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ON THE DESIGN OF A DEDICATED SAMPLE FOR INTERLABORATORY COMPARISON OF FREQUENCY RESPONSE ANALYSIS

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Abstract. *When qualifying prototype samples for vibration response and dynamic characteristics, an accredited laboratory is required to implement monitoring procedures to assure the validity of the test results. According to ISO17025, such monitoring may include interlaboratory comparison or proficiency testing.*

This paper presents a mechanical structure, which has been designed specifically to be used as a generic reference sample during such a comparative study in which resonant frequencies of a structure need to be quantified. This paper elaborates on the analysis and design issues, which encompass theoretical analysis, both purely mathematical and by FEM. In addition, to allow statistical analysis of test data resulting from measurements performed by different test laboratories, the uncertainty budget of the reference value of this sample is determined.

As a first step towards a European project, a limited group of accredited test laboratories in Belgium have participated in a first Round Robin proficiency analysis. The results and interpretation of this exercise conclude this paper. Additional analysis was required for a specific setup as described in this paper..

1 INTRODUCTION

Test laboratories which are accredited according to ISO17025:2005 [2] need to assure the quality of the test results they deliver, which can be monitored by participating in inter-laboratory comparisons, often referred to as a third line of control where the reproducibility of obtained test results is evaluated. In addition, intra-laboratory comparison tests are also applied for evaluation of the repeatability of test methods.

Within Europe, accreditation bodies have recently become very strict in evaluating the accredited laboratory's participation to round robin sessions during the technical audits. Round Robin samples for vibration testing facilities however are not available in large amounts and are even difficult to find. Therefore a cooperation between Belgian accredited labs has been set up in order to create an acceptable sample, as described in this paper.

During inter-laboratory comparison, each individual participant applies specific testing methods according to defined standards to obtain measurement results. Possible deviations between results delivered by different test laboratories are due to differences in interpretation of standards, the use of different test equipment, influence of human interaction or environmental parameters. Comparison of inter-laboratory results allow participants to evaluate their implementation of the standard method, to assess the reliability of obtained measurement data and to initiate a root cause analysis in case significant deviation from the peer group is identified.

During vibration qualification assessments, a pass-fail criterion is often related to quantification of dynamic behavior of structures, where resonant frequencies or relative shifts of a fundamental resonant frequency is measured. One of the most common related test standards is IEC 60068-2-6 – Sine vibration [3]. The inter-laboratory sample which is described in this paper is designed specifically to measure these parameters for low frequency phenomena (lower then 500Hz), however for a specific setup significant deviations between test laboratories were noticed and possible causes are listed in this paper.

2 SAMPLE DESIGN FOR FREQUENCY RESPONSE

A generic test sample which will be used for inter-laboratory comparison is supposed to be:

1. Representative with respect to the intended test specifications,
2. Stable over time,
3. Homogeneous,
4. (not too) elementary.

Considering these characteristics, the proposed sample which has been developed consists of a fixed-fixed beam structure with uniform mass distribution. By applying a uniaxial forced vibration, the resonant frequency at which a first bending mode appears can be measured. This value will be used for mutual verification between test laboratories.

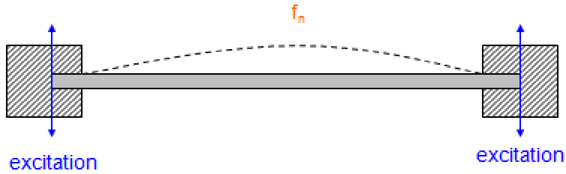

Figure 1: Sample concept.

2.1 Sample suspension

A specific fixture is required to serve as suspension system for the considered beam. This fixture will ideally transfer the applied vibration from the shaker armature straight to the fixed ends of the beam, without introducing undesired influences on measurement results, such as additional resonances or cross axis vibration. Figure 2 illustrates the design of such a rigid reference structure. Aluminum is used, where all parts are interconnected by welding joints, which approximates an ideal cast structure. A generic hole pattern in the bottom plate allows mounting of the fixture on divers shaker armatures or lab specific mounting expanders. The reference beam is bolted to this structure at both ends. Later on in this paper it is indicated that the use of a solid bar at each end could have been a more appropriate choice in simulating a fixed-fixed beam suspension.

