ON STATISTICAL SAMPLING IN STANDARDIZED FLANKING TRANSMISSION MEASUREMENTS

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Abstract

A recurring issue in standardized building acoustic measurements is determining the number of sampling positions required to achieve a prescribed confidence interval. Although measurement uncertainty can be reduced by increasing the number of samples, practical constraints limit the feasible number of excitation and measurement positions. This paper examines the measurement of the velocity level difference of rigid heavyweight junctions according to ISO 10848-1, currently under revision. Monte Carlo simulations with a wave based model are used to quantify the error and uncertainty associated with different numbers of excitation and measurement positions. While the results are influenced by junction type, transmission direction and plate properties, clear general trends emerge. Increasing the number of excitation positions is most effective in reducing uncertainty, whereas increasing the number of measurement positions beyond four provides only limited additional improvement. General formulations are proposed to determine the required sampling for a specified maximum allowable error or uncertainty. The current ISO 10848-1 requirement for Type A elements, namely a minimum of four excitation positions and three measurement positions per excitation position, appears to be an efficient compromise between accuracy and practical feasibility.

Keywords: *flanking transmission, standards, measurements, uncertainty*

1. Introduction

The international standard ISO 10848-1 [1] provides the framework for measuring flanking transmission in a laboratory test facility or in the field. Flanking transmission can either be characterized by an overall quantity (such as the normalized flanking level difference $D_{\mathrm{n,f}}$) or by a junction property (such as the vibration reduction index K_{ij}). Several studies have revealed gaps in the current standard, which are often related to the rise of new building materials like CLT and resilient interlayers [2][3][4]. These shortcomings will be accounted for in the revision of the standard. Currently, the uncertainty of the measurement method is not known but the reproducibility of the measurement method is being investigated in a round robin test [5]. The results of this inter-laboratory test, for which different teams are measuring the same CLT junction, will give insight into the measurement uncertainty related to the choice of excitation and receiver positions, when following the current prescriptions. The spatial variation in velocity levels can be very large, with for example measured variations of more than 30 dB at low and high frequencies for CLT elements [6]. The minimum number of measurement positions to achieve a 95 % confidence interval of 2 dB for the average velocity level proves much larger than the number required by ISO 10848 (on average 10 at mid frequencies, up to 20 at low and high frequencies) [6]. Due to large variations in driving-point mobility at low frequencies, the variation with excitation position is also significant.

This study aims to provide practical guidelines to determine the required sampling for a specified maximum allowable error or uncertainty for measurements of velocity level differences in junctions composed of Type A elements.

2. Methodology

2.1. Wave based model

The vibration transmission across junctions composed of finite-sized plates is modeled using a wave based model [7] which accounts for the modal behaviour of the structure. The model assumes a rigid junction of rectangular plates with simply supported boundary conditions connected along the entire width of a common edge. The plates are assumed solid, homogeneous and isotropic and are modeled using thin plate theory.

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A transverse harmonic point force is applied on one of the plates. The plate responses are described by three wave types: bending, quasi-longitudinal and in-plane transverse shear waves.

For each junction, different virtual measurements of the velocity level difference $D_{v,ij,mn}$ were simulated by varying the excitation position and evaluation positions. The calculations were performed at 9 frequencies per one-third octave band from 50 Hz to 5000 Hz.

The averaged velocity level difference from different virtual measurements were calculated using the arithmetic mean of the $D_{v,ij,mn}$ for different excitation positions and different sets of measurement positions, as proposed in the revision of ISO 10848-1.

$$D_{v,ij} = \frac{1}{MN} \sum_{m=1}^{M} \sum_{n=1}^{N} D_{v,ij,mn} \tag{1}$$

with M the number of excitations positions, N the number of sets of measurements for each excitation position and

$$D_{v,ij,mn} = 10 \lg(\overline{v_{i,mn}^2} / \overline{v_{j,mn}^2}) \tag{2}$$

with

$$\overline{v_{mn}^2} = \frac{1}{P} \sum_{p=1}^{P} v_{mn,p}^2 \tag{3}$$

the average squared velocity over P measurement positions on the excited elements i and the receiving element j .

