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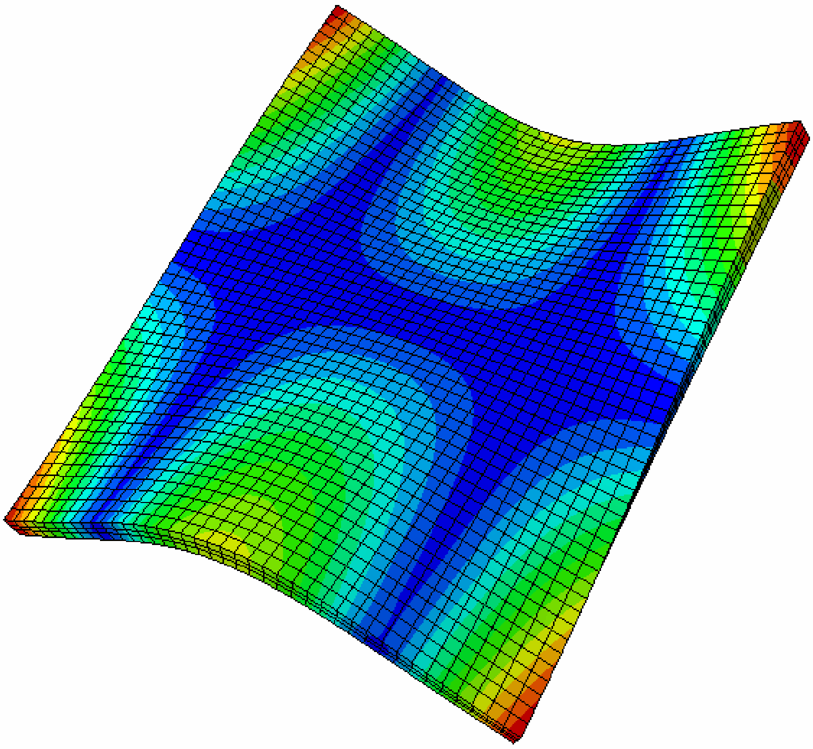

VIBRATIONS IN A HIGH FREQUENCY CLT FLOOR PANEL

Measurement, prediction and evaluation

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Structural Mechanics

Master's Dissertation

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MASTER'S DISSERTATION

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Measurement, prediction and evaluation

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Abstract

There is an increased need for floors that can accommodate different type of sensitive equipment [1]. Further, it is recommended to design these floors as high frequency floors (HFF) to be able to meet the stringent vibration criteria [1].

This work used experimental measurements and numerical simulations to gain a deeper knowledge about the measurement, prediction and evaluation of vibrations in HFF. The experimental measurements consisted of modal measurements and walking measurements, and a finite element (FE) model was used for the numerical simulations. The test specimen was a CLT floor panel with the dimensions 2.45 m $\times$ 2.025 m, consisting of three layers with a total thickness of 80 mm.

The purpose of the modal measurements was to validate the material parameters and displacement boundary conditions of the FE-model. From these measurements it appeared that it was possible to find a set of material parameter that was suitable. However, the boundary conditions had a large influence on the dynamic properties of the floor system, and this effect was not incorporated in the FE-model due to its complexity.

To investigate the response in the floor triggered by a a single pedestrian, twelve different persons walked across the floor in two directions, at three pacing rates. This measurement campaign resulted in a total of 72 measurements. The measured response was evaluated with the one-second running root mean square (RMS). This showed that the response varied to a large extent between individuals, and between the path and position of the transducers. Further, the weight of the persons was measured. It was therefore also possible to evaluate the potential effect of the pedestrian´s mass had on the dynamic properties of the floor. Hereby, the correlation could be observed to be negligible between the mass of the pedestrian, natural frequencies and vibration amplitude, respectively.

As recommended in ISO 10137:2007 [2] and ISO 2631-1:1997 [3], the measured response for one sample was evaluated with the RMS, running RMS and vibration dose value. Thereby, it was illustrated that there is some ambiguity in the guidelines about how these quantities should be calculated to ensure comparable results.

An FE-model was developed to predict the response from a single pedestrian. The load was applied in the time domain for each footstep. It was found that the vibration in the FE-model is governed by the response at resonance. Furthermore, the effect of varying the striding length and the pacing rate was investigated. This showed that the variation in striding length was negligible, while the change in the pacing rate increased the response.

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Contents

1 Introduction

1.1 Background

The development in the construction industry is moving towards more material efficient and slender constructions, for which vibrations can often can be critical [1]. The vibration criteria for floors was traditionally related to the human perception [4]. However, with increased technical advancement, primarily in the health sector, there has been an increased need for floors that can accommodate different types of sensitive equipment [1]. As the vibration criteria for machines can be $2 - 3$ times stricter than for human perception [4], it is recommended that the floors in facilities which house sensitive equipment, only allow low transient vibrations and therefore be designed as so called high frequency floors (HFF) [1].

HFF are said to be floors with a fundamental frequency above $8 - 10$ Hz while low frequency floors (LFF) have the fundamental frequency below this limit [1, 2]. The limit, which is also called the cut off frequency, originates from different calculations methods. Above this limit the energy in the foot-step is generally low and therefore not enough to trigger resonance. Below the cutoff frequency the energy in the foot step are normally higher, which is why resonance can occur [4]. However some research has shown that resonance build up can also occur in HFF [1].

To predict vibrations in HFF many design guides use some sort of impulse load for analysing the response [5, 6, 7, 8]. For LFF, it is common to use calculation models that consists of Fourier expansion [1, 9, 2]. Another calculation method is to use a finite element (FE) model in the time domain, where the reaction forces from each step are considered. Hicks et al. [10] proposed a load function in the time domain, using a 8-th grade polynomial based on 75 measurements. This model was tested on low frequency floors with promising results.

1.2 Purpose and aims

The purpose of this master´s dissertation is to gain greater knowledge about measurement, prediction and evaluation of vibrations in HFF. The following questions will be investigated:

- How should response measurements of a walking person be conducted: How will the path of the pedestrian affect the response measurements? How will the vibrations deviate between individuals?
- Can the weight from a single pedestrian be neglected when calculating the modal properties of floor panels?

- Which evaluation method according to ISO 10137:2007 [2] and ISO 2631-1:1997 [3] will be decisive when evaluating footfall induced vibrations in HFF?
- Will the time domain model developed by Hicks et al. [10] be able to predict the vibrations in HFF with adequate accuracy?

1.3 Method

The aims of this dissertation was achieved by conducting a literature review and performing measurements and simulations on a cross laminated (CLT) floor.

The literature review focused on how vibration measurement should be conducted for floors. The different dynamic characteristics of LFF and HFF. Further, different evaluation criteria for HFF and modelling approaches for floor vibrations using the FE-element method was elucidated.

The measurements consisted of experimental modal measurements to validate the applied FE-model regarding material properties and boundary conditions. In addition, structural response measurements were conducted using twelve different individuals that walked across the floor, each with three pacing rates in two different directions.

Finally, numerical simulations were conducted using a FE-model created with the software Abaqus.

1.4 Limitations

Only vibrations in the vertical direction from a single pedestrian will be investigated. Further, the conclusions are based on experimental modal measurements, response measurements and simulations on a single CLT element.

2 Literature review

2.1 Vibration criteria

2.1.1 Human perception

Human perception to vibrations can be explained by a lumped mass model where different part of the body have different resonance frequencies [11]. Studies have shown that humans are especially sensitive to frequencies between $4-8$ Hz, which corresponds to the resonance frequencies of certain internal organs [11]. When evaluating the vibrations in relation to human perception, frequencies in the range $1-80$ Hz should be accounted for [2].

In ISO-2631-1:1997 [3] and ISO 10137:2008 [2], frequency weighting is used for attenuating frequencies in certain ranges. The frequency weighted response can then be compared with the base curve which is shown in Figure 2.1. This curve should be multiplied by a specific factor which depends on the type of environment that is evaluated e.g., residential, office or hospital. If the vibration level is above the base curve for any frequency, the criteria for human perception is not fulfilled [2]. However, the base curve should not be interpreted as deterministic. For example, there is a 50% probability that a human will detect a weighted acceleration with a peak magnitude of 0.015 m/s^2. Furthermore, there is a large variation of how different individuals perceive vibrations [3].

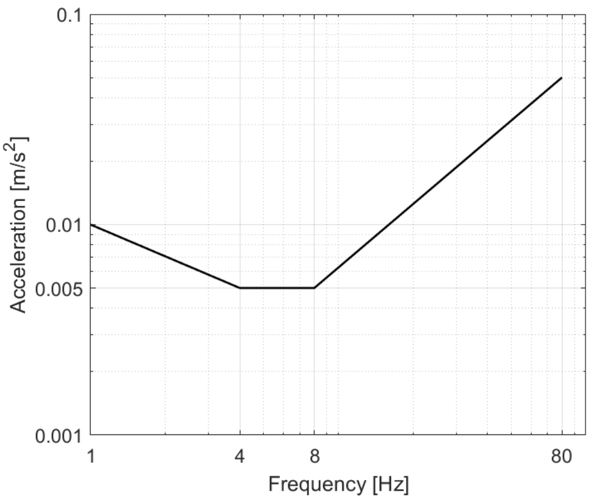

Figure 2.1: Base curve for human perception according to ISO-2631-1:1997 and ISO 10137:2008

2.1.2 Sensitive equipment

Due to technical advances in primarily the health sector, laboratories and the micro-electronic industry, the dimensional precision of the equipment used in these facilities have increased. As a consequence of this, also the vibration criteria for these type of buildings have become more stringent [4]. The vibration criteria for machines can sometimes be $2-3$ times less than humans can tolerate, which is why the design criterion used for human perception is not suitable to evaluate facilities which house sensitive equipment [4].

The structural design of buildings often proceeds the selection of equipment, which is why it is rare that the specification for the maximum vibration limit is known during the design phase [12]. Moreover, it is important that the facility is not only designed for a single piece of equipment, to increase the flexibility [13]. To overcome these problems, a set of generic vibration criteria (VC) curves, which are depicted in Figure 2.2, were developed during the early 1980s by Eric Ungar and Colin Gordon [12]. As they developed it while working at Bolt Beranek and Newman (BBN), the criteria was originally known as the BBN criteria [12]. In the beginning, these curves where developed for the semiconductor industries, however, today they are more widely used for different vibration sensitive environments [13]. The curves have also been adapted in commonly used design guides for floor vibration [5, 6]. Over the years, the curves have been revised. In 2002 some of the curves were flattened to account for the increased vibration sensitivity in machines at low frequencies [13, 12]. It should be noted that there also exist other types of generic criteria for machines, such as the NIST-A criterion which is popular in the nano-technology community [13]. Nevertheless, in the following section the discussion will be limited to VC criteria.

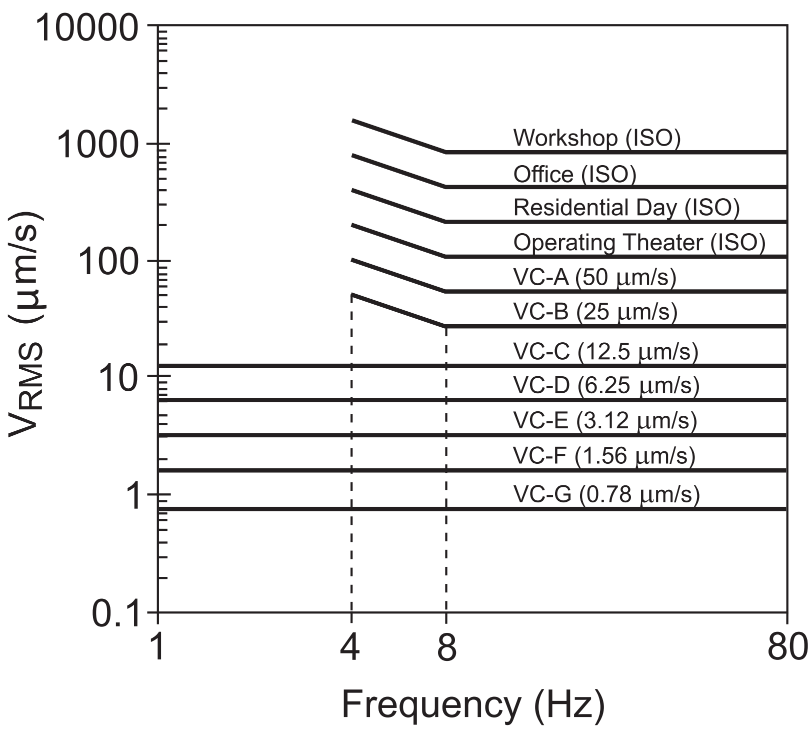

Figure 2.2: VC curves for sensitive equipment, compared against ISO-criterion for human perception. Figure used with permission from [14]

The VC-curves were constructed from vibration data from manufactures and case studies from facilities with vibration problems [13]. They are based on the assumption that the machines are supplied with built-in isolation and are resting on benches or pedestals that are rigidly constructed and damped [13]. When designing floors it is generally necessary that they are of the type HFF to be able to meet the VC-criterion of interest [1]. For large floor areas, the response in one point is generally not representative for the whole floor. To overcome this, Amick et al. [13] recommended to statistically combine the responses from different points by creating a mean plus one standard deviation spectrum. This could then be compared against the specific VC-curve.

Choosing which VC-curve the construction should be designed for should, of course be based on the limiting amplitudes. However, another important aspect, is to include some reference to how long the vibration criteria have to be fulfilled without interrupting the operation of the equipment. For example, the consequences can be larger when interrupting a 24 hour operation, explaining why a more stringent criterion should be chosen, compared to an operation that takes 5 minutes [12]. Despite the fact that VC-curves are a good tool in the early design, it is also important to obtain the vibration specification of the actual equipment, to ensure an appropriate and economical design [12].

To use the VC-curves the measured data should be processed into 1/3-octave bands with the amplitude units RMS velocity [13]. The bandwidth will then be proportional to the frequency, and this is motivated by that vibrations in facilitates that house sensitive equipment is generally dominated by broadband energy (random) rather than tonal (periodic) energy. The VC-curves represent an upper-bond limit for the vibration requirement. However, it is not encouraged that they are interpreted too strictly. An accuracy within 1 to 2 dB ($12-26\%$) is generally accepted. For example, if the measured result falls above the VC-curve with 1 dB, it should be seen as fulfilling the criterion [13].

2.2 Floor vibrations

2.2.1 Footfall induced vibrations

Footfall induced vibrations consists of three components, namely the vertical, horizontal and longitudinal direction. However, for floors which are relatively flexible in the vertical direction, the vertical component is often most dominant and in this direction the energy concentration is also relatively high. Therefore, the vertical direction is of main interest for analysis of floors [9]. For slender bridges however the horizontal component can cause problems and is, therefore, of major importance when evaluating the dynamic behaviour [10].

When evaluating footfall induced vibrations, stride length, walking pace, overlapping of the footsteps and the amplitude of the dynamic force are all important variables [15, 16, 9]. Some studies have shown that the stride length can be negligible when designing against the criterion for human perception, but when evaluating with consideration to sensitive equipment it can be important to include [9]. There is however a general consensus that the walking frequency can have a large effect on the response [9]. Studies have shown the pacing rate to be normal distributed, with a mean value of approximately 1.9 Hz and a standard deviation of 0.19 Hz [16]. In *Preliminary Eurocode 5* [8], the following typical walking frequencies are given:

- 1.5 Hz for floors where the pedestrian cannot walk a distance of more than 5 m unobstructed in a single direction;
- 2.0 Hz for floors where the walker can walk a distance of between 5 and 10 m unobstructed in a single direction;
- 2.5 Hz for all floors where the walker can walk a distance higher than 10 m unobstructed in a single direction.

2.2.2 Low frequency floors

Even if LFF are outside the scoop of this thesis, a brief description will be given, motivated by that there is no clear definition of the low and high frequency regions. A floor categorized as a LFF can still exhibit properties that belongs in the HFF region. [1]. The categorization originates rather from different modelling approaches that are suitable to the respectively region.

LFF are categorized as structures with a fundamental frequency (first natural frequency) below $8 - 10$ Hz [1, 2]. This limit is also called the cutoff frequency [1]. In these floor types there is normally enough energy in footsteps to trigger resonance if the amplitude of the harmonic force coincide with the fundamental frequency [1].

There exist a large collection of design guides for LFF, the majority of these analyse the vibrations in the frequency domain [5, 6, 2, 7, 8]. The frequency domain method generally consists of a Fourier expansion, which normally includes four harmonic coefficients [1, 9, 2]. But more recent developed methods includes up to eight harmonic coefficients, increasing the cutoff frequency to 20 Hz [15].

2.2.3 High frequency floors

HFF are said to be floors with a fundamental frequency above 8-10 Hz [1, 2]. These floors are typical stiff in relation to the mass of the floor, e.g a short span concrete or composite floors can be such a structure [17].