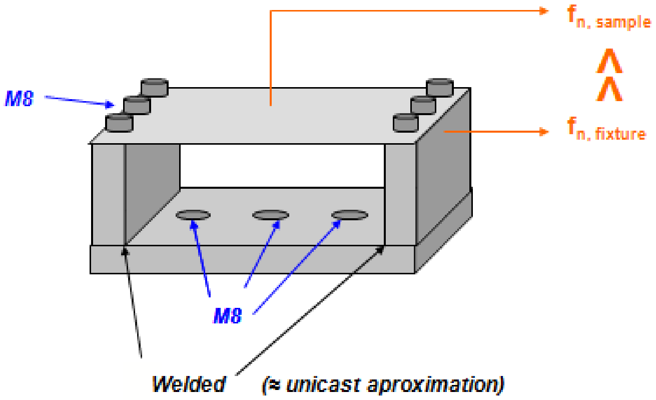

Figure 2: sample suspension.

As previously stated, the frequency band of our interest lies below 500Hz. Dynamic response analysis of the fixture is performed to assure a one to one transfer function. The analysis consists of measuring the responses of the fixture on three relevant locations with triaxial accelerometers (Figure 3). The measurement results showed that a first resonance of the fixture occurred at a frequency of 860Hz with a relative high Q factor (Figure 4). Considering this result, it is reasonable to state that this fixture is allowed to be used at frequencies not exceeding 500Hz.

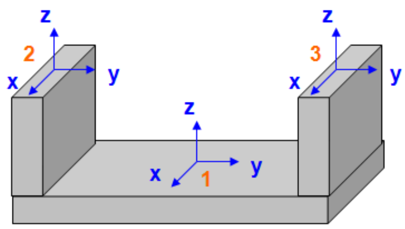

Figure 3. Suspension analysis.

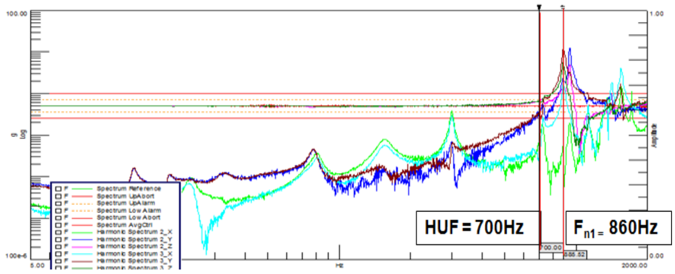

Figure 4. Suspension analysis results.

2.2 Choice of reference samples

To increase the set of comparable and representative measurement values, a group of distinct reference beams with deviating properties is provided. Each participating lab will therefore obtain three measurement results which will be used as inter-laboratory comparison data. The characteristics of the beam differ in terms of thickness and material properties, as listed below:

1. Sample 1: Thin Al plate (thickness: 1.5mm, length: 300mm, width: 97mm)
2. Sample 2: Thick Al plate (thickness: 5mm, length: 300mm, width: 103.2mm)
3. Sample 3: Copper plate (thickness: 3mm, length: 300mm, width: 97mm)

3 FREQUENCY RESPONSE PREDICTION

Due to the elementary setup of the samples, the expected fundamental frequency of each beam can be obtained both by mathematical calculations and by FEM respectively. Later on, these theoretically obtained values can be used to verify the correctness of the measurement results with a reasonable certainty.

3.1 Mathematical analysis

The first order resonant frequency of each beam is calculated in two consecutive steps.

In a first step, for each beam the Young's modulus (E-modulus) is calculated, based on the first resonant frequency of the beam while suspended in a cantilever setup (Figure 5). It has been decided to rely on measurements and calculations in determining the E-modulus, instead of relying on theoretical values as can be found in literature. This avoids the introduction of uncertainties due to material properties.

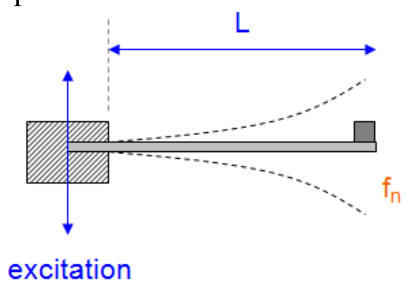

Figure 5. Cantilever setup.

After determining the first resonant frequency f_n by measurement, the E-modulus of each beam with dimensions width B, height h and suspended length L can be calculating by applying Eq. (1)[4][5][6].

$$E = [2\pi f_n]^2 \cdot L^3 . \left[\frac{0.2235.(m_{sample}) + m_{accelerometer}}{3I} \right] \quad (1)$$

With $I = \frac{1}{12} B h^3$

As a second step, the first resonant frequency f_n for each beam in a fixed-fixed setup is calculated, based on the beam dimensions, the E-modulus for each beam as obtained from step 1, and by applying Eq. (2) using the latter parameters.

$$f_n = \frac{1}{2\pi} \left[\frac{22.373}{L^2} \right] \sqrt{\frac{EI}{m_{sample}/L}} \quad (2)$$

Table 1 indicates the calculation results after performing step 1 and 2, where $f_{n,calc}$ equals the resulting first resonant frequency of each sample as derived from mathematical analysis.