In this paper, the influence of the number of sets of measurements is not investigated, taking $N = 1$ for all cases.

2.2. Monte Carlo simulations

The vibration transmission was calculated for 20 different junction configurations. Each configuration is denoted by the junction type (L, T, T^* or X, Fig. 1) and two subscripts that indicate the plate types of respectively plates p1/p3 and plates p2/p4.

First, the influence of the junction type was investigated. Second, the influence of plate type was investigated by varying the plate properties of p1 and p2 of the L-junction. Four different elements were considered for each plate: a 12 cm concrete element, a 15 cm sandlimestone brick element, a 10 cm gypsum block element and a 9 cm masonry brick element (Table 1).

Table 1: Plate properties (thickness t, density ρ, Young's modulus E, Poisson's ratio ν, loss factor η)

Plate type	t [m]	ρ [kg/m^2]	E [Pa]	ν [-]	η [-]
1	0.12	2500	33×10^9	0.2	0.015
2	0.15	1300	11×10^9	0.2	0.015
3	0.10	800	2.8×10^9	0.2	0.015
4	0.09	1100	6.6×10^9	0.2	0.015

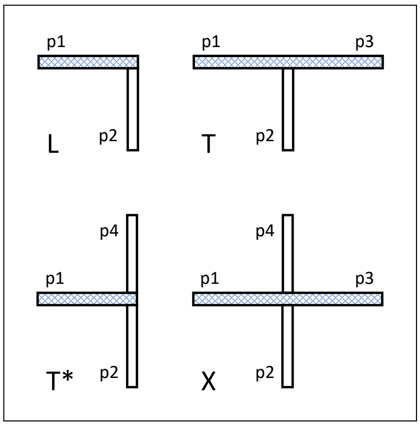

Figure 1: Junction types

The plate dimensions were chosen such that they follow the requirements of ISO 10848 [1] but as small as possible (Table 2).

Table 2: Plate lengths l_p and junction length l_{ij}.

l_{p1} [m]	l_{p2} [m]	l_{p3} [m]	l_{p4} [m]	l_{ij} [m]
3.70	3.00	4.10	3.33	2.30

For each junction, the velocity level difference between plate p1 and plate p2 was simulated for different combinations of excitation and measurement positions. The number of excitation positions M was varied from 1 to 10. To increase the randomness, 10 different cases were simulated for each M. For each excitation position, the velocity level was determined at 10 different measurement positions on each element. Afterwards, the velocity level difference was calculated following Eqs. (1)-(3) for different numbers of measurement positions $P = 1 \ldots 10$.

The excitation and measurement positions were randomly chosen following the rules for minimum distances of ISO 10848-1. All requirements of the standard could be met, except for the minimum distance d_S between excitation positions. The ISO-requirement $d_S \geq 1.0$ m could only be met for $M \leq 5$. For larger M, the distance was maximized but smaller than 1.0 m (Table 3).

Table 3: Minimum distance between excitation positions.

M [-]	≤ 5	6	7	8	9	10
d_s [m]	1.00	0.95	0.80	0.70	0.65	0.60

2.3. Error

To estimate the error related to the choice of excitation and measurement positions, a reference solution was calculated for each junction configuration. The reference is the $D_{v,ij}$ for 100 random excitation positions, each position respecting the minimum distances of 0.5 m to the plate boundaries and 1.0 m to the junction line. The squared velocity was determined at 200 random measurement positions on each plate, with each position at least 0.25 m from the plate boundaries and junction line. For each excitation position, the averaged velocity level of the source plate was determined from all measurement positions that are located at a minimum distance of 1.0 m from the respective excitation position. For the receiver plate, all 200 measurement positions were used to determine the average velocity level.