For HFF there is normally not enough energy in the foot-step to trigger resonance [4]. Even if there was enough energy, it is probable that the persons variation in pace rate would not allow resonance build up to occur [4]. Instead, the response will normally die out between footsteps, why the force can be treated as a series of impulses [9]. This characteristic is include in many design guides, which use some sort of impulse load for analysing the response for HFF [5, 6, 7, 8]. However, some research have shown that resonance build up can also occur for HFF [1]. This can be thought to be particularly true if the fundamental frequency is just above 10 Hz [1].

2.3 Quantities for evaluating floor vibrations

The *root mean square* (RMS), also called the *Overall RMS* is a commonly used quantity for evaluating floor vibrations [9, 10]. The definition of the frequency weighted RMS is as follows [3]:

$$a_w(t) = \left[\frac{1}{T} \int_0^T a_w^2(t) dt \right]^{1/2} \tag{2.1}$$

where $a_w(t)$ is the frequency weighted acceleration as a function of time, with weightings according to ISO 2631-1:1997 [3]. And T is duration of the measurement in seconds.

The RMS can underestimate the severity of the vibration with respect to discomfort when the vibration originates from occasional shocks or categorized as highly transient. To validate if the basic RMS is sufficient as evaluator, or if additional methods are needed, the *crest factor* can be used. It is defined as quotient between the maximum peak value of the frequency weighted acceleration and the RMS [3]. In ISO 10137:2007 [2], the limit for the crest factor is when it is greater than six, or when doubt about the transient properties exists [3] In ISO 2631-1:1997 [3], the limit is set to when the crest factor is greater than nine. When theses limits are exceeded, it is recommended to either use the *Running RMS* or the *Fourth power vibration dose value* (VDV) to evaluate floor vibration [3, 2].

The *Running RMS* is calculated over a time window that moves along the signal. It will therefore result in a collection of RMS values of which the largest of these should be compared to the design criterion [10]. The Running RMS is defined as [3]:

$$a_w(t_0) = \left[\frac{1}{\tau} \int_{t_0-\tau}^{t_0} a_w^2(t) dt \right]^{1/2} \tag{2.2}$$

where $a_w(t)$ is the frequency weighted acceleration as a function of time, with weightings according to ISO 2631-1:1997 [3]; τ is the integration time for the averaging; t is the time in seconds; and t_0 is the time of observation in seconds. The length of the time window varies between design guides [10]. For example, in ISO 10137:2007 [2] and ISO 2631-1:1997 [3] it is recommended to use the window $\tau = 1$ second; while in DIN 4150-2 [18] it is recommended to use $\tau = 0.125$ second.

From the Running RMS, the maximum transient vibration value (MTVV) can be defined as [3]:

$$\text{MTVV} = \max[a_w(t_0)] \tag{2.3}$$

Moreover, when the following ratio is exceeded, the Running RMS will be important for evaluating how vibrations affects health and comfort of humans [3]:

$$\frac{\text{MTVV}}{a_w} = 1.5 \tag{2.4}$$

Evaluations methods that are based on an average or peak values are not ideal for transient vibrations [19]. To overcome this problem, a cumulative (i.e. dose) measure, as the VDV, can be used instead [19]. The VDV is defined as [3]:

$$a_w = \left[\int_0^T a_w^4(t)dt\right]^{1/4} \tag{2.5}$$

where $a_w(t)$ is the frequency weighted acceleration as a function of time, with weightings according to ISO 2631-1:1997 [3]; T is the evaluation period in seconds. According to BS 6472-1:2008 [17], the VDV can be approximated with the RMS over the same time period as:

$$eVDV = 1.4 \cdot a_{w,RMS} \cdot t^{0.25} \tag{2.6}$$

where $a_{w,RMS}$ is the frequency weighted RMS, calculated with Equation 2.1

The VDV value concerns severe discomfort and possible effects on health [19]. This is considered by amplifying the peak values with the fourth power, which is especially important when evaluating damage to biological tissue [20]. For vibrations in buildings, severe discomfort to vibrations is not normally expected. However, the method has been adopted in various design guides [3, 2, 17]. The attraction of the method is probably the possibility to sum the vibration over a period of time [19]. Recommended limits for the VDV is given in ISO 10137:2007 [2] Table C.2 for when adverse comments may be excepted. The same multiplying factors used for the base curve in Figure 2.1 can also be used for the VDV.

2.4 Modelling of floor vibration

2.4.1 Human structure interaction

Stationary people can change the dynamic properties of a floors by affecting the mass and the damping. This can have an especially large effect for light weight structures. Stationary humans can be modelled as a spring damper system; that is connected to the main structure. However, when people move, they act more like a dynamic force and therefore only have a negligible influence on the dynamic properties of the structure [21].

2.4.2 Time domain method

For the numerical simulations in this thesis, a load function applied in the time domain will be used. The load function will be based on the research conducted by Hicks et al. [10], where five test persons walked five times with three different shoes, along a 20 meter long walkway fitted with force plates. The researchers concluded that the effects from different shoes could be disregarded (except for high heels). Furthermore, they found that the vertical load from a footstep could be expressed as a function of the pacing rate, by fitting an eight grade polynomial to the measurement data, according to:

$$F(t) = G(K_1 t + K_2 t^2 + K_3 t^3 + K_4^4 + K_5^5 + K_6^6 + K_7^7 + K_8^8) \tag{2.7}$$

where G is the static force from the body weight ($G = m \cdot g$) of one pedestrian. The mass can generally be assumed to be approximately 80 kg [10]. The coefficients for the load as function of the pacing rate f_s is given in Table 2.1.

Table 2.1: Coefficients for the load as a function of the pacing rate with permission to use from [22]

	$f_s \leq 1.75$ Hz	$1.75 \leq f_s \leq 2.00$ Hz	$f_s \geq 2.00$ Hz
K_1	$-8f_s + 38$	$24f_s - 18$	$75f_s - 120$
K_2	$376f_s - 844$	$-404f_s + 521$	$-172f_s + 3\ 153$
K_3	$-2\ 804f_s + 6\ 025$	$4\ 224f_s - 6\ 274$	$17\ 055f_s - 31\ 936$
K_4	$6\ 308f_s - 16\ 573$	$-29\ 144f_s + 45\ 468$	$-94\ 265f_s + 175\ 710$
K_5	$1\ 732f_s + 13\ 619$	$109\ 976f_s - 175\ 808$	$298\ 940f_s - 553\ 736$
K_6	$-24\ 648f_s + 16\ 045$	$-217\ 424f_s + 353\ 403$	$-529\ 390f_s + 977\ 335$
K_7	$31\ 836f_s - 33\ 614$	$212\ 776f_s - 350\ 259$	$481\ 665f_s - 888\ 037$
K_8	$-12\ 948f_s + 15\ 532$	$-81\ 572f_s + 135\ 624$	$-174\ 265f_s + 321\ 008$

To determine in which points the load should be applied, the striding length can be calculated according to Equation 2.8, where v is the walking velocity, which can be calculated according to the formula proposed by Bachmann and Ammann [23] in Equation 2.9.

$$l_s = v/f_s \tag{2.8}$$

$$v = 1.67f_s^2 - 4.83f_s + 4.5 \tag{2.9}$$

It is possible to make the model more realistic by varying the pacing rate with a deviation Δf [10]. This deviation can be calculated with a sinusoidal formula, with an abrupt change in the frequency at the beginning of each step according to:

$$\Delta f = A_f \cdot \sin(f_c \cdot n_c \cdot \pi) \tag{2.10}$$

where A_f is the amplitude (max) increase or decrease in the pacing rate, $f_c = 1/n_c$ is the frequency of deviation; n_c is the number of steps for one deviation cycle and n_i is the total number of steps. For example, for the base pacing rate 2.0 Hz it is recommended to use the value $A_f = 0.15$ Hz for the maximum deviation [10].

2.5 Measurement of floor vibration

2.5.1 Quantities and equipment

Parameters that can be measured and used in dynamic evaluation are displacement, velocity, acceleration and sometimes strain. Respectively quantity should be measured over frequency [2]. The choice of quantity depends on the objective of the analysis and the governing criteria. Even if it is possible to convert between spatial quantities by differentiating, this is not recommended due to inaccuracies; with exception for harmonic signals. It is preferable to directly measure the quantity of interest or by integration over the measured data [2].

In ISO 10137:2007 [2] they give the following example of the quantity ranges that are commonly encountered in building vibrations:

- Frequency range: 0.15 to 100 Hz, except when measuring impulsive responses and for buildings on bedrock, then it may be higher than 100 Hz;
- Accelerations: 10^{-3} to 10 m/s^2
- Velocities: 10^{-5} to 10^{-1} m/s; for measurements involving micro-electronic, optical and similar technologies (nano-technology), lower limits may apply;
- Displacements: 10^{-7} to 10^{-2} m

More specific recommendations for measuring the response from a walking person is given by Hicks et al. [10]; where it is advised that the equipment should be able to capture the following ranges:

- Frequency range: $0 - 300$ Hz, but as most floor do not have natural frequency below 1 Hz, the range $1 - 300$ Hz is generally sufficient for evaluating floor vibration.
- Sampling frequency: 100 Hz is generally sufficient, this is because the most energy in the load from a foot step is below 12 Hz.
- Measurement period: around 16 seconds, but when measuring the response from walking, the measurement period should be at least the period that the person walks.
- Accelerations: -5 to 5 m/s^2
- Velocities: -10 to 10 mm/s

2.5.2 Experimental modal analysis

Experimental modal analysis (EMA) is important for understanding the dynamic properties of a structure. It can be used to validate mathematical models of the structure, to obtain design information e.g. structural damping and as a support when conducting structural dynamic modifications [24]. There are two main methods for conducting a EMA, when the exaction force is not measured e.g. heel-impact testing and when it is measured, e.g. impact testing [6].

Heel-impact testing is conducted as the name suggests: a person drop the the heel on the floor and the response is measured. It is therefore relatively simple to perform and can give good information about the dynamic properties, if there exist some approximate knowledge about the modal shapes of the structure before the measurement is conducted [5]. One of the biggest challenges with the heel-drops test is to accurately calculate the damping in the structure, because this demands careful filtering and averaging of the signal [5].

Impact testing is done by hitting the structure at a number of points with a impact hammer. Hereby, the force in the hammer is measured at the impact and if also the response is measured with a transducer, the FRF can be calculated [24]. Two important parameters when conducting impact testing is the selection of mass and tip for the hammer. The mass of the hammer gives the peak force imparted to the structure, which can be approximated as the mass of the hammer head times the velocity at impact [24]. The excited frequency range is then controlled by the selection of hammer tip [25]. A hard tip results in a short duration impact and gives a broad spectrum, while a soft tip results in a long duration impact and narrow spectrum [24]. A hard tip can therefore be favourable, although consideration should be taken not to deform the structure, which would affect the measurements. For impact testing it can also be difficult to get reliable measurements of the damping, which is especially true when the natural frequencies are closely spaced [5].

The most important component needed for EMA is the frequency response function FRF which contains information about the systems frequency dependence and damping [25]. The FRF can be interpreted as a proportionality coefficient, relating the magnitude and phase of a harmonic excitation component to the magnitude and phase of a harmonic response at a single point for a linear system [26]. By interpolating the peaks from a collection of FRFs, the modeshapes can be generated [25]. The FRF is calculated from the relationship:

$$U(\omega) = H(\omega)P(\omega) \tag{2.11}$$

where $U(\omega)$ can be interpreted as the response of the system for each harmonic, $P(\omega)$ the exaction and $H(\omega)$ the complex frequency response function (FRF) [27]. Since the FRF is calculated as a function of the angular frequency, the response most be transformed from the time domain to the frequency domain with a Fourier Transformation (FT) [27]. The challenge when using FT, is the limitations regarding the measurement time and sampling rate which will always result in some energy leakage when applying the transformation [25]. To compensate for this, weighting functions, so called windows, are used on the measured signal. There exists a multitude of different windows which will "modify" the signal in different ways [25]. The choice of which one to use depends on the properties of the signal [25]. The use of a window will create a less accurate signal, and the damping of the signal will increase [25]. But the errors are generally more acceptable than the energy leakage [25].

2.5.3 Response measurement

There are two main types of tests for measuring the response in a floor due to foot fall vibrations [10]:

- walking test, by measuring the response from when a test person walk across the floor
- impulse measurement from a heel-droop or impact hammer

The advantage with the walking test is that the experimental measurement mimics the response that will frequently occur after the building is finished [10, 6]. However, the exaction load from foot-steps can vary a lot between different individuals. Therefore, it is necessary to include a large group of different people in the measurement [10]. For example, Hicks et al. [10] recommends that 50 people should be included for a statistically valid evaluation. Another challenge is to decide the position for the transducers. It is recommended to place the transducers where the largest response is predicted [2, 10]. However, this point can be hard to determine, especially for complex floor structures [9].

Impulse measurements are conducted by measuring both the exaction and response. For a heel-droop test, this requires some type of special device for capturing the excitation, and for a hammer-test a impact hammer is needed. The advantage for both these types of measurement, is that the reproducibility is good. For the hammer-test, the major drawback; is that for low frequencies, the method is not valid [10].

Independent of the measurement type, some kind of post processing can be useful to be able to analyse the data. The appropriate technique will normally take two forms, either a calculated single value quantity e.g., a response factor, or the signal filtered in 1/3 octave bands or narrow bands. The choice depends on the characteristic of the signal and the criterion used as reference. If for example the signal is dominated by a single frequency component and the criterion regarding annoyance is evaluated, a response factor may be sufficient [5]. In contrast, when investigating vibrations affecting sensitive equipment, a narrow band filter can be more appropriate [12].

2.6 Structural dynamics

2.6.1 Modal analysis

The equations in this section, are based on the derivations from Chopra [27]. The principal notations are thereafter: lower case letters for scalar, bold lower case letters for square matrices and bold capital letters for square diagonal matrices.

To arrive at the equations that governs the modal analysis, the starting point will be the equation of motion for a multi-degree of freedom (MDOF) system which is damped and excited by an external force, defined as:

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = \mathbf{p}(t) \tag{2.12}$$

where $\mathbf{m}, \mathbf{c}, \mathbf{k}$ are the mass, damping and stiffness matrix. $\mathbf{u}$ represents the displacement vector, which with modal expansion can be expressed as:

$$\mathbf{u} = \sum_{r=1}^{N} \phi_r q_r = \mathbf{\Phi}\mathbf{q} \tag{2.13}$$

where q_r are the modal coordinates and ϕ_r is the natural modes of the system without damping. Assuming classical damping (diagonal damping matrix), and inserting Equation 2.13 into Equation 2.12; a uncoupled system of equations will be generated, expressed in the modal coordinates $q_r(t)$:

$$\sum_{r=1}^{N} [\mathbf{m}\phi_r \ddot{q}_r(t) + \mathbf{c}\phi_r \dot{q}_r(t) + \mathbf{k}\phi_r q_r(t)] = \mathbf{p}(t) \tag{2.14}$$

Premultiplying each term in Equation 2.13 with ϕ_n^T:

$$\sum_{r=1}^{N} \left[\phi_r^T \mathbf{m}\phi_r \ddot{q}_r(t) + \phi_r^T \mathbf{c}\phi_r \dot{q}_r(t) + \phi_r^T \mathbf{k}\phi_r q_r(t)\right] = \phi_r^T \mathbf{p}(t) \tag{2.15}$$

where Equation 2.15 will be orthogonal for the case of classical damping and all terms except the $r = n$ will vanish:

$$\phi_n^T \mathbf{m}\phi_n \ddot{q}_n(t) + \phi_n^T \mathbf{c}\phi_n \dot{q}_r(t) + \phi^T \mathbf{k}\phi_n q_n(t) = \phi_n^T \mathbf{p}(t) \tag{2.16}$$

Which cam be rewritten as:

$$M_n \ddot{q}_n(t) + C_n \dot{q}_n K_n q_n(t) = P_n(t) \tag{2.17}$$

Equation 2.17 is the uncoupled modal equation for the n-th natural mode, with:

$$M_n = \phi_n^T \mathbf{m} \phi_n, \quad C_n = \phi_n^T \mathbf{c} \phi_n, \quad K_n = \phi_n^T \mathbf{k} \phi_n \tag{2.18}$$

The set of N uncoupled modal equations for the entire system, can be expressed in matrix form as:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{P}(t) \tag{2.19}$$

where:

$$\mathbf{M} = \mathbf{\Phi}^T \mathbf{m} \mathbf{\Phi}, \quad \mathbf{K} = \mathbf{\Phi}^T \mathbf{k} \mathbf{\Phi}, \quad \mathbf{C} = \mathbf{\Phi}^T \mathbf{c} \mathbf{\Phi} \tag{2.20}$$

The matrices in Equation 2.19 will have the size $N \times N$ and are diagonal; with the $n \times n$ element defined by Equation 2.18

2.6.2 Finite element method

In this section, the finite element method will be described in broad terms. For a more detailed explanation the reader is referred to Ottosen et al. [28], which is also the source to the theory in this section.

