DEVELOPMENT OF AN EXPERIMENT FOR IMPEDANCE MEASUREMENT OF STRUCTURED SANDWICH SHEET METALS BY USING A FULL FACTORIAL MULTI-STAGE APPROACH

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Abstract

Purpose - Structured sheet metals and structured sandwich sheet metals are three-dimensional, lightweight structures with increased stiffness which are used in the automotive industry. The impedance, a figure of resistance of a structure to vibrations, will be determined regarding plain sheets, structured sheets and structured sandwich sheets. The aim of this paper is generating an experimental design in order to minimize costs and duration of experiments.

Methodology - The design of experiments is used to reduce the large amount of experiments required for the determination of correlation between the impedance and its influencing factors. Full and fractional factorials are applied in order to systematize and plan the experiments. Their major advantages are high quality results given small amount of experiments, their ability to determine the most important influencing factors and their correlations.

Findings - In contrast to the study of plain sheets, the respective impedance analysis used on structured sheets and structured sandwich sheets should be split into three phases. The first phase consists of preliminary experiments which identify relevant factor levels. These factor levels are subsequently employed in main experiments, which have the objective of identifying complex relationships between the parameters and the reference variable. Possible post experiments can follow up in case additional study of factor levels or other factors are necessary. By using full and fractional factorial experimental designs, the required number of experiments is reduced by half.

Value of Paper - In the context of this paper, the benefits from the application of design for experiments are presented. Furthermore, a multi-stage approach is shown to take into account unrealizable factor combinations and minimize experiments.

Keywords - structured sheet metals, structured sandwich sheet metals, impedance measurement, design of experiment

Research paper

1. Introduction

Structured sheet metals and structured sandwich sheet metals are three-dimensional, flat, light weight structures commonly used in car manufacturing (Sterzing, 2005; Hoppe, 2002; Sasse, 2014). Among others, the advantages of its structuring are higher stiffness (Hoppe, 2002; Sasse, 2014), no visible deformation due to heat and a low-glare surface (Sterzing, 2005; Mirtsch, Behrens, & Ellert, 2004). Studies concerning excitation characteristics of structured sheet metals do currently not exist. The resistance of a structure to alternating force excitation, the impedance (Kollmann, 2000), should therefore be determined for flat sheet metals, structured sheet metals and structured sandwich sheet metals. Creating an experimental design in order to realize the upcoming experiences efficiently is the aim of this study. Since there are too many factors to take into account all factors and all correlations.

The statistical experimental design is used to analyze and improve products and processes through the use of target-oriented experiments. It is based on the general methodology of altering several influential variables on the system in order to assess the effect on the target figure (Holst, 1995). The one-factor-at-a-time and the ceteris paribus-experiments were very common until the beginning 20th century (Holst, 1995; Scheffler, 1997; Härtler, 1976; Gundlach, 2004). Both approaches are based on the modification of just one influential variable to get optimal process results (Holst, 1995). The modern design of experiments was founded by Ronald Fisher who contributed an essential part of the work in the field of factorial experiments (Holst, 1995; Gundlach, 2004; Antony, 2008). They are mainly characterized by the multifactorial modification of the influential variables.

For the exploration of the impedance this means that several influencing factors on the sheet metal oscillation will be altered and the impedance modification will be analyzed and evaluated (Holst, 1995). Full and fractional factorial experimental designs are used to determine the yet unknown correlation effects within the experiment. Depending on the available data regarding construction, output stage and correlations between the factorsto be examined, a combination of full and fractional factorial experimental designs seems expedient appropriate.

2. Impedance experiments with structured sheet metals and sandwich sheet metals

2.1. Basic definitions for the experiment

The experiments deal with the acoustic characteristics of structured sheet metal and structured sandwich sheet metal. Structured sheet metals are flat light weight structures which are stiffened by secondary design elements like structures, beading, ribs, etc. (Hoppe, 2002). Those elements appear in different structural forms like truncated cones or truncated pyramids and create a three-dimensional, structured sheet metal, as shown in Figure 1 (Sasse, 2014). Consequences of the structuring are for example a higher stiffness (Hoppe, 2002; Sasse, 2014).