Using this reference solution, the root mean squared error (RMSE) of $D_{v,ij}$ for a certain M and P was determined from the 10 cases in each frequency band. The global error for the frequency averaged value of $D_{v,ij}$ was then determined as the arithmetic average of the RMSE error in the one-third octave bands 200 Hz – 1250 Hz (i.e. the frequency range used to calculate the single-number value in ISO 10848-1).

2.4. Uncertainty (GUM)

The uncertainty of the velocity level difference $D_{v,ij}$ due to the variation in the number of excitation and measurement positions was quantified using GUM assuming that the different input quantities are uncorrelated [8].

The variance in squared velocity between different measurement positions on an element leads to following squared uncertainty for the averaged squared velocity:

$$u^2(\overline{v_{mn}^2}) = \left[\frac{s^2(v_{mn}^2)}{P}\right] \tag{4}$$

where s is the sample standard deviation. Here, it is assumed that v^2 has a Gaussian probably density function (PDF). Although it has been found that v^2 has a log-normal PDF [9], this is a reasonable assumption if the standard deviation of L_v is small. Furthermore, this approach is consistent with the standard, where the estimate of the mean of v^2 is based on a Gaussian PDF.

Using propagation of uncertainty, the uncertainty of $D_{v,ij,mn}$ equals

$$u^2(D_{v,ij,mn}) = c_i^2 u^2(\overline{v_{i,mn}^2}) + c_j^2 u^2(\overline{v_{j,mn}^2}) \tag{5}$$

with the sensitivity coefficients $c_i = \frac{\partial D_{v,ij,mn}}{\partial \overline{v_{i,mn}^2}}$ and $c_j = \frac{\partial D_{v,ij,mn}}{\partial \overline{v_{j,mn}^2}}$.

The uncertainty of the averaged velocity level difference consists of the propagated uncertainty of the uncertainty of each of the $D_{v,ij,mn}$-values (Eq. (5)) and the uncertainty based on the variance of the $D_{v,ij,mn}$-values.

$$u^2(D_{v,ij}) = \frac{1}{(MN)^2}\sum_{m=1}^{M}\sum_{n=1}^{N} u^2(D_{v,ij,mn}) + \left[\frac{s^2(D_{v,ij,mn})}{MN}\right]. \tag{6}$$

The first part is related with the variation due to measurement positions and the second part to the variation with excitation positions and the variation between sets of measurement positions.

The global uncertainty shown in section 3 is the square root of the arithmetic mean of the u^2-values for the 10 cases in the frequency bands 200 Hz – 1250 Hz.

3. Results

3.1. Junction L_{13}

As an example, the velocity level difference $D_{v,ij}$ of the junction L_{13} composed of a 12 cm concrete element (p1) and a 10 cm gypsum block wall (p2) is considered. The reference solution is compared with 10 cases using $M = 4$ excitation positions and $P = 3$ measurement positions, as minimally required by ISO 10848. At low frequencies, the modal behaviour clearly determines the velocity level difference (Fig. 2). The shaded area indicates the frequency region over which the uncertainty and error is averaged. For this example, the global error is 1.8 dB and the global uncertainty equals 2.3 dB. As expected, the uncertainty and error generally decrease when increasing the number of measurement and excitation positions (Fig. 3). Increasing the number of measurements positions beyond four has little effect on the error, although the calculated uncertainty according to GUM keeps decreasing for $P > 4$.