Sample	**E (kN/mm²)**	**$f_{n,calc}$ (Hz)**
Thin Al	59.8	79.17
Thick Al	56.4	273.14
Cu	124.9	128.72

Table 1. Calculation results of mathematical sample analysis.

3.2 FEM analysis

For each beam sample, a FEM model is designed, which allows simulation of the first three out-of-plane modes as illustrated in Figure 6. For each beam, the values for E-modulus which have been used are those values resulting from step 1 in the mathematical analysis. Table 2 illustrates the first resonant frequency as obtained from FEM analysis. When comparing these results with $f_{n,calc}$ which results from the mathematical analysis, a maximum difference between values of 3,5% is observed.

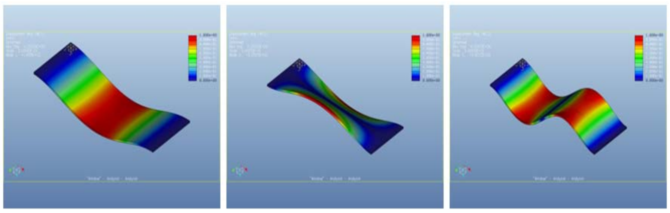

Figure 6. FEM analysis

Sample	**$f_{n,calc}$ (Hz)**	**$f_{n,FEM}$ (Hz)**
Thin Al	79.17	81.4
Thick Al	273.14	272.4
Cu	128.72	133.4

Table 2. Calculation results of mathematical sample analysis.

4 UNCERTAINTY ON FREQUENCY RESPONSE ANALYSIS

When comparing test results between participants, it is important to provide the uncertainty budget of the test sample itself, which by definition includes all sources of uncertainty [1]. Two main contributions to the uncertainty budget are examined.

4.1 Intermediary precision

The effect of random events in one single test laboratory is investigated. Possible variables are the test setup itself (such as the use of a head expander, bare table mounting, use etc), manipulations by the test engineer, accelerometer positioning and fixation, torque values used (specified within interval 20-25Nm). Typically, intermediary precision is determined by repeating the same test for a number of times within the same laboratory. Worst case deviations were observed for the sample existing of the thin Al beam. The test was repeated 9 times, which resulted in measurement data of Table 3. The standard deviation σ_1 for these values equals 0.97, the relative standard deviation RSD equals 1.14% and the expanded uncertainty U equals $\pm$ 2.62% under the assumption that a Gaussian distribution is applicable, where the distribution factor *k* for 9 measurement samples equals 2.3 [6]. From this expanded uncertainty we learn that due to intermediary precision, 95% of the measurement results will lie within an interval of $\pm$2.62% from the reference value.

n	f_n (Hz)
1	86.94
2	85.04
3	84.8
4	84.57
5	86.07
6	85.51
7	86.7
8	85.04
9	84.1

Table 3. Intermediary precision – measurement data.

4.2 Stability during excitation

During the inter-laboratory comparison study, the test samples will repeatedly be subjected to vibration stress. Due to this repeated vibration stress, material fatigue may occur, possibly resulting in a shift of the fundamental resonant frequency. It needs to be verified beforehand whether this effect may occur. Representative samples are therefore examined by applying a tracked sine dwell at the resonant frequency f_n of each beam. A time recording of the measured f_n allows trend analysis of the measured f_n over time. Figure 7 represents the changes in recorded f_n in terms of measurement time.

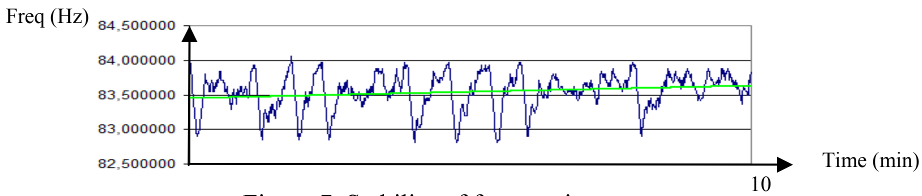

Figure 7. Stability of f_n over time

At first glance, the value of f_n varies within certain boundaries as shown in the curve (blue line) of Figure 7. This variation is however due to the tracking algorithm which is applied by the vibration control system; within specific boundaries the algorithm periodically deviates the excited vibration frequency to check whether higher response amplitudes can be detected at nearby frequencies. If this would be the case, this nearby frequency would represent the fundamental frequency f_n thus implying a shift with respect to the original value of f_n. Based on the given data as depicted in figure 7, a linear trend analysis is performed on the recorded values over a long time frame. By applying this trend analysis, the effects of the search algorithm will not be part of the quantification of the actual shift in frequency. The green line on the graph shown in Figure 7 is the resulting trend analysis, where f_n as recorded at the first timeframe almost equals the recorded f_n after 10 minutes test time. Therefore it is considered that for the test sequences which will be used during inter-laboratory comparison, stability of f_n over time is proven and no uncertainties will be taken into account on this behalf.