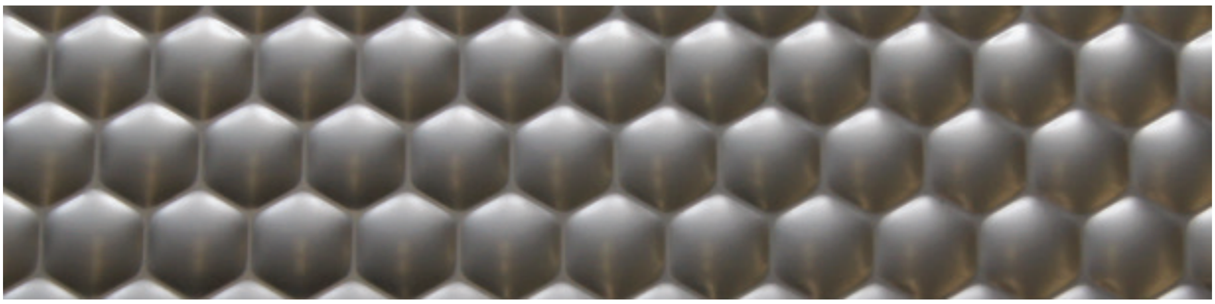


Figure 1: hexagonal honeycomb structure of a structured sheet

The sheet metals used for the experiments were produced by the sheet hydroforming process through reshaping (Kornieko, 2014). The semi-finished product, which should be reformed, will be pressed against the molding tools inside a cavity using hydrostatic pressure and external mechanical loading (Neugebauer, 2007). As a result, the three-dimensional hexagonal honeycomb structure shown in Figure 1 is produced (Kornieko, 2014).
The sheet metals have fixed dimensions and variable thickness between 0.5 mm to 1 mm. Structured sheet metals possess a positive and a negative structure position, as shown in Figure 2. The positive structure position corresponds to an upwardly curved structure whereas the honeycombs of the negative structure position are on the bottom (Kornieko, 2014). The metal sheets examined in this study are distinguished by wrench size between 33 mm and 51 mm, a web width of 2 mm and a honeycomb height of 2.7 mm.

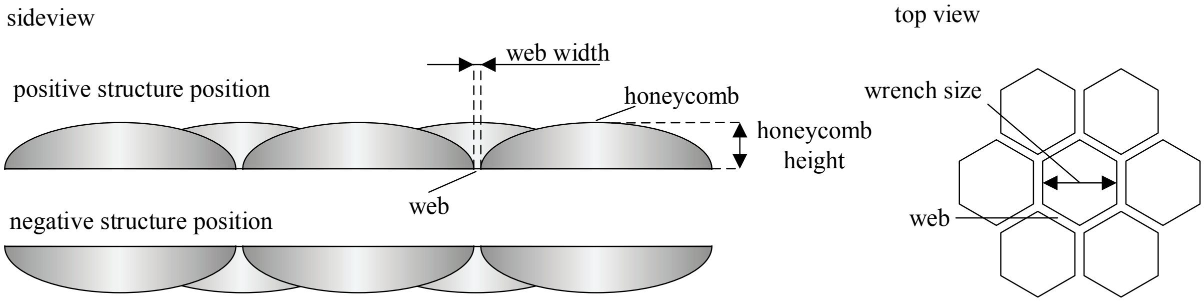
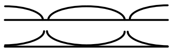


Figure 2: geometry of the structured sheet metals (Kornieko, 2014)

In addition to the experiments on the already introduced structured sheet metals there are further acoustic experiments to be performed on so-called structured sandwich sheet metals. These sheet metals are generated through the connection of structural sheet metals or the combination of a structured and a flat sheet metal (Sasse, 2014). The two sheet metal components have no solid core. Possible sheet metal pairings are shown in Table I.
Velocity is the speed at which the particles of a medium move during vibration, in this case the particles of the sheet metals (Gold, 2007). The velocity and the force are the response variables that ought to be measured during the experiments.

Table I: possible structural pairings of structured sandwich sheet metals (Sasse, 2014)

symbol	pairings	type of connection
	a structured, a flat joining partner	web on flat sheet - linear
	a structured, a flat joining partner	web on flat sheet - punctual
	two structured joining partner	web on web - linear
	two structured joining partner	honeycomb on honeycomb - punctual
	two structured joining partner	honeycomb on web - punctual

The planned experiments shall examine the excitation characteristics of structured sheet metals and structured sandwich sheet metals. Previous studies have shown that structured sheet metals reveal a reduced sound insulation in contrast to flat sheets. This reduced insulation of up to 15 dB occurs at frequencies between 4 kHz and 12.5 kHz (Langhof, 2015). In order to conduct the current experiments, the mechanical impedance $\underline{Z}$ was chosen as target figures. The impedance is the excitation resistance of a structure against excitation by an external force (Kollmann, 2000). The mechanical impedance is a complex-valued quantity defined as the quotient of the exciting alternating force $\underline{\hat{F}}$ and the resulting vibration velocity $\underline{\hat{v}}$ at the excitation location. It is indicated as $\frac{Ns}{m}$ (Möser & Kropp, 2010):