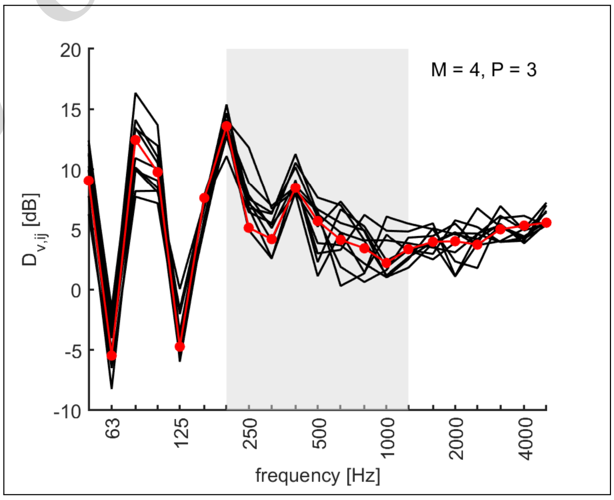

Figure 2: Velocity level difference of junction L_{13} for 10 cases with $M = 4$ and $P = 3$ (black lines) and for the reference solution (red bullets)

3.2. Influence of plate damping

The requirements of ISO 10848-4 regarding the mode count and the modal overlap factor are not met for the junctions considered in this paper. The modal density of the plates p1 and p2 of the junction L_{13} equals 0.0332 Hz^{-1} and 0.0629 Hz^{-1}, respectively, resulting in a mode count larger than 5 starting in the one-third octave band of 800 Hz and 400 Hz for p1 and p2, respectively. For a specific element type, the mode

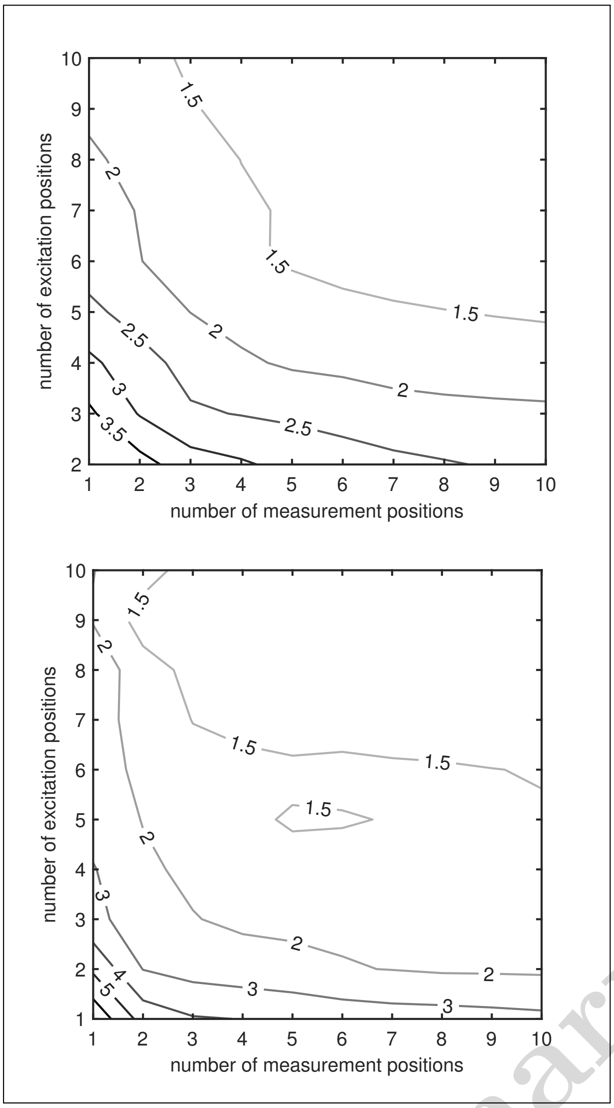

Figure 3: Frequency average uncertainty $u(D_{v,ij})$ (top) and error (bottom) for junction L_{13}

count can only be increased by increasing the size of the element. Due to the low loss factor used in the wave based calculations, the modal overlap factor is relatively small, becoming larger than unity only in the one-third octave bands of 2000 Hz and 1250 Hz for p1 and p2, respectively. By increasing the loss factor, the modal overlap is increased but the uncertainty and error are only slightly reduced (Fig. 4). For high damping ($\eta > 0.15$), the uncertainty and error even increases again, which may be explained by the larger decrease in vibration level with distance. For the junction L_{13}, the criterium of a modal overlap factor of at least unity at 250 Hz is respected when $\eta_{p1} > 0.12$ and $\eta_{p2} > 0.064$. Because these values are often not attained in a laboratory setup and the influence of damping on the uncertainty and error is limited, further calculations have been made with a loss factor of 0.015 for all plates.