The finite element method can be used to solve differential equations that is governing physical problems. The key feature of this method is to use a discrete system (finite unknowns) to approximate a continuous system (infinite unknowns). Hereby, the method also owes it name. For solid mechanics, this characteristic can be described as that a finite number of elements is used to describe a region. By decreasing the element size, the solution will convergence, i.e the approximate solution will approach the true solution

The approximation will be some kind of interpolation over each element. Where it is assumed that the solution is known in some points, so called node points, which are usually positioned along the boundary of the elements. Using more node points will give a more accurate solution. The approximation used should be at least a linear polynomial or of higher order. Choosing a higher order of polynomial can give a higher rate of convergence. But this is only valid to a certain point. One important criterion is that the polynomial contains all terms of a specific order and all terms of the polynomial below, to increase the convergence rate.

By applying some relationship between the elements, they can be assembled to describe the entire region. This can result in a system of equations with thousands of unknowns. To make it easier to solve this, it is common to reformulate the system with matrices. To solve such a system, some computer program is needed. In this thesis the program Abaqus will be used for the Fe-modeling.

2.7 Cross laminated timber

Cross laminated timber (CLT) is made up of layers with boards that are glued together and where two adjacent layers are orientated orthogonal to each other. The boards can be 20 to 60 millimetre thick and is normally organized in three, five or seven layers. The use of uneven layers is to increase the stiffness by orientating the top and bottom layer in the lengthwise direction. One CLT element can be up to 0.5 meter thick, 3 meters width and 24 meters long and can be used as both load bearing floors and walls [29]. The mechanical properties in the wood will differ over the cross section. Nevertheless, three different principal directions can be recognized, namely: the longitudinal direction (L), the radial (R) and the tangential direction (T), illustrated in Figure 2.3 [30].

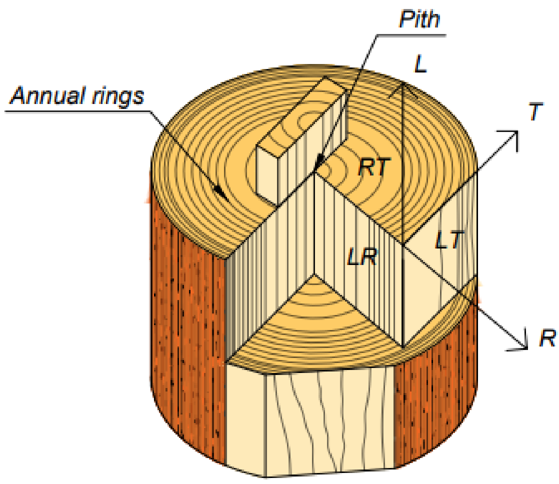

Figure 2.3: Principal directions of wood. Figure used with permission from [30]

3 Modal measurements

In this chapter, two types of modal measurement that were conducted are presented. The first measurement is for the floor resting on air cushions, while the second is for the floor when resting on two beams of laminated veneer lumber (LVL). The purpose of the measurements is to find material parameters and boundary conditions that can be used in the FE-model. Another reason is to investigate where to position the transducers when conducting the response measurement.

3.1 Test specimen

The CLT floor that was used for the measurements was manufactured by Stora Enso-The slab measured 2.45 m × 2.025 m and consisted of three layers with a total thickness of 80 mm. The layer at the top and bottom were each of 30 mm, and the middle layer was 20 mm thick. The bottom and top layer were orientated in the length wise direction while the layer in the middle was orientated orthogonal to the top and bottom layer, according to Figure 3.1.

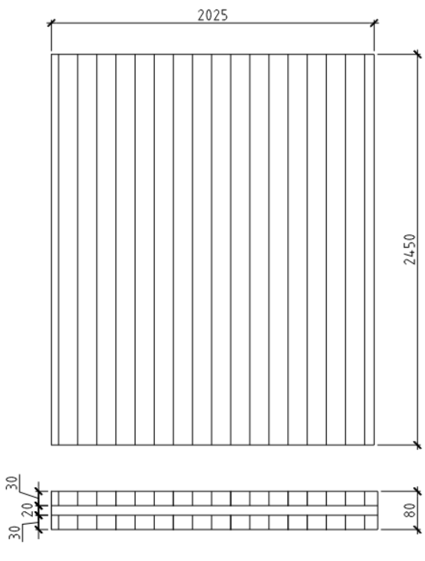

Figure 3.1: The CLT floor used for measurements

For the numerical simulations, the density was set to 420 kg/m^3, according to recommendations from [7]. Using this value, the mass for the floor could be calculated to 167 kg. The modulus that was used, are the ones given by SS-EN 338:2016 [31]. Because SS-EN 338:2016, does not present a value for the rolling shear modulus, G_{RT} or the poisons values, v, these were instead taken from [22]. All the different material parameters used in the simulation is gathered in Table 3.1 where the descriptor index is according to Figure 2.3.

Table 3.1: Stiffness parameters and density for C24 according to SS-EN 338:2016 [31] and with the rolling shear modulus from [22]. Moduli in (MPa) and mass density in (kg/m^3)

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E_L	E_T	E_R	v_{LR}	v_{LT}	v_{RT}	G_{LT}	G_{LR}	G_{RT}	ρ
11 000	370	370	0.48	0.42	0.28	690	690	49.0	420

3.2 Solid element model

A model based on solid elements will be used throughout the entire work (see Figure 3.2. The material properties in the top and bottom of the CLT-plate were defined by the lamellas spanning in the lengthwise direction. While the material properties in the middle layer were orientated orthogonal, along the width of the plate.

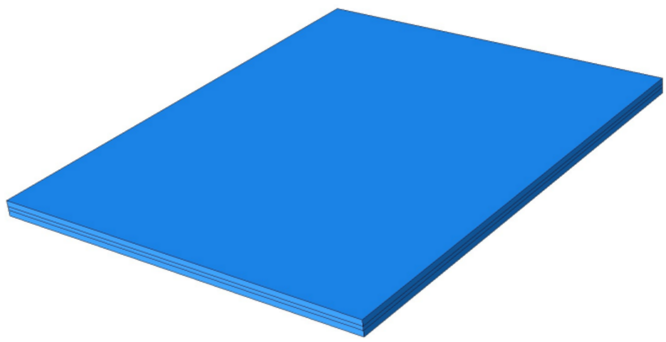

Figure 3.2: Model in Abaqus based on solid elements

3.3 Convergence study of the mesh

The convergence study for the mesh was done by first changing the size of the mesh in the plane and then in the thickness of the element. The investigation was conducted for the free-body model with the material properties according to Table 3.1. The elements in the mesh consisted of quadratic brick elements with 20 nodes and with reduced integration.

In the plane of the floor, the change in natural frequencies relative the element size 50 mm was calculated according to Figure 3.3. It can be noticed that the error is very small already at the element size 200 mm (0.035%). However, since the positions of the supports, transducers and impact points, will introduce some “restraints” in the mesh, the element size 50 mm will be used hereafter to minimize possible distortion.

In the thickness direction of the floor the mesh size was initially set to be equivalent to the board layers of the CLT, i.e elements with the size 20 mm, 30 mm and 20 mm. Another mesh size was also tested, where the element size was set to 10 mm for all board layers. The difference in natural frequencies is presented in Table 3.2 and is below 0.025% for all modes, why the mesh defined by the board layer will be used in the following.

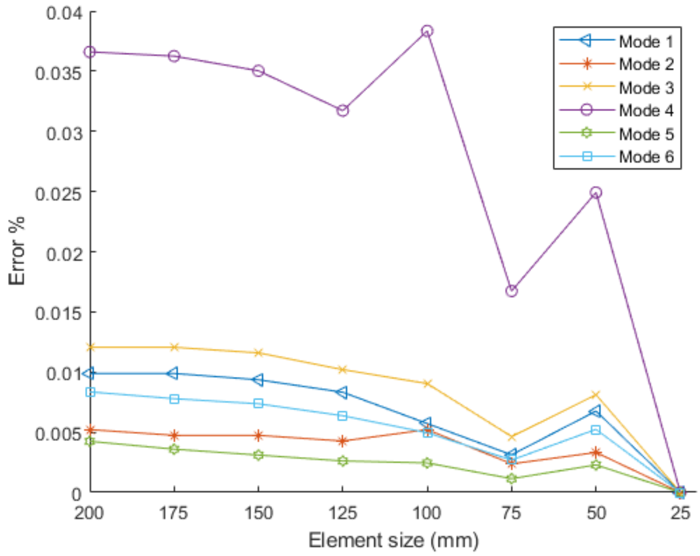

Figure 3.3: Convergence study for the floor when changing the element size in the plane of the floor

Table 3.2: Convergence study for the floor when changing the element size in the direction of the thickness for the floor. f_{1n} is the natural frequencies with the element size defined by the board thickness and f_{2n} is the natural frequencies with the equidistant element size, 10 mm

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Mode	f_{1n} (Hz)	f_{2n} (Hz)	Error (%)
1	20.554	20.553	0.001
2	22.533	22.532	0.006
3	46.100	46.095	0.009
4	61.317	61.305	0.021
5	65.453	65.450	0.005
6	75.490	74.486	0.005

3.4 Pre-experimental study

To calculate the modal properties of the floor when resting on “air cushions, a free body model was used, i.e. no boundary conditions were used in the FE-model. The first six mode shapes with their corresponding natural frequencies are given in Figure 3.7. To get a better overview of the natural frequencies, they are plotted against the mode number and are compared to the experimental measurement in Figure 3.8.

For the floor resting on LVL beams, a simply supported model was used; with only vertical boundary conditions which also; restrained it from lifting at the supports. Since the floor had a relatively low mass, the assumption about that no lifting occurred at the supports when a human walked across the floor, was controlled. This was done by applying a static mass of 120 kg at different positions on the slab. A static analysis was then conducted. Where the reaction forces at the supports were controlled, no lifting could be observed, therefore no consideration was taken to this in the FE-model used for predicting the response of the floor. The first six mode shapes with corresponding natural frequencies for the FE-model are given in Figure 3.10. And the natural frequencies plotted against the mode number and compared to the experimental measurement are presented in Figure 3.11.

3.5 Measurement grid

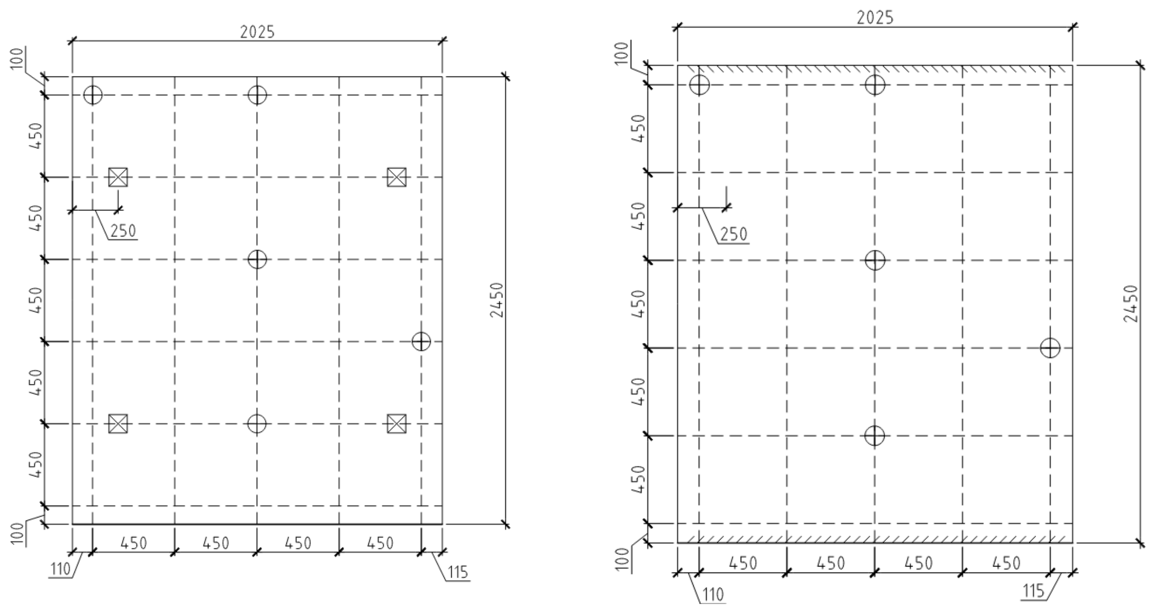
The method of deciding the position of the impact points can be described as a visual and iterative procedure. The mode shapes from the pre-experimental study were used as "blueprints". Then, a grid with a certain number of impact points was proposed. Subsequently, these were visually interpolated to check whether the proposed grid could capture the mode shapes of interest. 30 impact points were deemed sufficient to capture the first six mode shapes with a reasonable resolution, according to Figure 3.4. This pattern was applied for both type of measurements, thus when the floor rested on air cushions and when being simply supported.

Five accelerometers were at different positions in both measurements. In theory, one transducer would have been sufficient; if it could have been assured that the transducer was not positioned in any node point of the modes of interest. To minimize the risk for this to happen and, consequently, ruin the measurement, five transducers were used. In Figure 3.4 are the transducer's positions marked with a circle for the case when the floor is resting on air cushions and when being simply supported.

3.6 Measurement setup

For the measurement of the free-body, the floor was supported by four "air cushions" placed in wooden frames (see Figure 3.5c). These supports were positioned where relatively little movement in the plate could be observed in the first six modes from the pre-experimental study. This was done to reduce the damping from the supports on the floor. The air pressure in the air pillows was set to 1 bar to minimize the stiffness and to get natural frequencies in the supports that was substantially lower than the fundamental frequency of the floor. The motive for this was to ensure that the modes from the floor and from the support could be separated from each other. In Figure 3.4a, the air cushions are marked with crossed squares.

For the simply supported model two LVL beams of 40 mm width and 100 mm height; was used as supports (see Figure 3.5). The LVL beams were placed along the width of the floor and is marked with hatched lines in Figure 3.4b.



(a) **(b)**

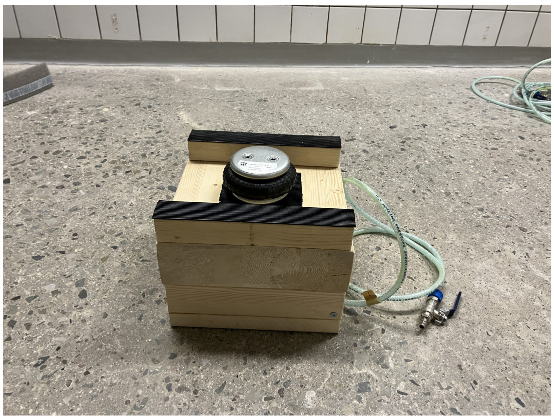
Figure 3.4: **(a)** Measurement grid and position of the supports for the floor when resting on air cushions. Intersection of the dashed lines marks impact points, circle marks accelerometer and square supports **(b)** Measurement grid and position of the supports for the floor when resting on two LWL beams. Intersection of the dashed lines marks impact points, circle marks accelerometer and hatched lines supports

One axial accelerometer from Brüel & Kjær with the sensitivity 1 mV^2 was used and fixed to the floor with poster putty. To minimize the risk of potential disturbance of the signals, the cables was fixed to the slab with duct-tape. Further, some extra consideration was also paid to the end of the cable that was connected to the accelerometer, to not restrain the transducer from moving.

The force hammer used, had a weight of 1.3 kg and sensitivity of 0.225 mV/N. A relatively hard tip was needed to properly trigger the response in the floor. Initially, a smaller hammer was tested. However, this gave a response that was too low to be properly measured, which might be explained by the relatively high damping in the CLT-floor.

(a)

(b)



(c)

(d)

Figure 3.5: **(a)** Floor supported by four air cushions **(b)** Floor supported by two LVL beams **(c)** Air cushions with the wooden frame that fixed it in position **(d)** Impact hammer used in the measurement

3.7 Measurement of the floor on air cushions

The mean frequency response function (FRF) for the measurement when the floor rested on air cushions is shown in Figure 3.6. Hereby, the values stable in both damping and frequency are plotted with a red square. The stable values should be sorted in a vertical line, meaning that the natural frequency is occurring at the same iteration. It is noticeable from the FRF, that resonance also occurs at 7 and 8 Hz. These were classified as false modes, based on the high damping and complexity. A reasonable explanation to these false modes is that there was resonance at the supports. The first six natural mode shapes from the measurement are presented in Figure 3.7 and the natural frequencies, modal damping and complexity in Table 3.3. In Figure 3.8 are the natural frequencies plotted against the mode number for both the measurement and the simulation.