$$\underline{Z} = \frac{\underline{\hat{F}}}{\underline{\hat{v}}} \quad (1)$$

2.2. Experimental setup

During the experiment the vibration velocity of the sheet metal at excitation through external force is measured. The general experimental setup which shall be used during experiments later on is shown in Figure 3. The sheet metals are analyzed while hanging from rubber ropes. The hanging sheet metals shall be stimulated with an impedance hammer. The hammer will be pushed mechanically or by hand against the chosen excitation point on the sheet metal in order to stimulate with a force F. The tip of the hammer can vary in weight and hardness to cover different frequency ranges. The special feature of the impedance hammer is the measurement of the force F during the short collision with the sheet metal. The impact force needed for the impedance calculation is determined with the help of piezoelectric force sensors.

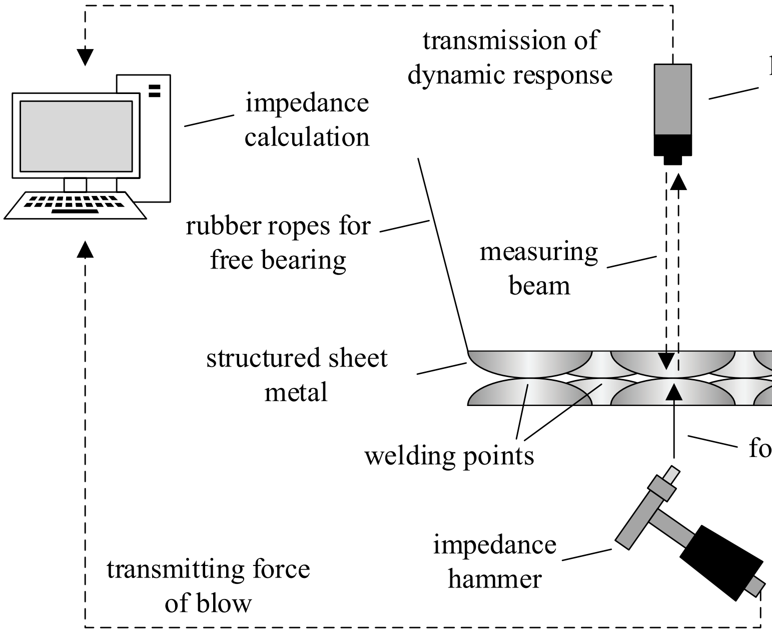


Figure 3: schematic experimental setup for determining the impedance

The induced force stimulates the sheet metal which starts to vibrate. Simultaneous with the excitation of the sheet metal, a Laser Doppler vibrometer is used to measure the velocity of the sheet metal. The measurement takes place as close to the excitation location as possible and is based on the frequency shift of the laser light. The frequency will be shifted by the Doppler effect due to the movement of the reflector which is in this case the sheet metal. The resulting difference can be used for determination of the velocity (Möser & Kropp, 2010). Afterward, the mechanical impedance of the system can be estimated according to equation (1) using the induced force and the resulting vibration velocity.

2.3. Choice of factors and factor levels

The Experiment can be split up in different parts. At first, the impedance behavior of flat sheet metals has to be determined. This produces comparable data for further experiments. Subsequently, measurements of the velocity and the used force are performed first on structured sheet metals and then on sandwich sheet metals.
In general, necessary parameters can be identified by using brainstorming, the Delphi-method or mind-mapping (Wappis & Jung, 2013; Klein, 2007). The subsequent evaluation of the influencing variables is based on defined criteria such as the impact of the problem, the arising costs in combination with the potential level variations, the repeatability or the suitability for