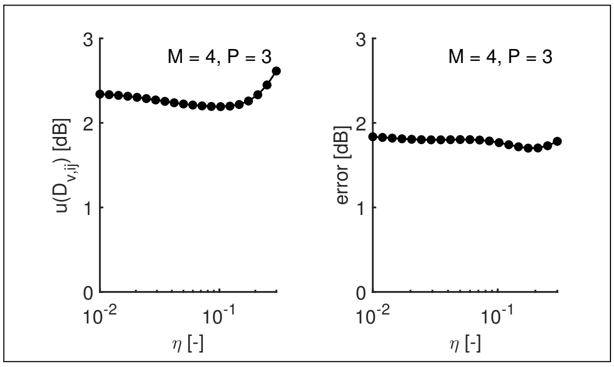

Figure 4: Influence of plate damping for junction L_{13}

3.3. Influence of junction type

The junction type has a minor influence on the uncertainty and error, with typical variations between $0.2 - 0.3$ dB (Fig. 5). Further calculations were therefore only performed for L-junctions.

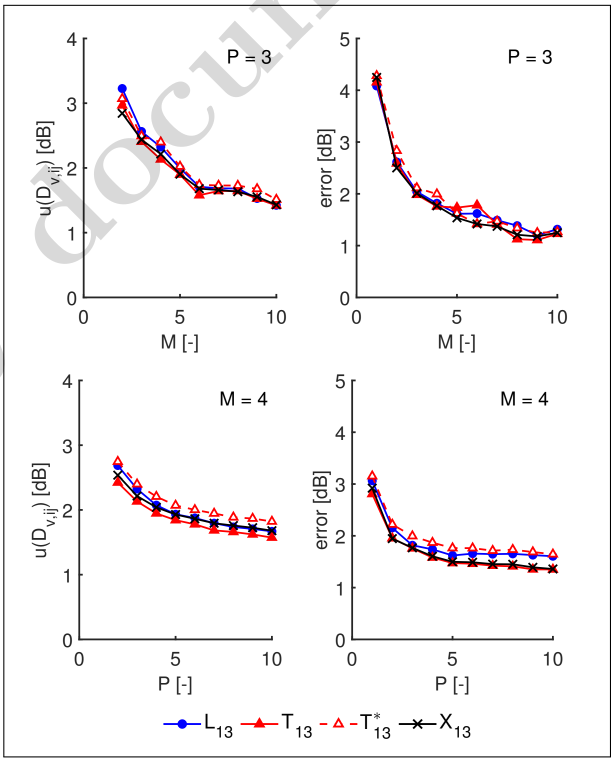

Figure 5: Influence of junction type

3.4. Influence of transmission direction

The influence of transmission direction on the uncertainty and error for junction L_{13} is of the same order of magnitude as the influence of junction type (results not shown for brevity). The variation can be partly explained by the different areas of p1 and p2, which influences the possible excitation locations.

3.5. Influence of plate properties

The influence of the type of elements of which the L-junction is composed has a significant influence on the uncertainty and error (Fig. 6). The variation in error and uncertainty is on average 1 dB and increases to 2 dB for small values of M. It is difficult to extract general conclusions from these simulations. The uncertainty and error seem not directly related to the modal density of the individual plates, which is the lowest for plate types 1 and 2 and the highest for plate type 3.