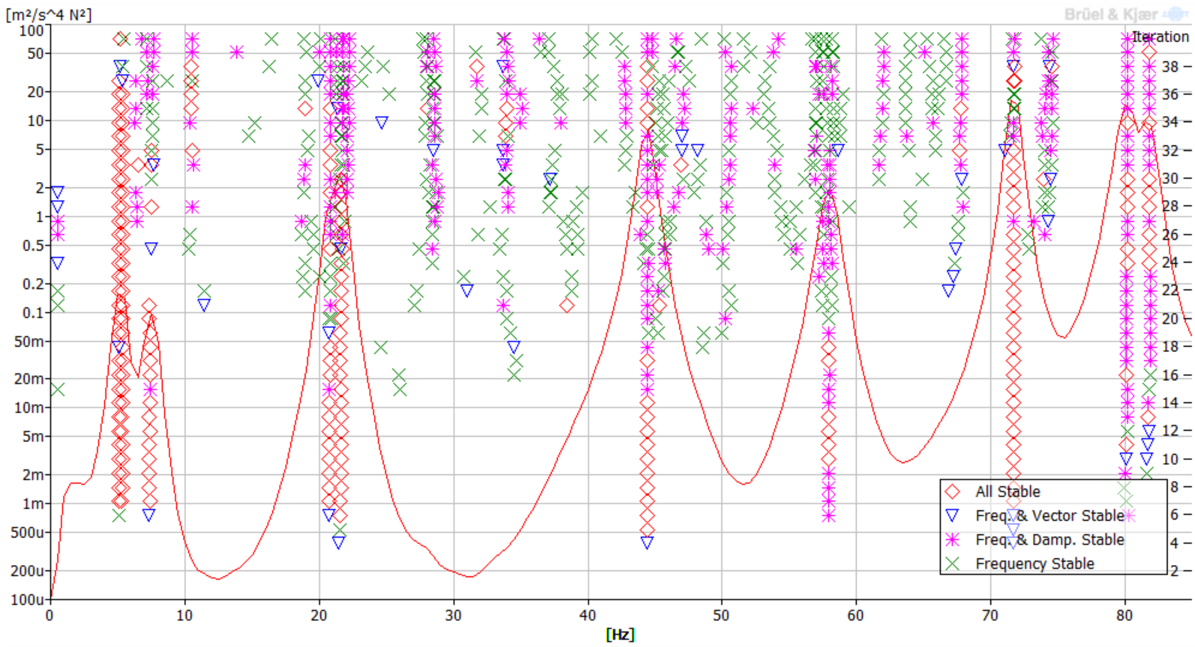


Figure 3.6: Mean frequency response function and stabilization plot when the floor was supported by air pillows

Table 3.3: The first six natural frequencies f, with corresponding damping ζ and complexity I for the experimental measurement when the floor was supported by four air cushions

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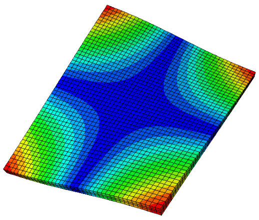
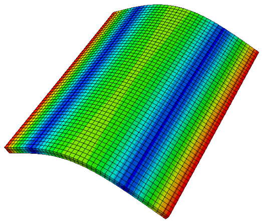
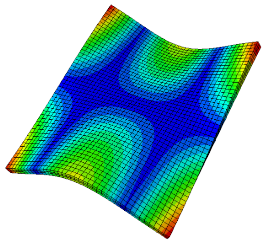
Mode	f_n (Hz)	$\zeta(\%)$	$I(\%$
1	20.8	2.9	12.6
2	21.6	2.8	2.5
3	44.4	1.9	0.5
4	58.0	1.6	3.9
5	71.7	0.9	2.2
6	80.1	1.2	10.2



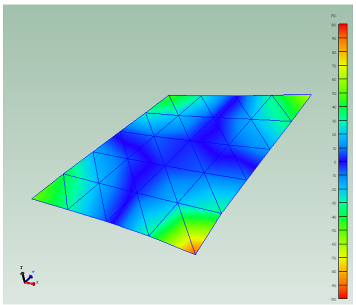
(a) Numerical Mode-1: $f = 19.2$ Hz



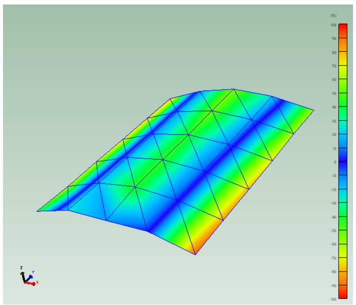
(b) Numerical Mode-2: $f = 21,1$ Hz



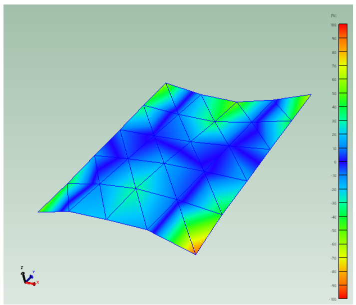
(c) Numerical Mode-3: $f = 43,1$ Hz



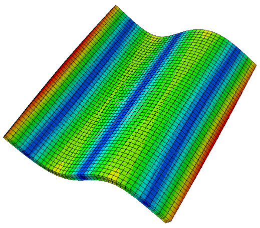
(d) Experimental Mode-1: $f = 20.8$ Hz



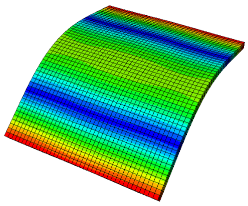
(e) Experimental Mode-2: $f = 21.6$ Hz



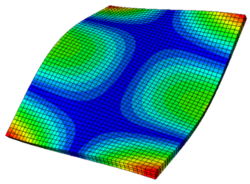
(f) Experimental Mode-3: $f = 44.4$ Hz



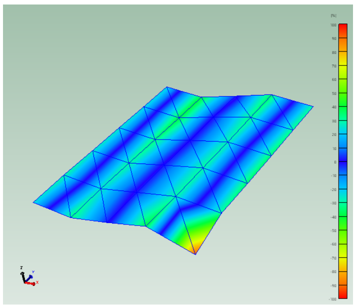
(g) Numerical Mode-4: $f = 57.4$ Hz



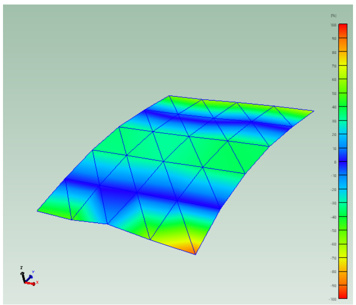
(h) Numerical Mode-5: $f = 61.2$ Hz



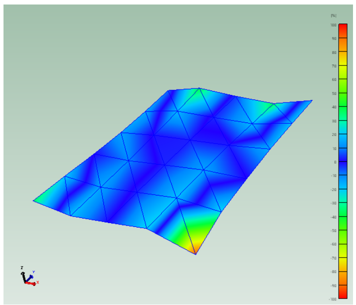
(i) Numerical Mode-6: $f = 70.6$ Hz



(j) Experimental Mode-4: $f = 58.0$ Hz



(k) Experimental Mode-5: $f = 71.7$ Hz



(l) Experimental Mode-6: $f = 80.1$ Hz

Figure 3.7: First six modes for the numerical simulation and experimental measurement when the floor was supported by four air cushions

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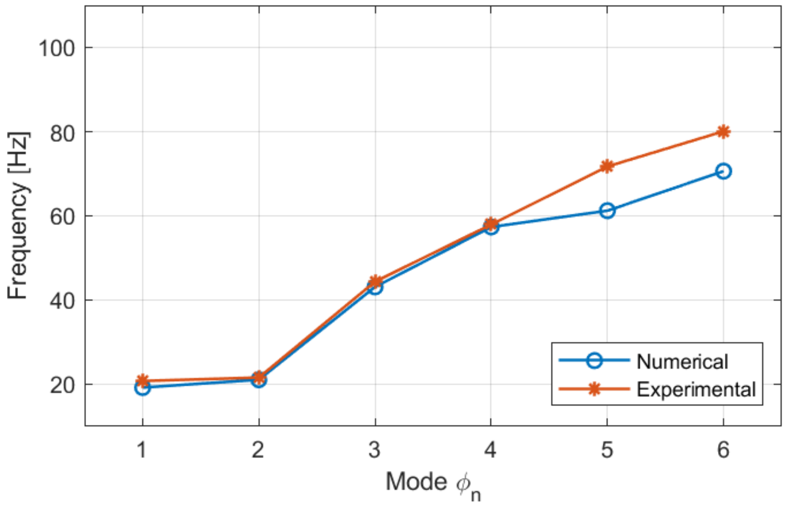

Figure 3.8: The natural frequencies for the numerical simulation and experimental measurement, respectively when the floor was supported by four air cushions

3.8 Measurement of the simply supported floor

The mean FRF for the measurement of the simply supported floor is shown in Figure 3.9. Again, values stable in both damping and frequency are plotted with a red square. The complexity and damping presented in Table 3.4 can be seen to be relative high for all modes and for the sixth the complexity was so high that it was discarded from further analysis. The first five mode shapes from the measurement are presented in Figure 3.10. Further, in Figure 3.11 the natural frequencies are plotted against the mode number for both the experimental measurement and the simulation.

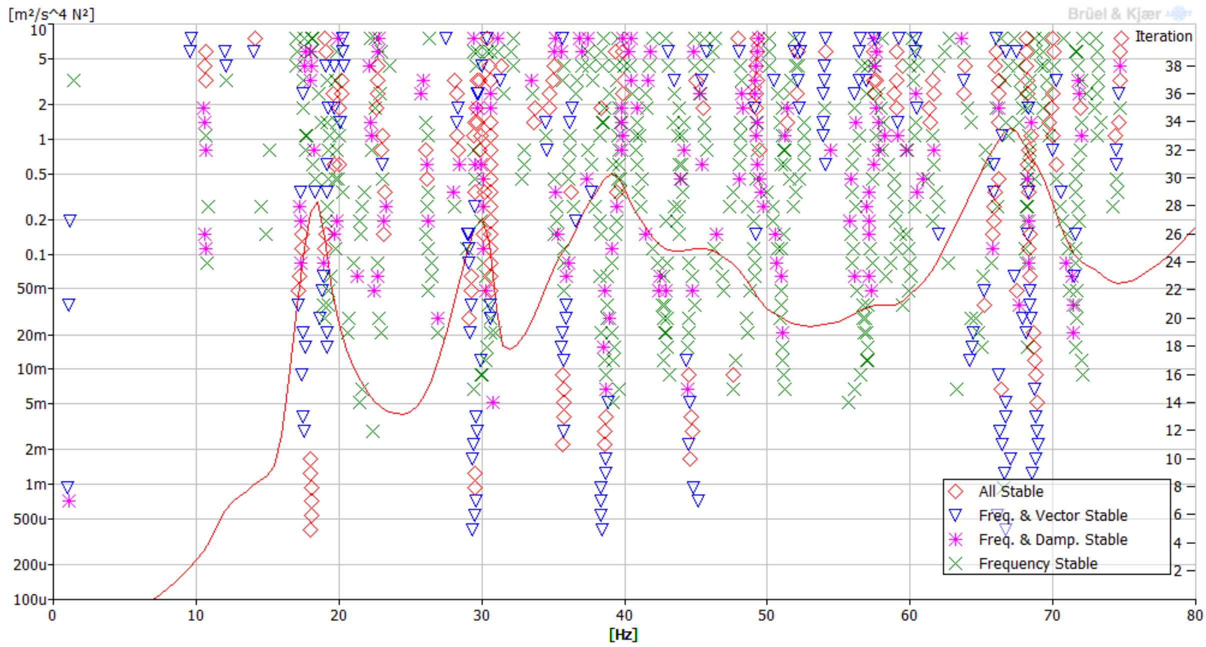

Figure 3.9: Mean frequency response function and stabilization plot when the floor was supported by two LVL beams

Table 3.4: The first five natural frequencies f, damping ζ and complexity I for the experimental measurement when the floor was supported by two LVL beams

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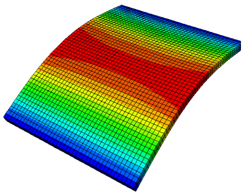
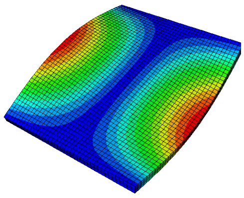
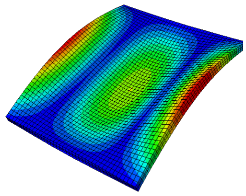
Mode	f_n (Hz)	ζ(%)	I(%
1	18.0	4.2	17.5
2	29.4	3.8	25.2
3	38.3	3.6	40.4
4	44.5	4.8	64.8
5	67.9	2.2	26.7



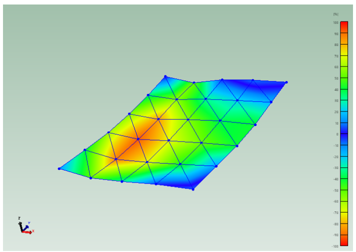
(a) Numerical Mode-1: $f = 29.1$ Hz



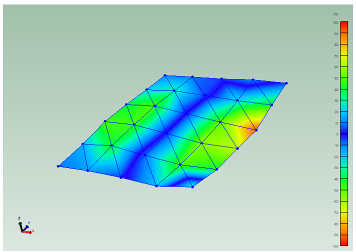
(b) Numerical Mode-2: $f = 33.9$ Hz



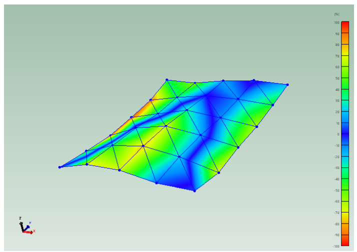
(c) Numerical Mode-3: $f = 50.5$ Hz



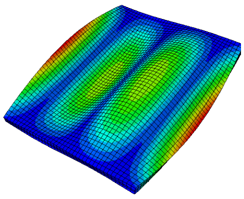
(d) Experimental Mode-1: $f = 18.0$ Hz



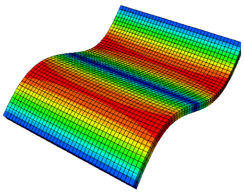
(e) Experimental Mode-2: $f = 29.4$ Hz



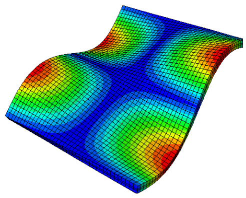
(f) Experimental Mode-3: $f = 38.3$ Hz



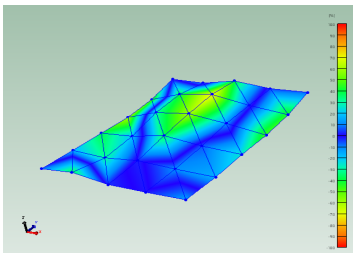
(g) Numerical Mode-4: $f = 84.2$ Hz



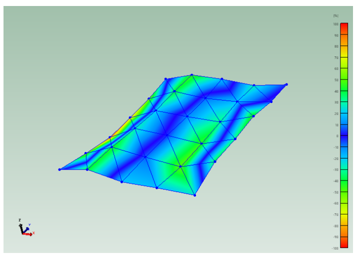
(h) Numerical Mode-5: $f = 102.0$ Hz



(i) Numerical Mode-6: $f = 106.2$ Hz



(j) Experimental Mode-4: $f = 44.5$ Hz



(k) Experimental Mode-5: $f = 68.0$ Hz

Figure 3.10: First five and six modes for the experimental measurement, respectively the numeral simulation, when the floor was supported by two LVL beams.

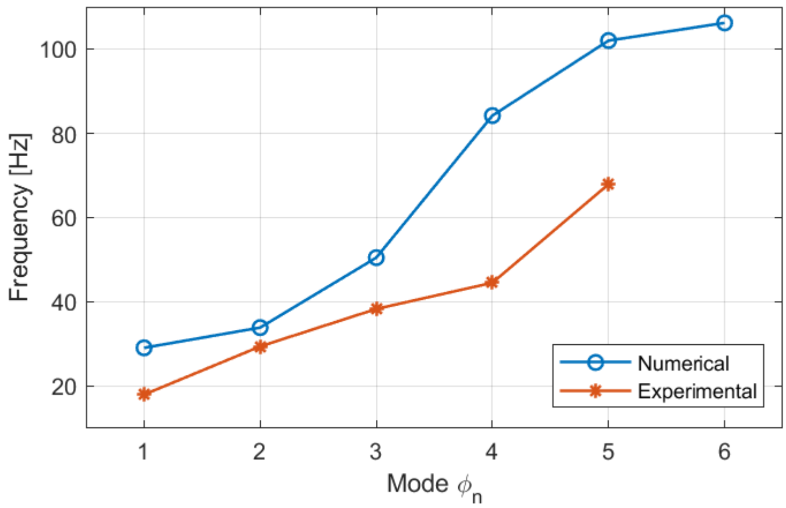


Figure 3.11: The natural frequencies for the numerical simulation and experimental measurement, respectively when the floor was supported by two LVL beams

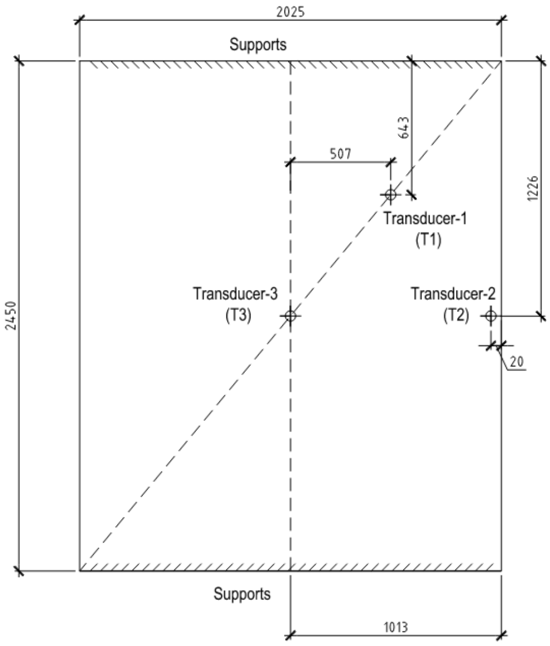
4 Measurement of structural response from walking

4.1 Measurement setup

For measuring the vibration in the test specimen, smaller CLT-plates was placed in the same level in front, behind and along one side (see Figure 4.1a). A small gap was left between the plates to minimize undesired vibrations in the CLT floor of interest. The use of multiple plates was to increase the effective area for the pedestrian to walk on, to ensure a normal walk pattern, and to achieve the prescribed pace rate.

