2.3 Operative deflection shape analysis

The ODS 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 of eq. (2). 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 3 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.

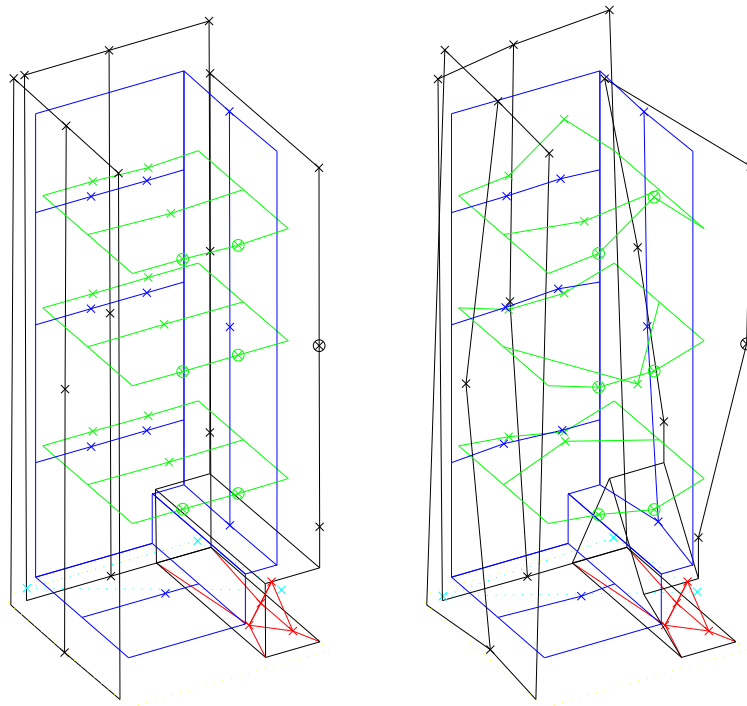


Figure 3: Visualization of a ODS analysis at a specific frequency. All points are measured and the lines connect the sensors to aid visualizing the original form of the device. High mobility of points indicates low stiffness and low mobility indicates that the points are only weakly excited by the measured source. This visualization can be helpful for future design decisions, e.g., stiffening of mobile areas.

3 Identification and quantification of vibrational sources

In order to prioritize the development time efficiently the impact of different vibrational sources is quantified. The considered sources can be categorized as follows:

- internal active sources
 - compressor
 - fans

- additional features, e.g., ice makers
- internal passive sources
 - movement of the cooling fluid
 - airflow due to the fans
- external sources
 - base excitation through the surroundings
 - people walking near the refrigerator
 - work being done in the vicinity of the refrigerator
 - opening of the refrigerator door
 - loading and unloading of the refrigerator

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

Several acceleration sensors are evaluated, one is placed at the compressor and the others are placed 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. 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 the varying frequencies. Finally, the refrigerator was activated to hold a temperature of 6 C autonomously without interference. A longterm measurement was conducted to show the impact of uninterrupted operational conditions and to observe the autonomous activation and deactivation of the compressor. Finally 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.

We assumed the squared RMS-values of the combinatory excitation to be the sum of the squared independent excitation sources. This allows the reduction of the operational RMS-measurement by the base measurement 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 all sources are quantified it is necessary to make assumptions. 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. These assumptions can vary based on the specific use case.

4 Results

Utilizing the discussed methods, we calculated the impact of the differing vibration sources. The exact numbers cannot be disclosed in this paper but using this method, we could prioritize future development

and suggest likely solutions. In figure 4 we see a transmissibility function for vibrations that are excited by the compressor. It is shown that this device has several natural frequencies in areas that are suitable for compressor operation. Operation within the marked frequency intervals hardly excites the cooled goods, minimizes the exposure to vibration and has the additional potential to reduce the audible noise.