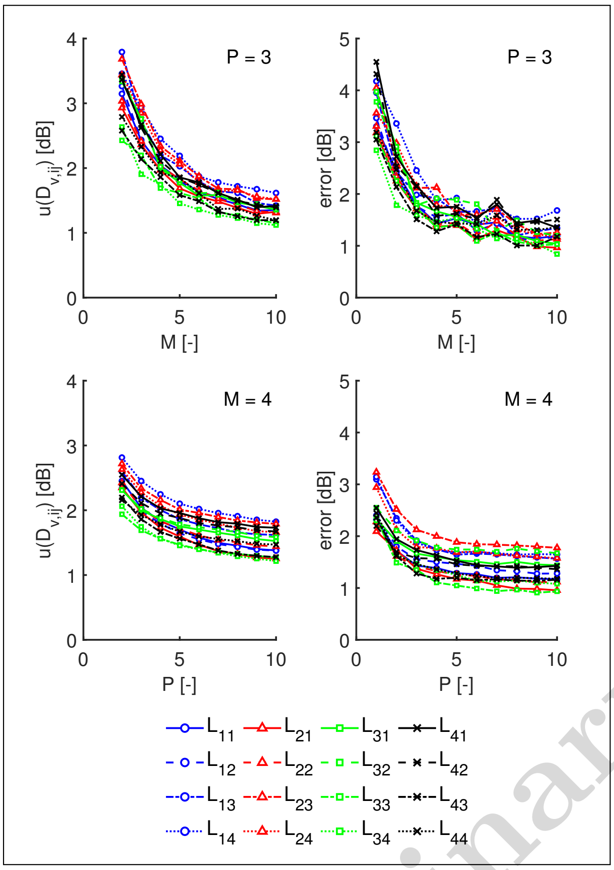

Figure 6: Influence of plate properties

3.6. Regression curves

To find general trends in the wave based simulations, a second order regression was fitted to the uncertainty u and error e in function of the logarithm of the number of excitation and measurement positions,

$$c_0 + c_1 \lg(M) + c_2 \lg(P) + c_3 \lg^2(M) + c_4 \lg^2(P) + c_5 \lg(M)\lg(P) \quad (7)$$

The regression coefficients were determined for the uncertainty and error of $D_{v,ij}$ of the 20 junctions shown in Fig. 5 and Fig. 6. The average coefficient of determination R^2 equals 0.985 and 0.966 for the uncertainty and error respectively, with minimum values of $R^2 = 0.971$ for the uncertainty and $R^2 = 0.945$ for the error. The average regression curve, determined from the average of the regression coefficients for the 20 junctions (Table 4), is shown in Fig. 7. This allows to estimate the required number of excitation and measurement positions for a specified maximum allowable error or uncertainty when measuring the velocity level difference of Type A junctions.

Table 4: Average regression coefficients

	uncertainty u	error e
c_0	5.8374	5.4033
c_1	-6.4423	-5.6121
c_2	-2.4549	-3.7954
c_3	2.3834	1.9998
c_4	0.2747	1.3109
c_5	1.4240	1.8392

The regression of Eq. (7) allows for an analytical calculation of the sensitivity of the uncertainty and error to a variation in number of excitation or measurement positions. Fig. 8 shows the sensitivity coefficients $\partial u/\partial M|_{P=3}$, $\partial u/\partial P|_{M=4}$, $\partial e/\partial M|_{P=3}$ and $\partial e/\partial P|_{M=4}$. Both the uncertainty and error are more sensitive to the number of excitation positions, indicating that it is more efficient to increase the number of excitation positions than the number of measurement positions. For larger M and P, the sensitivity coefficients reach almost 0, showing that the additional gain is very limited. These results indicate that the current ISO 10848-1 requirement for Type A elements, namely a minimum of four excitation positions and three measurement positions per excitation position, is an efficient compromise between accuracy and practical feasibility.