The transducers were placed in a pattern according to Figure 4.1b. The positions were chosen to maximize the response from the different modal shapes. For example, if a transducer is only placed in the centre of the plate, the response from the first bending mode should be captured fairly well, while the second mode will be in a node point and therefore the response small.

(a)



(b)

Figure 4.1: **(a)** The measurement setup, with the longer plate in front of the test specimen and a shorter in the end **(b)** The setup for measuring the response in the floor. Dashed line marks walking path, crossed circles marks accelerometers, and the hatched contour lines are where the supports were placed

The response from twelve different persons was measured. The age of the persons was between $20-60$ years and composed of both men and women. The weight from all participants was measured and is given in Table 4.1. Each person walked straight and diagonally across the plate for the pacing rate 1.5, 1.7 and 2.0 Hz, giving a total of 72 measurements. A metronome was used to keep track of the pace rate.

Table 4.1: Weight of the persons that participated in the measurements

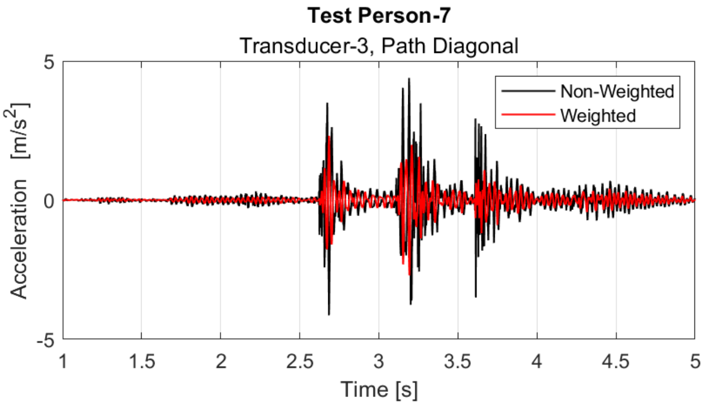
Person	Weight (kg)
1	82.4
2	69.7
3	87.5
4	77.1
5	72.2
6	95.8
7	96.7
8	82.1
9	113.0
10	62.6
11	65.6
12	77.4

4.2 Post-processing

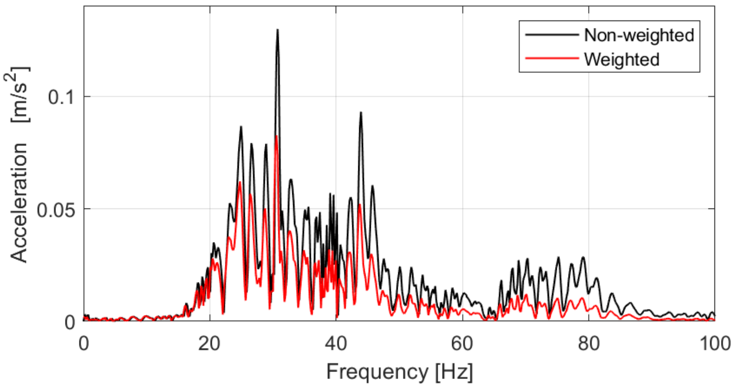
The purpose of the post-processing was to get a frequency weighted signal in the time domain to which different types of numerical evaluation methods can be applied on. To achieve this, the measured signals were first transformed to the frequency domain with the help of a Fast Fourier Transformation (FFT), and then weighted according to ISO 2631-1:1997 [3]. Since the weightings only exist for values up to the center frequency 400 Hz, all frequencies above this limit were set to the weight that corresponds to this maximum limit. After that, the signal was transformed back to the time domain by applying the Inverse-Fast Fourier Transformation (IFFT). To illustrate the difference between the measured signal and processed signal, this difference is shown in Figure 4.2 for Person-7 when walking along the diagonal path with the pace rate 2.0 Hz. The corresponding FFT can be seen in Figure 4.2b. It can be noticed that the frequency weight reduces the amplitude of the signal, resulting in a 48% reduction of the RMS over the full signal.

4.3 Response variation between people

To compare the response between the test persons, all measurements was normalized to the weight 80 kg. This is the mass recommended by Hicks et al. [10] for predicting



(a)



(b) 1

Figure 4.2: **(a)** Frequency weighted and non-frequency weighted response, respectively in Transducer-2 for Person-7 when walking along the diagonal path with the pace rate 2.0 Hz **(b)** FFT of the weighted respectively the non-weighted signal, respectively

vibrations and is also relatively close to the mean value, 82 kg of the test persons in this study.

Since all signals are of different lengths, an average over the whole signal will not be comparable. Instead, a Running RMS was used, consisting of a 1 second window shifting along the signal in steps of 0.01 seconds. As a illustrative example, the Running RMS is for Person-7 when walking along the diagonal path with the pace rate 2.0 Hz shown in Figure 4.3.

The maximum Running RMS of all persons are compared for the diagonal path in Figure 4.4 and sorted by the respective transducer. The corresponding result for the straight path can be seen in Appendix A. The mean values of the maximum Running RMS for all test persons, compared between the different transducers for the two paths, are presented in Figure 4.5a and Figure 4.5b, respectively.

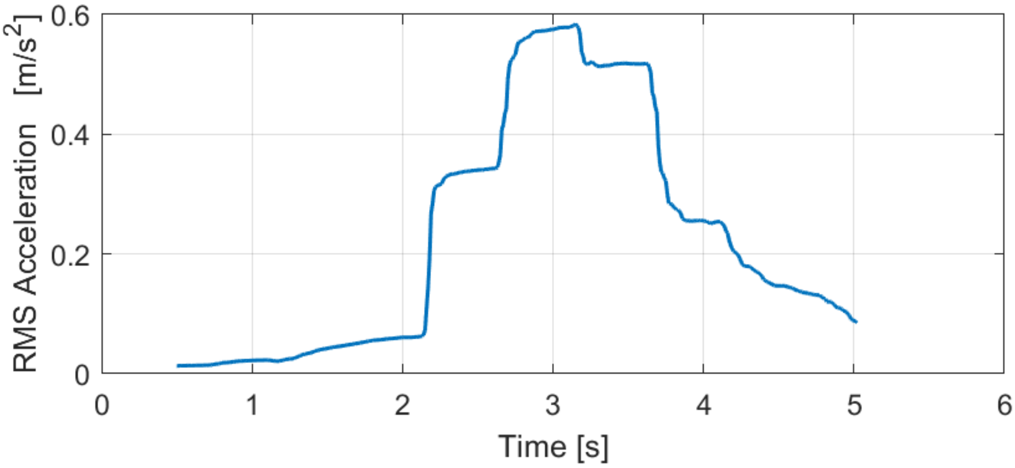


Figure 4.3: The Running RMS for Person-7, using a 1 second time window that shifts along the signal with increments of 0.01 seconds.

4.4 Investigation of walking path and transducer position

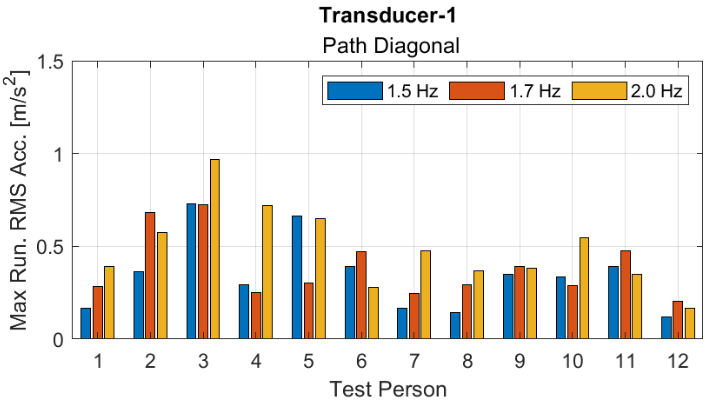
To investigate how the straight and diagonal walking path triggered different harmonic components in the floor, the signals was processed into a frequency spectrum with 1 Hz bands. This was achieved by:

- Applying the FFT on all signals
- The spectrum for all signals was then overlapped in one spectrum, containing all individual amplitudes for all persons.
- The overlapped spectrum was then divided into 1 Hz bands for which the amplitude for each band was calculated by taking the RMS of all values included in the respective band.
- A curve was then fitted to the centre frequencies of each band.
- As the signals from the different measurements did not have the same length, the amplitudes were not comparable. The overlapped signal was therefore normalized to the peak amplitude, giving a unit-less y-axis.

As example Figure 4.6 shows, the overlapped 1 Hz band spectrum for the transducers while walking along the diagonal, respectively straight path for the pacing rate 2.0 Hz.

4.5 Influence of the pedestrian´s weight

To analyse how the weight from the test persons effected the natural frequencies of the floor, the frequency spectrum processed in 1 Hz bands for the persons with the



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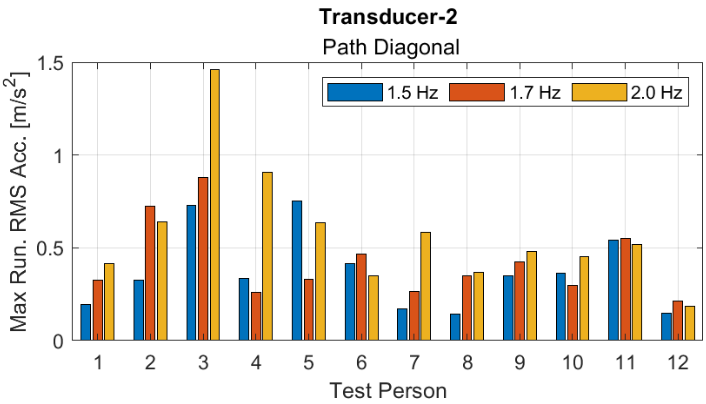

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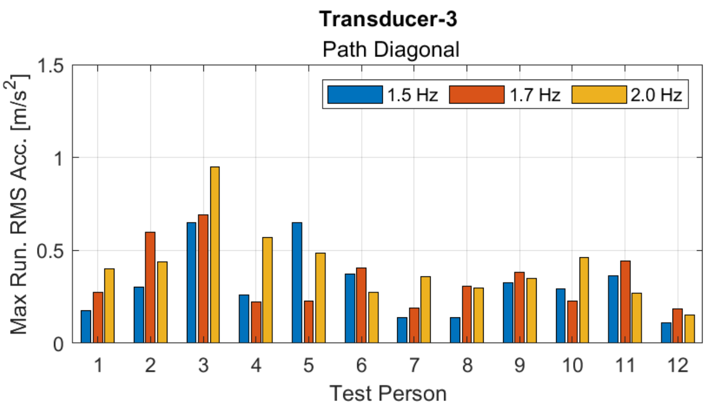
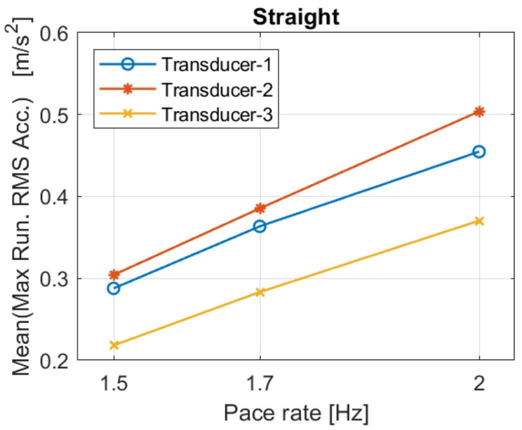


(c)

Figure 4.4: The maximum 1 second Running RMS when walking along the diagonal path for the different persons **(a)** Transducer-1 **(b)** Transducer-2 **(c)** Transducer-3

highest (113 kg) and the lowest weight (63 kg) were compared with the measured natural frequencies of the floor. This comparison is depicted in Figure 4.7. Since the amplitudes of the frequency spectrum are not comparable due to different signal lengths used in the FFT, the amplitudes were normalized to the maximum peak value for respectively curve, making the result unitless.

In Figure 4.8 is the maximum Running RMS plotted against the weight of the test



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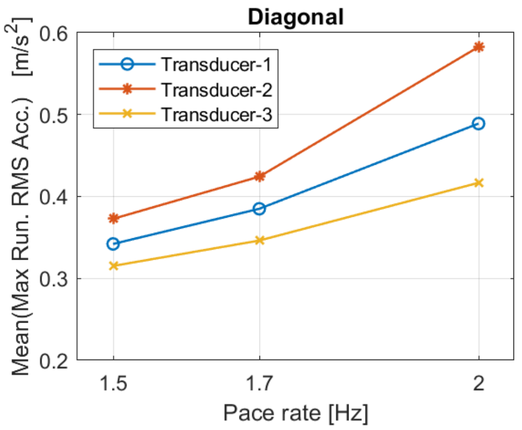
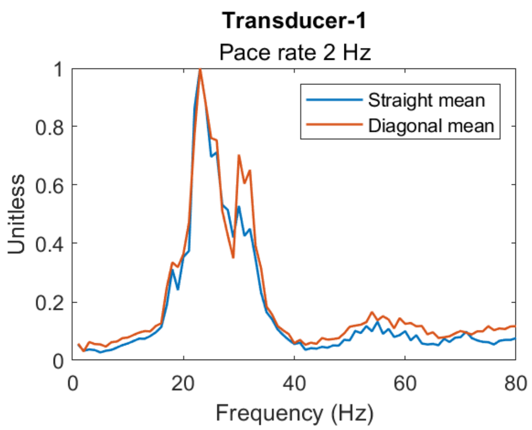


(b)

Figure 4.5: Mean of the maximum Running RMS for all test persons **(a)** Straight path **(b)** Diagonal path



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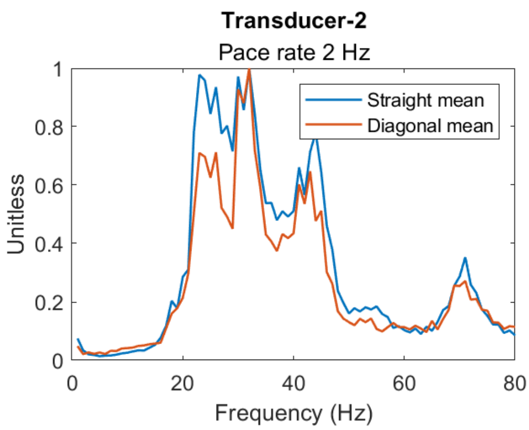

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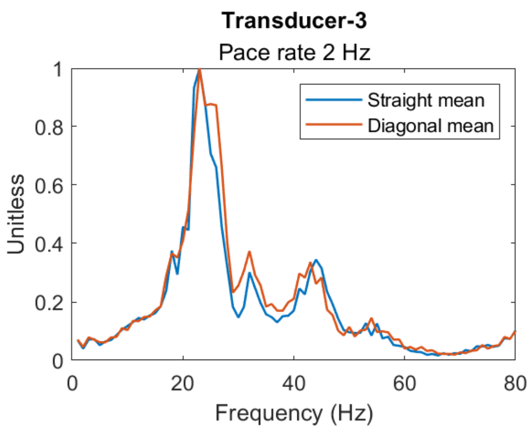

(c)

Figure 4.6: Overlapped response processed into 1 Hz bands, when walking along the straight and the diagonal path for the pacing rate 2.0 Hz. The amplitudes between the diagonal and the straight path is not comparable, due to different signal lengths