5 INTERLABORATORY COMPARISON RESULTS

During the first trial run, three Belgian ISO17025 accredited vibration test laboratories have participated in the comparison study. The three beam samples as discussed in the previous section have been subjected to sine vibrations according to IEC 60068-2-6, between 5 and 500Hz, with a sweep rate equal to 1 oct/min, where the fundamental resonant frequency f_n is measured at the center of each beam. Each laboratory provided measurement results with corresponding measurement uncertainty as applicable within their proper laboratory.

For each beam sample, the following paragraphs present the obtained measurement values with associated measurement uncertainties for each test laboratory. The uncertainties of each lab are to be considered as a given value. The methodology used by each lab is evaluated during ISO17025 audits. How these values are obtained is of no importance to the research as described in this paper.

The mean value of all measurement results has been used as a reference value to compare with. The uncertainty budget, which consists of the intermediary precision as discussed earlier has been applied on this mean value. The test laboratories who’s measurement values are within the measurement uncertainty limits around the mean value are considered to be acceptable. Those values lying outside these boundaries are a trigger for further investigation.

5.1 Thick aluminum

Table 4 represents the measurement values for each test laboratory with associated measurement uncertainty, expressed in absolute values.

Test lab	f_n (Hz (± Hz))
Lab x	289.2 (± 1.45)
Lab y	282.7 (± 5.65)
Lab z	293.43 (± 1.00)
Mean value	288.44 (± 7.56)

Table 4.Thick Al plate – measurement values.

The graph as shown in Figure 8 represents these values and corresponding reference value boundaries. The measured values all lie within the reference boundaries, therefore it may be stated that the measurement procedures of each test lab are acceptable. The graph also illustrate the calculated value $f_{n,calc}$ and the resonant frequency value as obtained from FEM analysis $f_{n,FEM}$. These theoretical values give a good impression of the overall correctness of the measured results, but are not used as reference values.

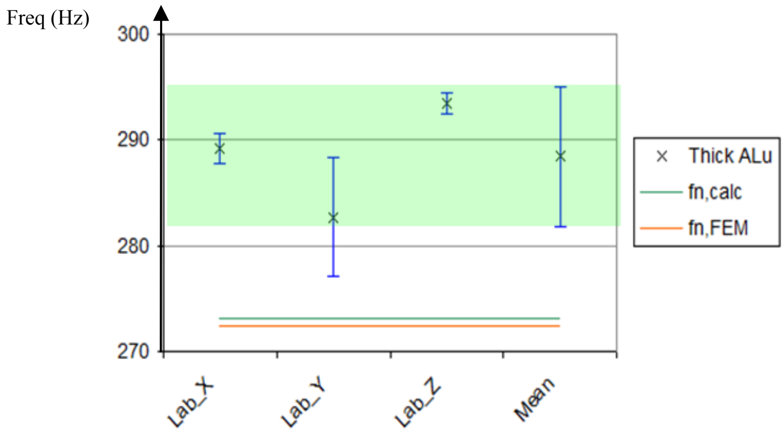

Figure 8. Measurement results for thick Al plate.

5.2 Copper sample

Table 5 represents the measurement values for each test laboratory with associated measurement uncertainty, expressed in absolute values.

Test lab	**f_n (Hz (± Hz))**
Lab x	130.86 (± 0.65)
Lab y	129.5 (± 2.59)
Lab Z	133.52 (± 0.45)
Mean value	131.29 (± 3.44)

Table 5. Copper plate – measurement values

The graph as shown in Figure 9 represents these values and corresponding reference value boundaries. For the Cu plate, the measured values also lie within the reference boundaries, confirming the conclusions of the analysis for sample 2.