Figure 5 shows a natural frequency of the condenser on the back of the refrigerator. This condenser is mounted on a lattice made of steel wire that is held on place by a sturdy frame. A quick analytical approximation of this structure can be made using the formulae for circular Euler-beams made of steel.

$$\begin{aligned}\omega_0 &= 2.55 \cdot 10^4 \frac{R}{L^2} \\ \omega_{n1} &= k_1 \omega_0\end{aligned}\quad (7)$$

The beams have a diameter of $R = 1.4$ mm and a length of $L = 1280$ mm. For fixed supports the multiplicative factor is $k_1 = 2.267$. Evaluating equation (7) the expected natural frequency is located at $\omega_{n1} = 24.71$ Hz. This closely aligns with the results of our measurements which are shown in figure 5. A change in the lattice dimensions could shift this natural frequency and influence the transmissibility of the overall system.

Utilizing the data gained from the TPA and ODS analysis areas of interest have been identified that will be addressed in design reviews. By combining these optimizations the cooled goods will be exposed to significantly reduced amounts of vibrations. These improved conditions facilitate long term storage without degradation of quality.

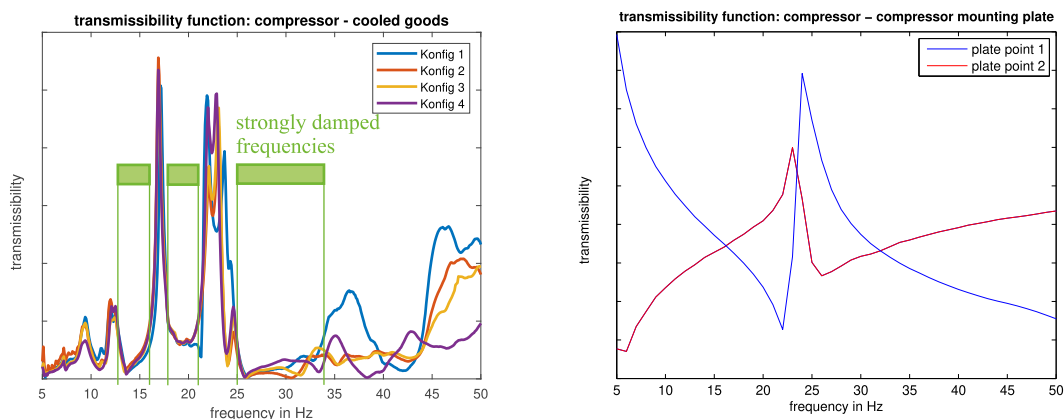


Figure 4: Examples of acquired transmissibility functions and their interpretation. Left: transmissibility from the compressor to the cooled goods for repeated measurements. The refrigerator has natural frequencies at 17.1 Hz, 22.2 Hz and around 23.5 Hz. Operation in the strongly dampened frequency intervals marked in green hardly excites the cooled goods. Right: transmissibility function from the compressor to points on the compressor mounting plate. This function describes the effectiveness of the grommets that isolate the compressor from the steel frame. The grommets show a natural frequency around 24 Hz.

5 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.

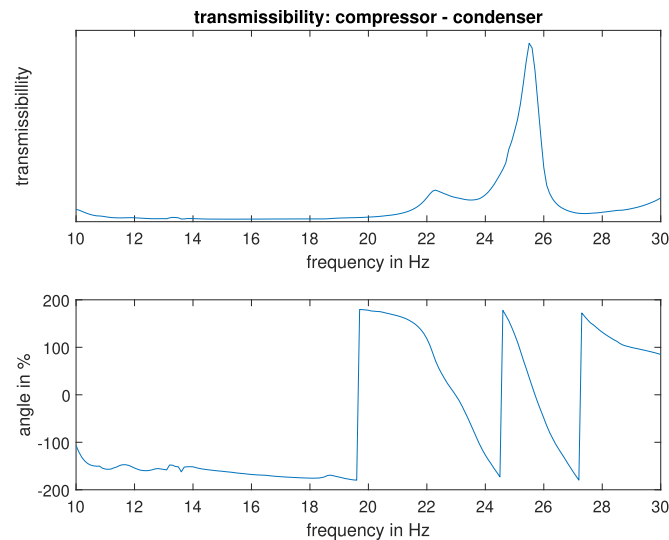


Figure 5: Transmissibility from the compressor to a point on the condenser at the back of the refrigerator. A natural frequency at 24.7 Hz is clearly visible.

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.

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