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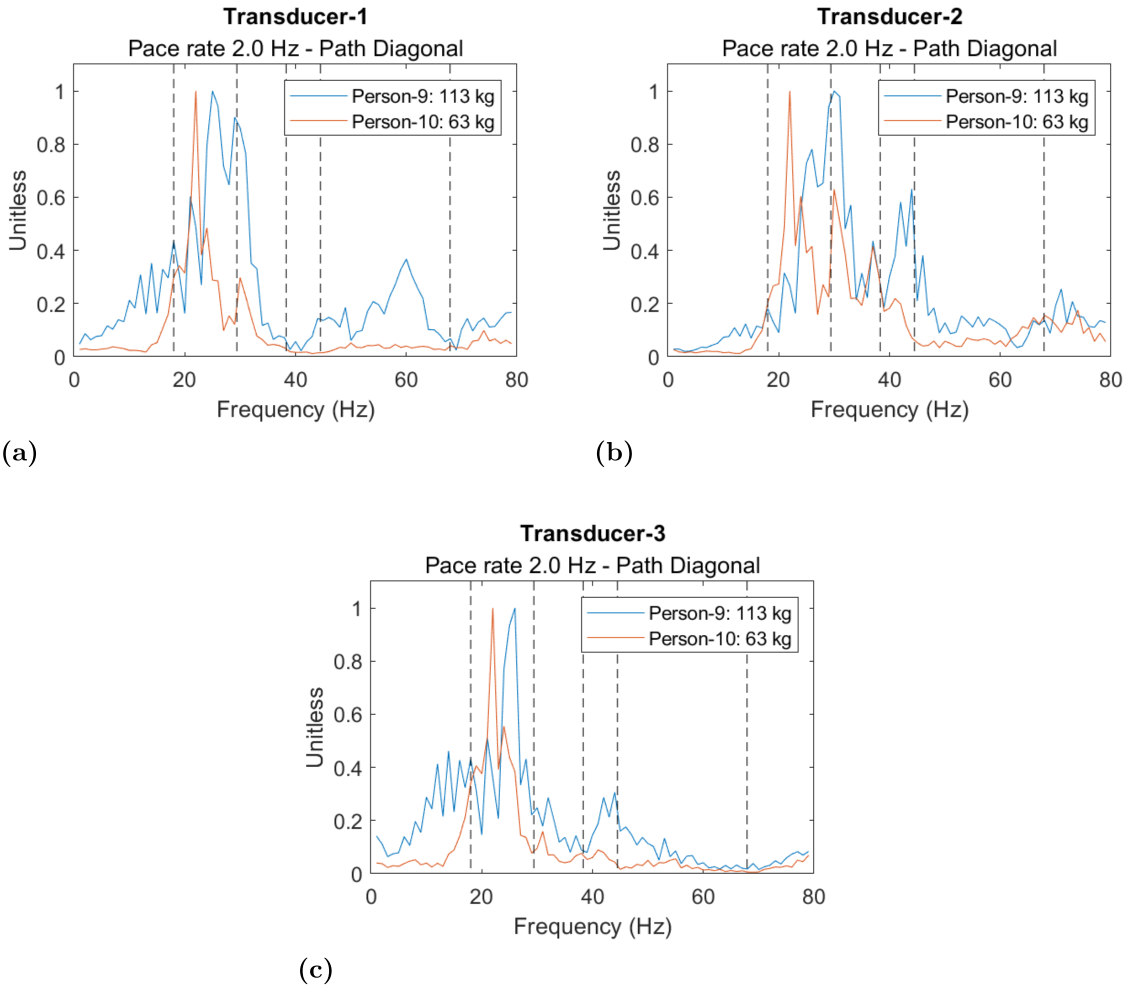

Figure 4.7: Comparison of how the weight affects the dynamic properties of the floor. The dashed line represents the natural frequencies

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person. The mass of the pedestrian was normalized to 80 kg and the Running RMS calculated as described in Section 4.3. The purpose with this plot, was to determine if the normalized response were decreasing with increased weight, which could indicate that the modal mass of the floor increased.

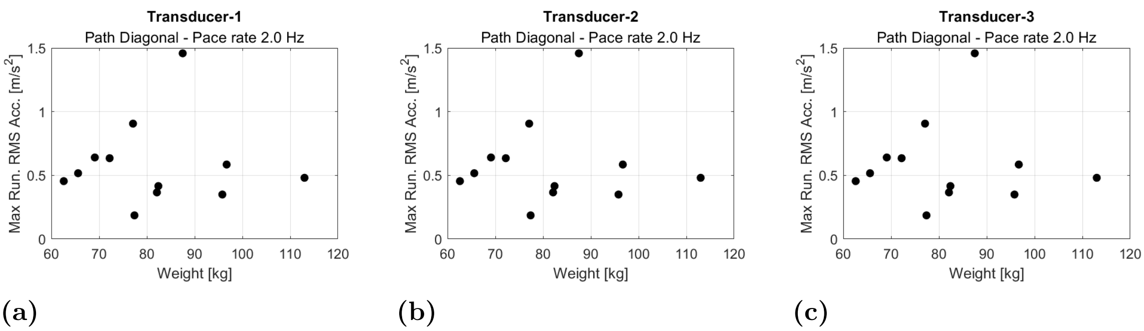


Figure 4.8: The response normalized to the body weight 80 kg, plotted against the test persons mas

4.6 Overall RMS, Running RMS and VDV

The different single value quantities, Overall RMS, Running RMS and VDV, used in ISO 2631-1:1997 [2] ISO 10137:2007 [3] will be investigated in this section to conclude which quantity that will be decisive. This is conducted for the frequency weighted response in Transducer-2 for Person-7 when walking along the diagonal path, with the pace rate 2.0 Hz, Figure 4.2a. The response for this signal was normalized to 80 kg. The choice of this measurement is motivated by that this sample has a maximum Running RMS that is very close to the mean value for this path and pacing rate (see Figure 4.4b and Figure 4.5b).

The overall RMS, Equation 2.1, was first calculated for the full signal length to 0.27 m/s^2. Since this average include parts with only background noise before and after the actual walking occurred. The RMS was also calculated for a smaller time window between $2.6 - 4.9$ seconds (see Figure 4.9a). This resulted in an effective RMS of 0.53 m/s^2, for the part that only contained the response.

The crest factor (quotient between max peak and RMS) was then calculated for the maximum peak, 2.31 m/s^2 and the effective RMS 0.53 m/s^2, to 4.4. As mentioned in Section 2.3, it is recommended to use a additional evaluation methods, either the Running RMS or VDV, when the crest factor is above 6 in ISO 10137:2007 [2] and above 9 in ISO 2631-1:1997 [3]. Even if this limit is not reached for this sample, the Running RMS and VDV will be further investigated, to illustrate their different characteristics.

For the running RMS calculated according to Equation 2.2, ISO 2631-1:1997 [3] recommend to use a one second window that shifts along the signal. The Running RMS for the sample is presented in Figure 4.3. Hereby, the maximum value can be seen to be 0.58 m/s^2, which corresponds to the position of the time window shown in Figure 4.9b. The ratio between the maximum Running RMS and the effective RMS can be calculated to 1.1. This should be compared to the limit of 1.5, after which additional evaluation methods are important according to ISO 2631-1:1997 [3].

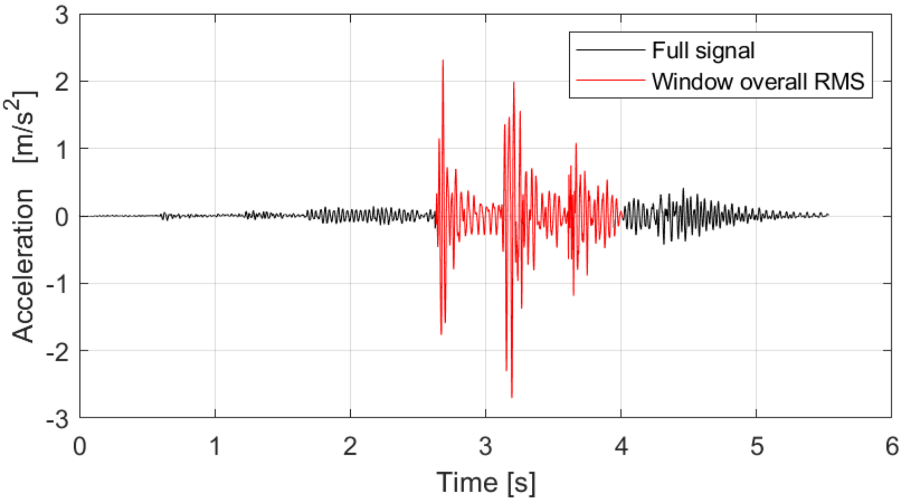
There is no advice in either ISO 2631-1:1997 or the more detailed description in BS 6472-1:2008 [3, 17] for which time period the VDV should be calculated. In this work the VDV will be calculated for the foot step with the highest peak amplitude according to Figure 4.9c, giving a interval between 3.1 s and 3.6 s. For this window the VDV was calculated with Equation 2.5 to 0.88 $m/s^{1.75}$. The RMS for the same window was calculated to 0.66 m/s^2.Applying these values into Equation 2.6 the approximate VDV can be calculated to 0.77 $m/s^{1.75}$. Comparing the calculated true VDV against the criterion, $0.8 - 1.6$ $m/s^{1.75}$, from ISO 10137:2007 [2] Table C.2 for residential buildings during day time. It can be concluded that even not one foot-step will fulfil this criterion.

4.7 Response in one-third octave band spectrum

In this section, the response in Transducer-2, normalized to 80 kg, when Person-7 walks along the diagonal path with the pace rate 2.0 Hz, (representing a mean response as elaborated in Section 5.3) will be analysed with a 1/3 octave spectrum. This will be done by using the frequency weighted signal and the none frequency weighted signal respectively, for the acceleration and velocity spectrum.

The full signal will be used in the FFT for transforming the time signal to the frequency domain, to get a denser spectrum and minimize the energy leakage. However, this reduces the amplitude of the spectrum, in comparison to only use the part of the signal that contains the response. To compensate for this, the amplitude of the weighted spectrum will be scaled by 1.96 which is the quotient between the weighted effective RMS, 0.53 m/s^2 and the RMS for the full weighted signal, 0.27 m/s^2, calculated according to Section 5.3. The scaled spectrum were then filtered into 1/3 octave bands. Hereby, the amplitudes for each band was calculated as the RMS of all values inside the specific band. The spectrum for the weighted acceleration processed into 1/3 octave bands is presented in Figure 4.10a. It is compared to the ISO 10137:2007 base curve with multiplying factor 1.

The velocity spectrum was calculated by doing a FFT on the non-weighted acceleration. The amplitudes were then scaled with the factor 1.93, calculated as the quotient between the non-weighted effective RMS, 0.89 m/s^2 and the RMS, 0.46 m/s^2, for the full none-weighted signal (see the paragraph above for a more detailed explanation of the scaling). The amplitudes was then divided with $2\pi f$, to convert them to velocity. The non-weighted velocity spectrum is given in Figure 4.10b in which it is compared to the generic vibration criteria for sensitive equipment, category-B and the ISO 10137:2007 base curve with multiplying factor 1.



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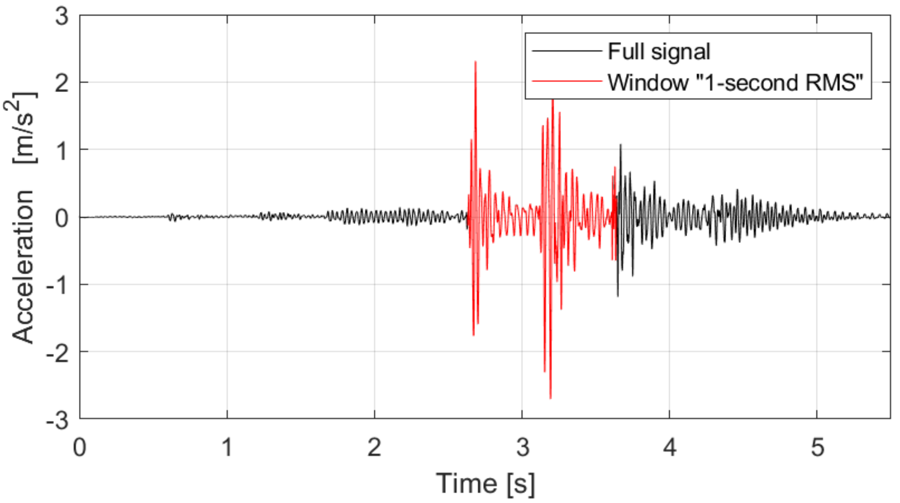

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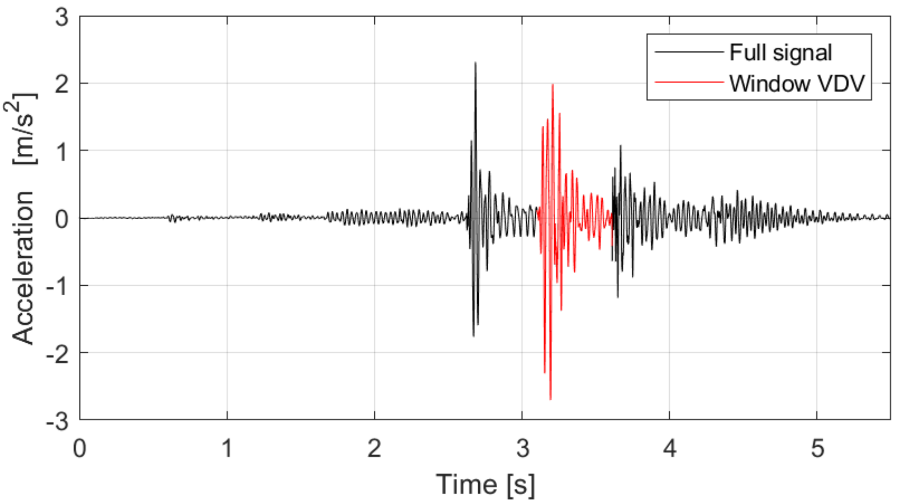

(c)

Figure 4.9: **(a)** The full signal length and the window used for calculating the effective overall RMS **(b)** The position of the 1 second window used for calculating the maximum Running RMS **(c)** The window used for calculating the VDV of one single foot step

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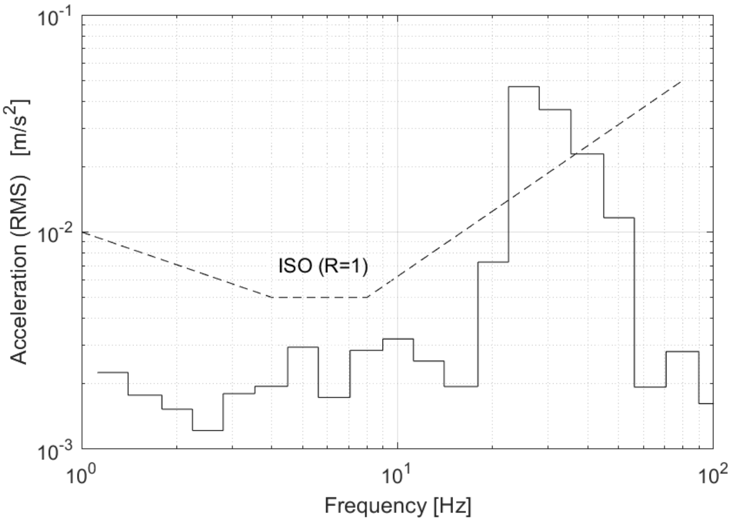
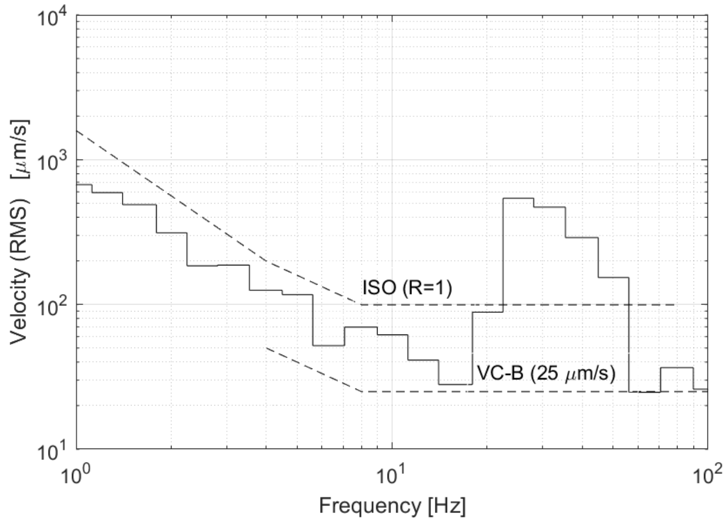


(a)



(b)

Figure 4.10: **(a)** Spectrum for the acceleration compared against the ISO 10137:2007 base curve with the multiplying factor 1 **(b)** Spectrum of the none-weighted velocity compared to the VC-B curve and the ISO 10137:2007 base curve with the multiplying factor 1

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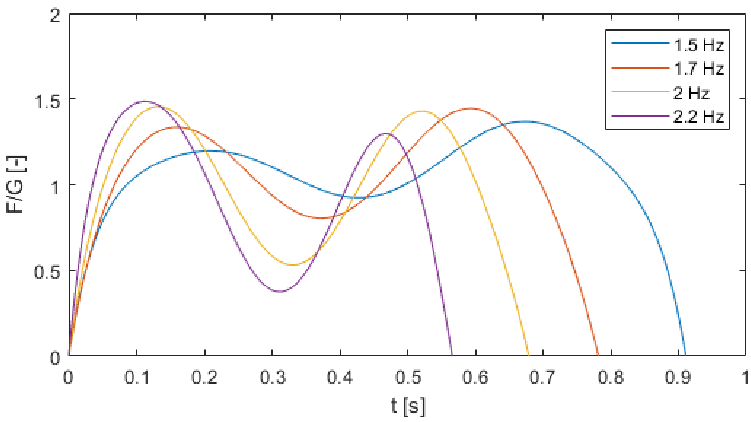
5 Prediction of structural response

5.1 Load function

For the numerical simulations, the time domain method from Hicks et al. [10] will be used in this thesis The force from each foot step is applied step-by-step with the load function according to Equation 2.7. Figure 5.1a illustrates the normalized load from one foot step at different pacing rates. It can be seen that the intensity increases with the step frequency. The functions have a butterfly shape, with the first maxima coming from the impact between the foot and the floor and, the second from the push off from the floor [10].