4. Conclusions

In velocity level difference measurements of junctions, the variation of velocity levels with different excitation and measurement positions can be very large. This urges the question whether the currently required number in ISO 10848-1 is sufficient. To investigate this problem, Monte Carlo simulations were carried out with a wave based model for 20 different junction combinations of Type A elements. The uncertainty due to the variation with excitation and measurement positions was quantified using GUM, while the error was estimated by comparison with a reference solution using 100 random excitation and 200 random measurement positions.

The uncertainty and error are only slignly influenced by the junction type, the direction of transmission and the plate damping. The plate properties have a significant influence on the predicted uncertainty and error, but no correlation is found with the modal density of the plates.

Second-order regression curves were fitted to the wave based simulations to extract general trends. This allows to determine the required number of excitation and measurement positions for a specified maximum allowable error or uncertainty when measuring the velocity level difference of Type A junctions.

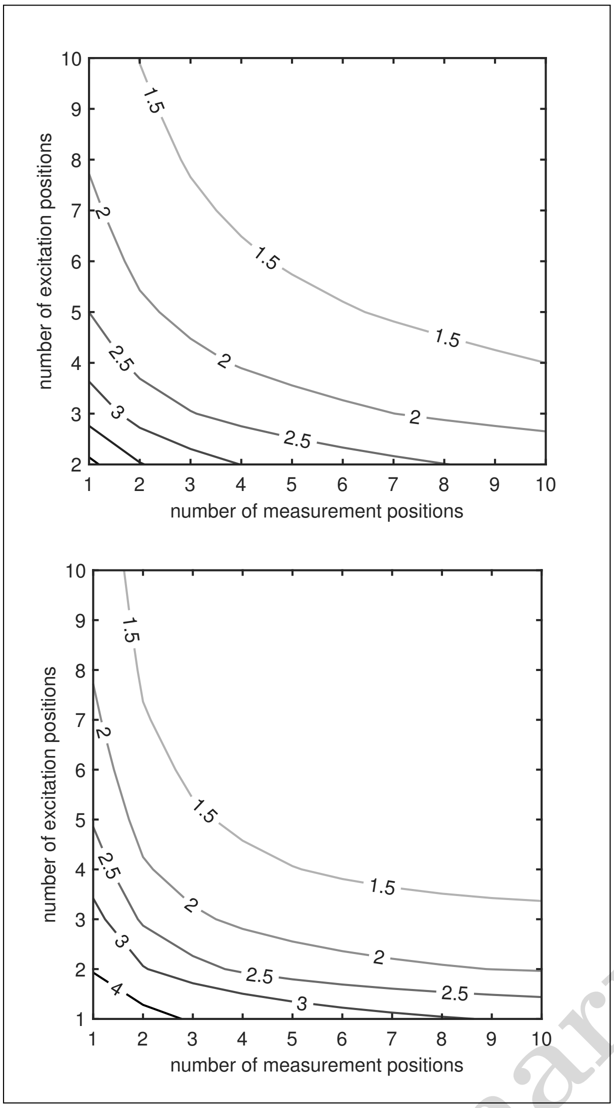

Figure 7: Average regression for frequency average uncertainty $u(D_{v,ij})$ (top) and error (bottom)

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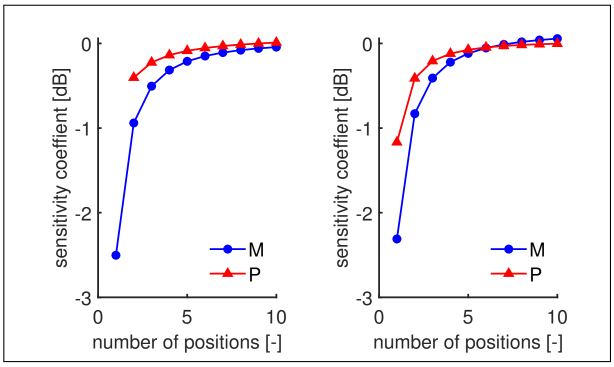

Figure 8: Sensitivity coefficients for frequency average uncertainty $u(D_{v,ij})$ (left) and error (right)

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