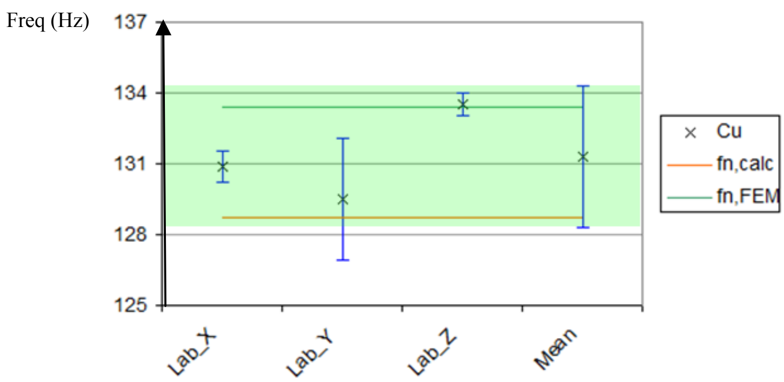

Figure 9. Measurement results for Cu plate.

5.3 Thin aluminum plate

Table 6 represents the measurement values for each test laboratory with associated measurement uncertainty, expressed in absolute values.

Test lab	**f_n (Hz (± Hz))**
Lab x	85.5 (±0.43)
Lab y	80 (±1.60)
Lab Z	88.98 (±0.30)
Mean value	84.83 (±2.22)

Table 6. Thin Al plate – measurement values

The graph as shown in Figure 10 represents these values and corresponding reference value boundaries. For the thin Al plate, the measured values lie outside the reference boundaries.

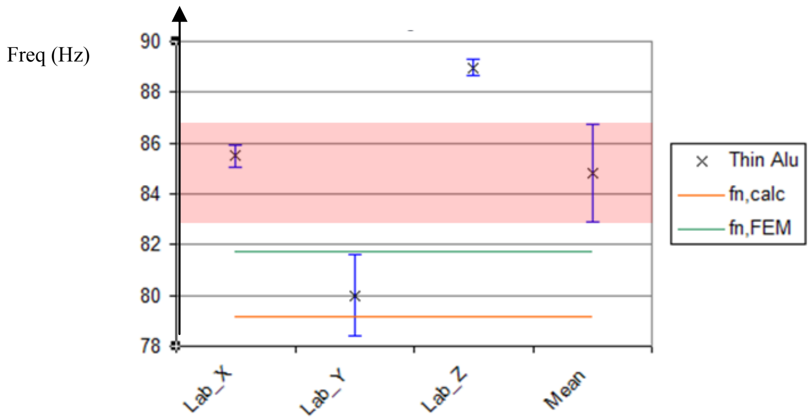

Figure 10. Measurement results for thin Al plate.

5.4 Thin aluminum plate evaluation

Further investigation is needed to identify the root cause of this mismatching. Possible causes are to be found in the boundary conditions of this sample. While the plate thickness has been verified to be uniform over the entire length, each laboratory has used different accelerometers which differ in mass. For this thin plate, such contribution can be more significant than for the thick Al plate and the copper plate since it is more flexible due to a limited thickness. Additionally, insufficient attention has been given to the exact location of the accelerometer on the thin Al plate. From further analysis we also learned that each lab has used different adhesive materials to mount the accelerometer (bee wax, glue).

In a first attempt to identify the cause of the deviations in test results, more attention has been given to possible variants in setup. For the thin aluminum plate, a more detailed intermediary precision session was performed. More then 30 runs were completed, for different test operators within one specific participating laboratory. Each setup was completely redone for each individual test, which means that remaining influences are depending on laboratory specific conditions, such as choice of accelerometers, type of adhesive and possibly the control system. For the repeated intermediary precision, a relative standard deviation equal to 0.81% was observed for one specific laboratory. When applying 30 test runs, the 2-sigma approximation can be applied, thus giving an expanded uncertainty for the 95% confidence interval equal to 1.62%. This leads to the conclusion that the differences for the thin aluminum plate will be related to differences in-between test laboratories, which still need further investigation to be identified.

6 CONCLUSIONS AND FUTURE WORK

The samples as described in this paper are a suitable tool to perform inter-laboratory comparison studies.

For one specific setup (thin Al plate), further investigation is needed as future work to retrieve the source of excessive deviations between measurement results. As indicated in the previous paragraph, boundary conditions are most likely causing these discrepancies. Further clarification is needed before this specific sample can be used for inter-laboratory comparisons within larger populations. Therefore, the test session as described in this paper was repeated for the thin Al sample, at first in one specific laboratory in an attempt to identify the root cause of the deviations. This step lead to the conclusion that variables which are related to these differences are to be sought in differences in between the different laboratories, which will be investigated further on.

Since no issues are noticeable for the remaining two samples, one may conclude that these samples are sufficiently stable to be used as an inter-laboratory comparison sample.

Although the population of three test laboratories is limited, it is noticeable that the deviation for the thin Al sample does not concern one single outlier, but rather a systematic error between each participants' results.

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