The overlapping force functions, where the load from each foot step was shifted by the time $1/f_s$ for the pace rate 2.0 Hz, are presented in Figure 5.1b. Figure 5.1c shows the the resulting function for the sum. Here, it is seen that the loading never disappears which is because one foot is always on the ground.



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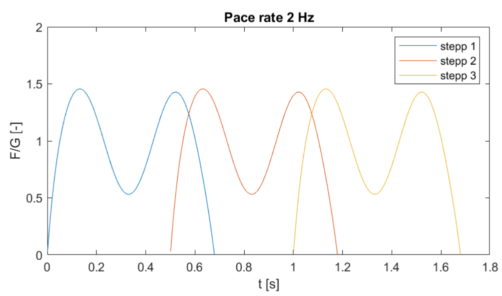

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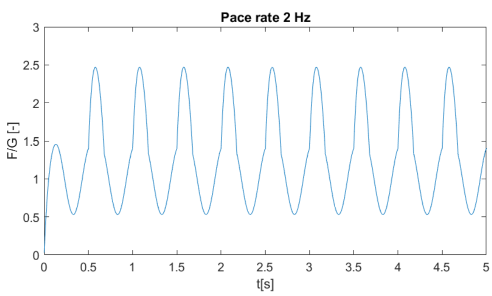


(c)

Figure 5.1: **(a)** The load function for different pacing rates **(b)** Illustration of how the load function overlap for three steps **(b)** The resulting load function when the steps are summed together

5.2 FE-model

In the FE-model the material parameters for the CLT-plate were set to C24 with values according to Table 3.1. A modal damping with the factor 1% was used, which reflects the damping of a simply supported CLT slab according to [32]. The simulations will be limited to the case when a person walks three steps along the diagonal path. One step will be fixed at the diagonal centre while the position of the other two steps will vary with the striding length (see Figure 5.2). The striding lengths were calculated according to Equation 2.8 and are summarized in Table 5.1. For convenience, these were rounded to the nearest one tenth of a meter. The width between the step was set to 0.2 m (see Figure 5.2). The simulations were conducted for 11 pacing rates in the range 1.5 – 2.5 Hz.

The load was calculated for the body weight 80 kg (as recommended in [10]) and applied in squares with the dimension 100 mm × 100 mm (see Figure 5.2); to reduce excessive deformations in the model. Since each square will introduce some "restraints" in the mesh, the elements size was decreased to 25 mm to minimize the distortion. In Section 4.5 it was demonstrated that the natural frequencies and the structural response were independent of the extra mass from the pedestrian. Therefore, the modal-mass of the floor will not be adjusted with the weight from the pedestrian.

Table 5.1: The step lengths used in the FE-model, rounded to one tenth of a meter

Pace rate (Hz)	Step length (m)
1.5	0.7
1.6	0.7
1.7	0.7
1.8	0.7
1.9	0.7
2.0	0.8
2.1	0.8
2.2	0.9
2.3	1.0
2.4	1.1
2.5	1.1

A convergence study for the time-step and modal truncation was done for Transducer-2 and the pace rate 2.0 Hz. The convergence criteria was set to the frequency limit 100 Hz and the appropriated time step was tested for 10 ms, 5 ms, 2 ms and 1 ms, using the first 50 modes and a signal length of six seconds. In Figure 5.3b, it can be seen in the spectrum, processed in 1 Hz bands, that the response has convergence for the step time 0.02 seconds. For this step, the number of modes was then reduced to 12 with the 12-th mode occurring at 199 Hz. In Figure 5.3a, the signal with 12 modes is compared to the signal with 50 modes. Thereby, no change in the frequency content could be observed, which is why the setup considered to be valid.

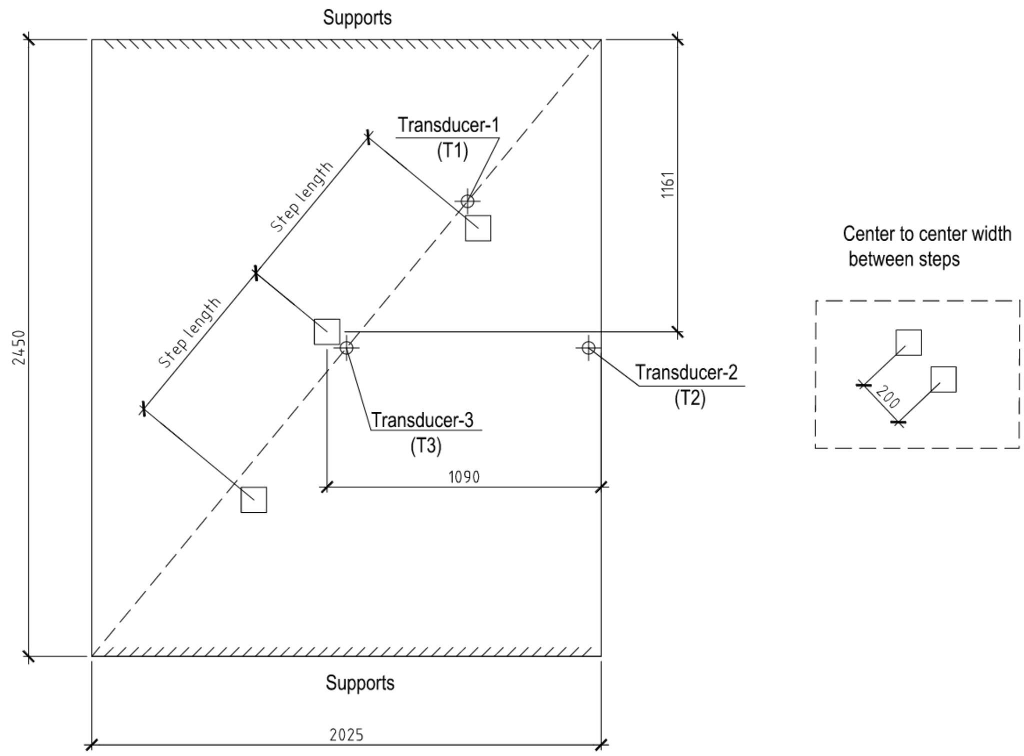
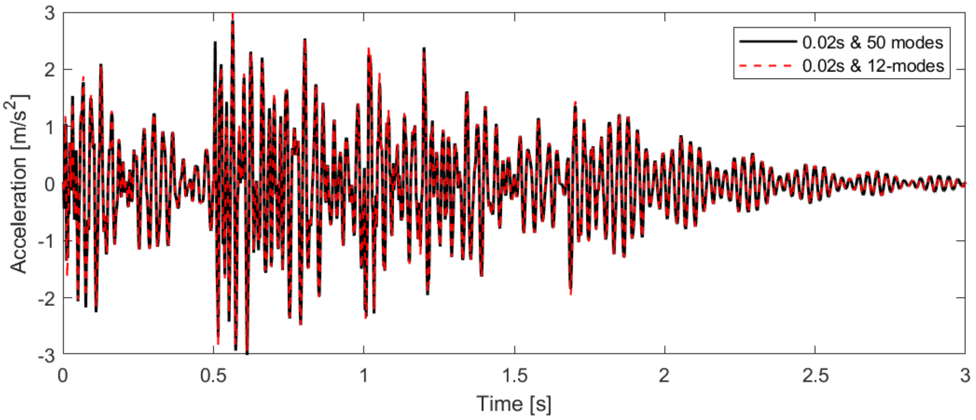


Figure 5.2: Illustrates how the load was applied in each of the three steps. The centre step was stationary while the position of the two other was changed as a function of the pace rate

5.3 Comparison between simulation and measured sample

The result from the simulations were post-processed with similar methods used for the measurements. The signals with a total length of 6 seconds were processed with a FFT. Then frequency weightings was applied according to ISO 2631-1:1997 [3]. After that the IFFT was used to transform the signal back to the time domain. In Figure 5.4 the frequency-weighted and none-weighted responses in Transducer-2 for the pace rate 2.0 Hz are compared.

To get a detailed picture of how the results of the numerical simulations relate to the experimental measurements, the response in Transducer-2 from Person-7, walking along the diagonal path with the pace rate of 2.0 Hz, will be compared against the corresponding simulation. The choice of Person-7 for the comparison, is motivated by that this sample is very close to the mean vibration level (see Section for further elaboration). The response for this measurement and the numerical simulation are plotted in Figure 5.5, where the result from the simulations have been shifted with 2.6 seconds.



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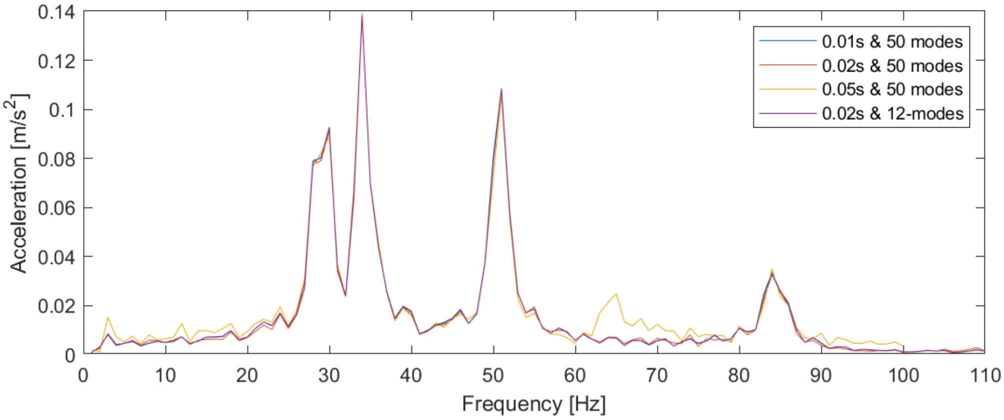

(b)

Figure 5.3: **(a)** Response in the floor at Transducer-2 for 12 modes and 50 modes for the time step 2 ms **(b)** Spectrum processed into 1 Hz bands for the signal length 6 seconds, comparing different time steps

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5.4 Response in all transducers

The maximum value of the 1-second Running RMS at the position of each transducer when walking along the diagonal path are presented in Figure 5.6. The numerical simulations are plotted against the result from the experimental measurement, which is represented by the mean value of all test persons for that particular path and pace rate.

The simulations were also conducted for a constant striding length of 0.8 meter, which corresponds to a pace rate of 2.0 Hz. The result from the simulations with constant respectively varying striding length for all pacing rates are presented in Figure 5.7.

To investigate how the response changes when the pacing rate is not constant, the second step was set to the pacing rates 1.5, 1.6, ..., 2.5 Hz (rounded to one tenth Hz). Thereby, the first step was reduced with 0.05 Hz respectively 0.1 Hz while the third step was increased with 0.05 Hz respectively 0.1 Hz relative the centre step. The

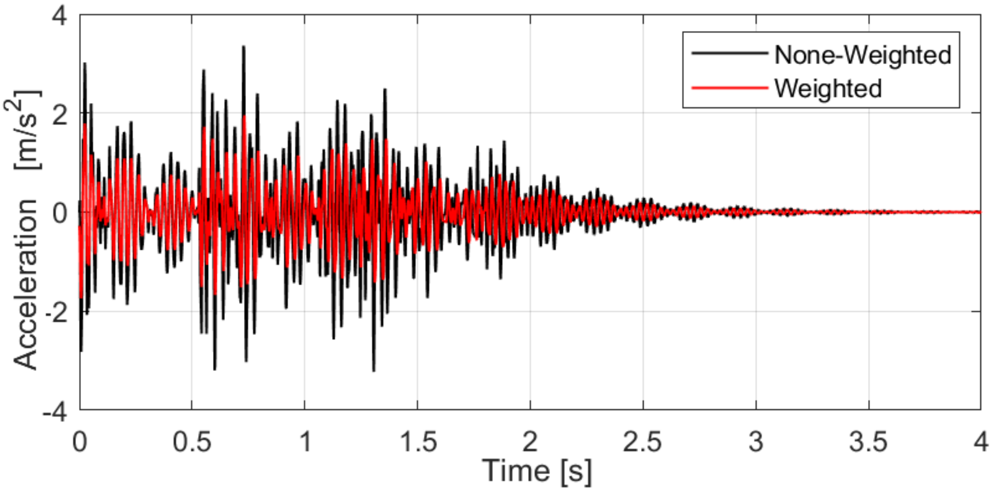

Figure 5.4: The weighed and non-weighted signal, respectively for the simulation in Transducer-2 when using the pace rate 2.0 Hz

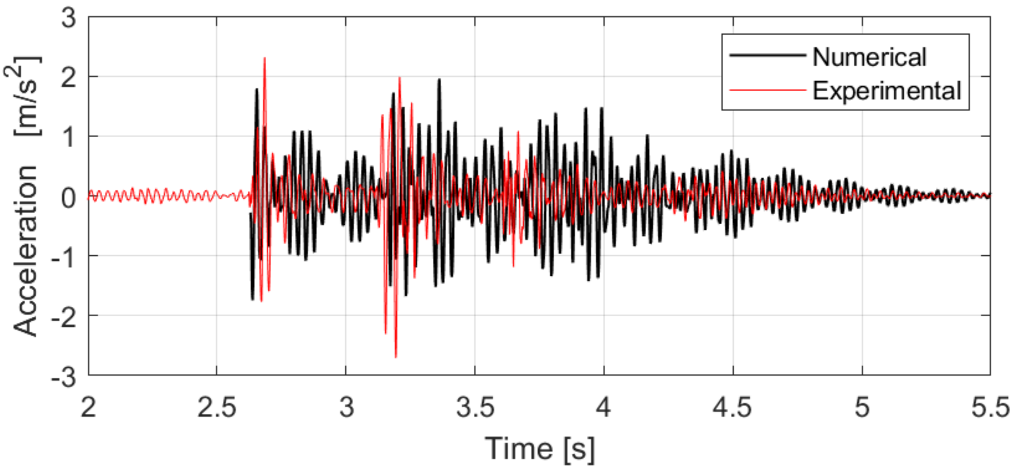

Figure 5.5: The response in Transducer-2 from Person-7 walking with the pace rate 2.0 Hz compared against corresponding simulation, shifted with 2.6 seconds

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varied pacing rates were then compared to a constant pacing rate. For all simulations the striding length was set to a constant of 0.8 meter, representing the step length for the pacing rate 2.0 Hz. The responses evaluated as the maximum 1-second Running RMS for Transducer-2 can be seen in Figure 5.8. The results for Transducer-1 and Transducer-3 the result are given in Appendix B.

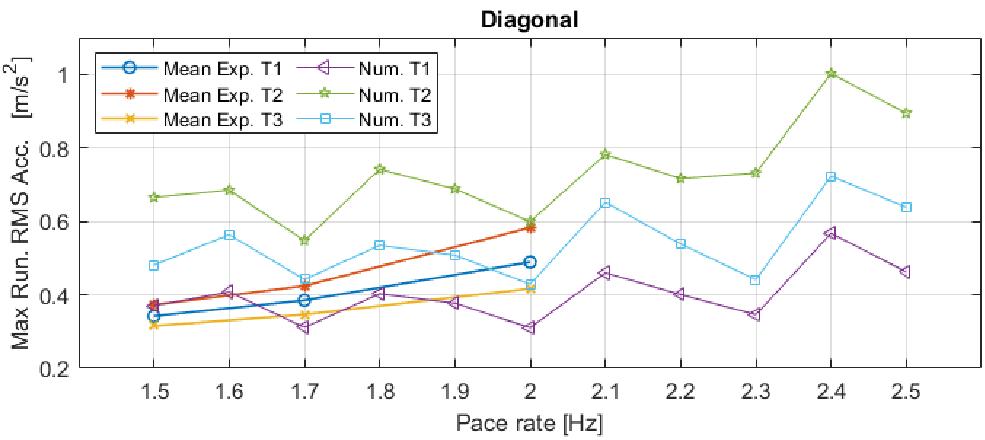

Figure 5.6: The maximum RMS for the numerical simulations compared against the mean value from the experimental measurements

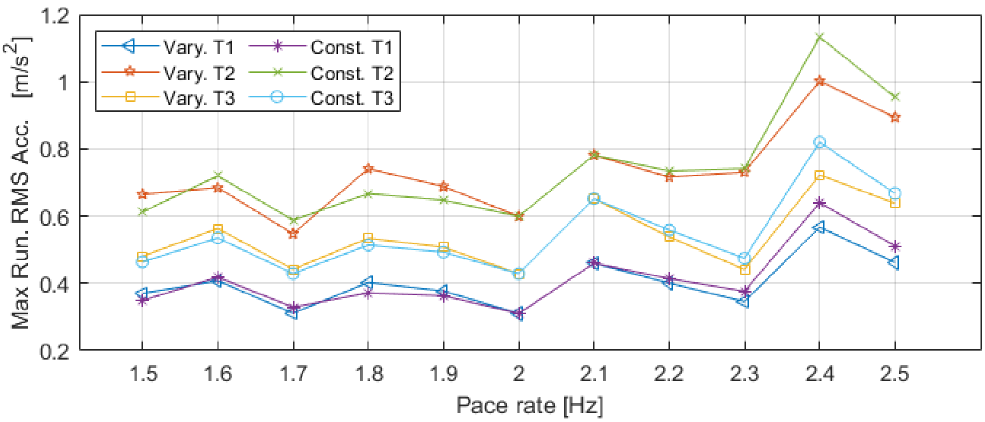

Figure 5.7: Varying striding length compared against a constant length of 0.8 meter

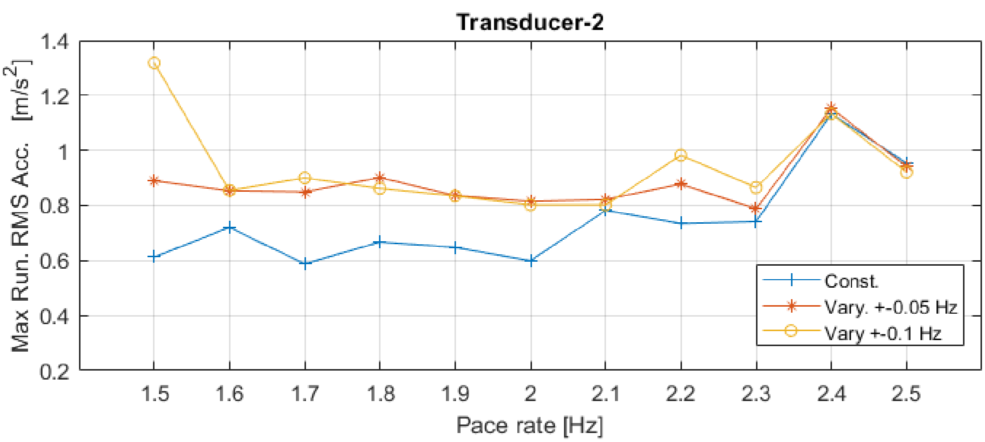

Figure 5.8: Response in Transducer-2 when the pedestrian has a constant pace rate and when the pace rate varies with ±0.05 Hz respectively ±0.1 Hz. The variation is relative to the second step which has a pace rate according to the x-axis

6 Discussion

6.1 Modal measurements

Even for the simple floor structure was it difficult to develop a calculation model that agreed well with the experimental measurements. The calculation model with the material parameters corresponding to C24 can be seen to correlate well to the measurements when the floor rested on the air-cushions for the first four natural frequencies. However, when using the LVL beams as supports, the dynamic properties were affected to a large extent, resulting in major deviations between the numerical simulation and the experimental measurements. For example, the first mode in the FE-model was 11 Hz (61%) higher than in the measurement. Further, many of the modes from the experiment were difficult to recognise in the numerical simulation. Probable causes to this are that the LVL beams used as supports were too weak and that there were small gaps between the supports and the panel, and the support and floor, respectively. This led to vibrations in the supports which affected the modes of the measured floor.

6.2 Measurement of structural response

The method of using single pedestrian to evaluate floor vibration has been and continues to be a topic for discussion [10]. From the measurements in this thesis, it was shown to be relatively large deviations for the response between different individuals (see Figure 4.4). However, the measurements were not statistically processed in this work, which is why it is not possible to give a recommendation about how many people that should be included in the measurements.

The walking path had a large impact on the overall response of the floor (cf. Figure 4.5). Therefore, this is something that is important to take into consideration when planning walking measurements. The CLT-plate that was investigated had a low weight and small size, which explains why the first four modes seems to be triggered independently of the path. For example, to not trigger the first twisting mode, the person walking would have to position their foot-steps very close to the centre line of the plate. It is therefore possible that the response will be more dependent of the walking path for larger floor constructions.

The response was dominated by the contribution from the first five modes, having frequencies from 18 – 68 Hz (cf. Figure 4.6 and Figure 4.10). However, it is not recommended to use such few modes in calculation models. For example, to use ten modes will increase the accuracy of the model, if only slightly, while the computational time for a normal sized system will still be low.

It was investigated how the weight of the pedestrians affected the natural frequencies and the response of the floor panel. It can be concluded that these properties were not affected by the mass of the pedestrian (cf. Figure 4.7 and Figure 4.8). As stated in Pavic and Paul [21], this is maybe explained by that the moving humans will act as a dynamic force and therefore only have a negligible effect on the dynamic properties of the floor.

A problem that was illustrated in Section 5.3 and Section 4.7, is the lack of guidance in ISO 10137:2007 [2] and ISO 2631-1:1997 [3] regarding how the overall RMS, running RMS, VDV and 1/3 octave spectrum, should be calculated. Using different lengths and parts of the signal will change the quantity used for evaluation, leading to ambiguity. For example, to obtain a frequency spectrum with low energy leakage from the raw data, it is necessary that the transformed signal is long enough. Yet, increasing the signal length will give lower average amplitudes for the spectrum, assuming that the length of the effective response in the signal is constant (see Figure 4.9a). The 1/3 octave spectrum for the acceleration and the velocity, respectively, was calculated for the full signal length. However, to compensate for the resulting reduced energy in the spectrum, the amplitudes were scaled with the quotient of the RMS over the full signal and over the effective signal. This scaled all the amplitudes in the spectrum by the same factor, which is not correct, but still, more conservative than not doing so. A better solution would be to minimize the energy leakage instead of compensating for it. This could be achieved by a more thorough post-processing technique, for example by reducing the signal to only contain the response and no background noise, and then apply an appropriate window. The signal could then also be overlapped to get a denser spectrum.

It could be seen that the Crest factor for the test floor was well below the limits used in ISO 10137:2007 [2] and ISO 2631-1:1997 [3]. For floors with a fundamental frequency lower than the test specimen at 18 Hz, the transient versus the steady state response will give a even lower crest factor with regards to foot-steps. It is therefore doubtful that it will be necessary to use any of the “additional methods” (the Running RMS or VDV), when analysing footfall induced vibrations for floors with a fundamental frequency below 18 Hz. Instead, the vibration criteria will be governed by the base curve for human annoyance or limited by a specific level for sensitive equipment.

The use of the approximate VDV, Equation 2.6, instead of the true VDV, Equation 2.5, can also be questioned. The authors guess is that this formula was developed to be able to directly calculate the VDV with the RMS given by the frequency spectrum. This would be convenient, since it is then not necessary to apply the IFFT. However, the problem with this approach is the same as elaborated in the previous paragraph; how to calculate the frequency spectrum for only the part of the measured signal that contains the response of interest and still ensure a sufficient quality of the transformation. If it is not possible to obtain a sufficient quality on the frequency spectrum, then it is not valid to calculate the RMS from this, why the approximate VDV also not will be valid.

6.3 Prediction of structural Response

The difference in the 1-second Running RMS of the measurements and the simulations can probably be explained by two factors:

- The difference in the natural frequencies between the FE-model and the experimental measurement according to Figure 3.11
- The assumed damping of 1% in the FE-model was too low, which can be seen in Figure 5.5

It is therefore not possible to draw any conclusions about how the FE-model performed against the experiments, by comparing respective RMS. However, it can be noticed from the simulations, that no significant trend exists for how the response changes with the pacing rate. This can probably be explained for the simulation by that the load from the foot-steps triggered resonance in the floor at certain frequencies. Comparing this to the experimental measurement, where there is an indication that the response seems to increase with the pacing rate. Nevertheless, it is important to emphasize that the measurement was only conducted for three pacing rates which is why this interpretation should be treated cautiously.

Both in the measurements and the simulations it could be seen that there was no vibration build up between adjacent steps. In other words, the overlap of the load from adjacent foot-steps did not lead to an increased vibration level. It is therefore not surprising that the striding length had no major impact on the response from the FE-model, except for the pace rate of 2.4 Hz; for which the response decreased slightly when using a constant striding length. A possible explanation to this phenomenon, is that the position of the load, triggered the modes in some unfavourable way and therefore increased the vibration level in this case. When using the investigated load function, it is therefore recommended to control if any response build up is noticed in any point with large response. If it can be concluded that this does not happen, there is no need to adjust the step length, which can save time when creating the model and reduce potential problems with the mesh.

When varying the pace rate instead of keeping it constant, the response increased. This may be a consequence of that the load will excite the structure with a broader spectrum of frequencies, and therefore an increasing chance of exciting resonances.

7 Concluding remarks

7.1 Conclusions

The purpose of this work was to gain a greater knowledge about how to measure, predict and evaluate vibrations in HFF. The conclusions are as follows:

- For the walking measurement the vibration response deviated to a large extent between the different individuals that participated.
- The pedestrian walking path had a large influence on the vibrations in the experimental measurements.
- When modelling floors due to footfall induced vibrations from a single pedestrian, the mass of the moving human can be neglected when calculating the modal properties.
- There is a lack of general guidance in ISO 10137:2007 [2] and ISO 2631-1:1997 [3] regarding the post processing of the signals. The length of the signals and how the signal should be transformed to the frequency domain, to ensure an adequate quality; needs to be specified to get comparable results regarding the RMS, running RMS or the VDV.
- When using ISO 10137:2007 [2] and ISO 2631-1:1997 [3] it is doubtful that the VDV and Running RMS will be the limiting criteria for footfall induced vibrations in floors with a fundamental frequency below 18 Hz. Instead, the base curve for human perception (cf. Figure 2.1) or a benchmark for sensitive equipment (cf. Figure 2.2) will be decisive.
- It was not possible to obtain a FE-model that had natural frequencies that was comparable to the experimental setup for the walking measurements. Therefore, it is not possible to draw any conclusions about how the amplitude of the vibrations from the investigated load function compare to the experimental measurement.
- The response predicted by the time domain model was to a large extent influenced by resonance. From the measurements of the three walking paces, the maximum running RMS indicates that the response is more transient and increases with the pacing rate (see figure 5.6).
- When using the time domain model, it is recommended to control if any response build-up occurs between adjacent foot-steps. If this does not happen, it is not necessary to vary the striding length in the FE-model for the investigated load function. This saves time creating the model and possible distortion in the mesh.
- The maximum running RMS calculated with the time domain model was sensitive to when the pacing rate was changed for each step (see Figure 5.8).

7.2 Future research

Suggestions for further work are as follows:

- Developing recommendations about how the post-processing of signals from measurement and simulations should be conducted to ensure comparable results from the used evaluation method.
- Investigation about how many individuals should be included in walking measurements and how the measurements should be statistically processed.
- More measurements and simulations on different type of HFF, e.g varying the material, stiffness, mass and span length, to explore how the response change with the pacing rate.
- A more thorough investigation of if the time domain model is appropriate for HFF. This can be done by using different materials and span length, but also by comparing it to other types of load models.

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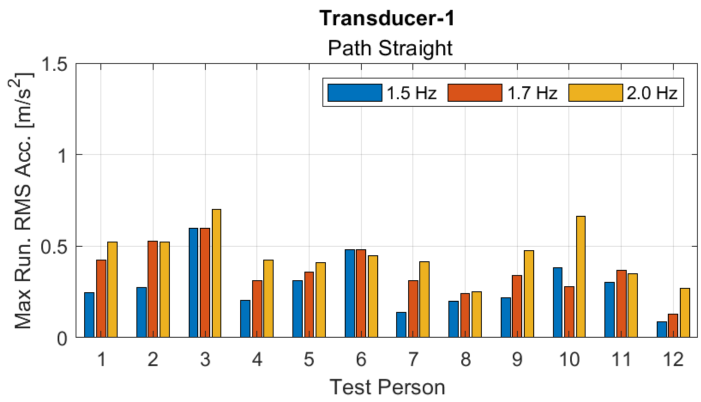
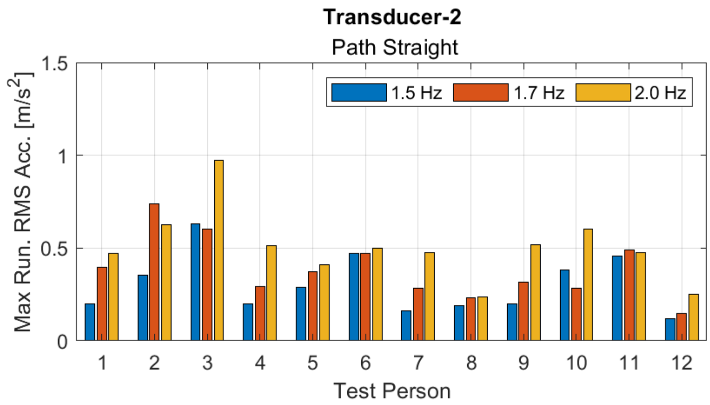
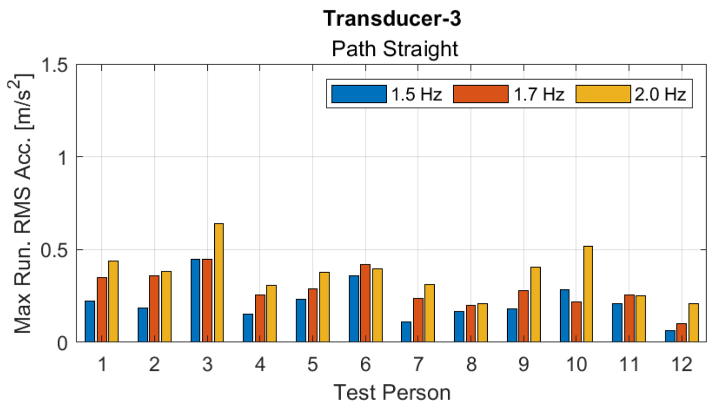
A Measured response - straight path



(a)



(b)



(c)

Figure A.1: The maximum 1 second Running RMS when walking along the straight path for the different persons **(a)** Transducer-1 **(b)** Transducer-2 **(c)** Transducer-3

B Varying pacing rate

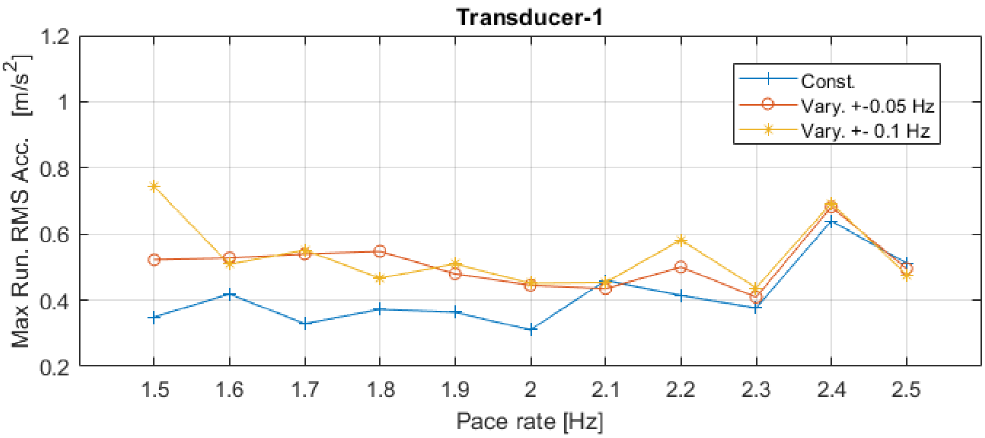


Figure B.1: Response in Transducer-1 when the pedestrian has a constant pace rate and when the pace rate varies with ±0.05 Hz respectively ±0.1 Hz. The variation is relative to the second step which has a pace rate according to the x-axis

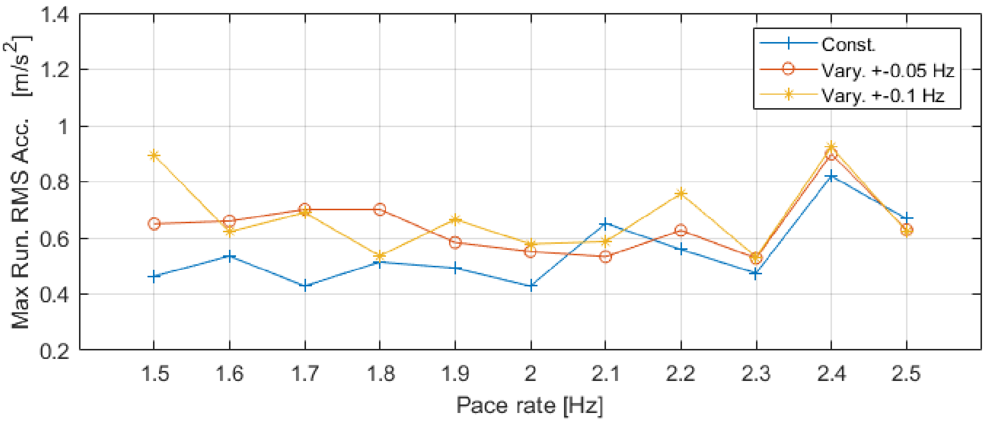


Figure B.2: Response in Transducer-3 when the pedestrian has a constant pace rate and when the pace rate varies with ±0.05 Hz respectively ±0.1 Hz. The variation is relative to the second step which has a pace rate according to the x-axis