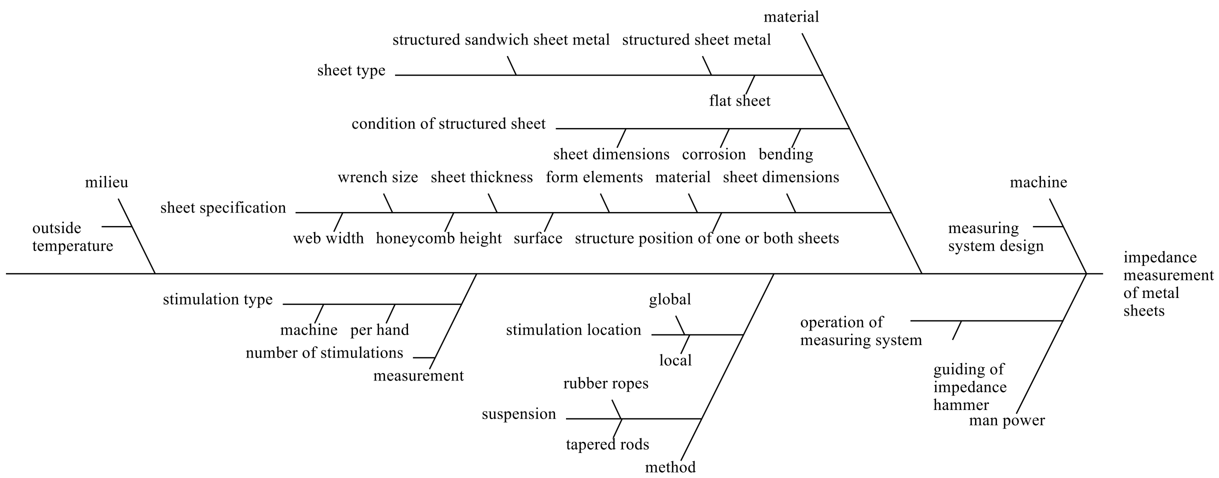


Figure 4: influencing factors of the impedance measurement of structured sandwich sheet metals

series production (Holst, 1995; Krottmaier, 1994). Through a multistage process a basic choice of factors for the experiment can be found (Holst, 1995). For the visualization and grouping of the defined parameters an Ishikawa-diagram can be used (Antony, 2008; Quentin & Kaminski, 1989). It is useful for the systematic classification of possible influencing variables by M-terms such as manpower, machine, milieu, etc., see Figure 4 (Klein, 2007).

In the following the influencing variable of the excitation location will be examined more detailed by the use of an example. The excitation location is one of the most important factors of the overall experiment and can be divided in two classes. The global excitation location is the position of the excitation on the entire sheet metal board. Possible locations of excitation are the center of the sheet metal and an eccentric force effect, outside of any axe of symmetry, see Figure 5. Throughout the experiment it has to be ensured that the sheet metal blanks have a center-honeycomb. Further, the eccentric excitation location must not be too close to the edge of the sheet metal. Otherwise there may be deviations in the velocity measurement because of the position that affects the vibrations of the sheet metal.

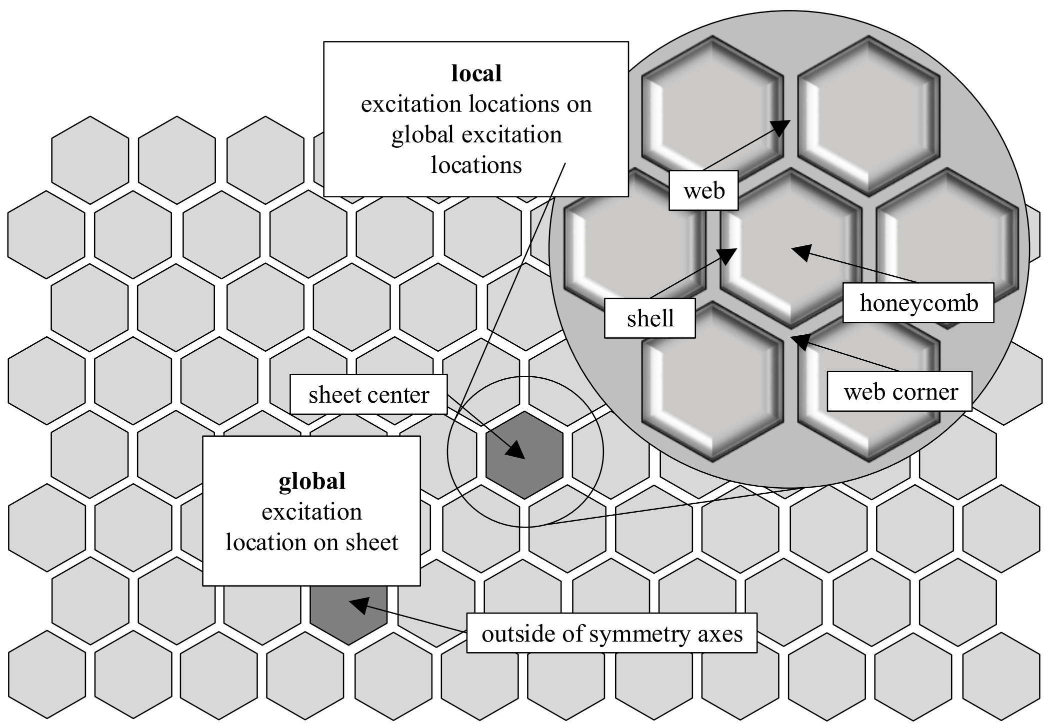


Figure 5: global and local excitation locations of structured sheet metals

The local excitation location is the place where the impedance hammer excites the sheet metal. It determines the global excitation location more precisely. The honeycomb center, the web corner, the web center and the center of the shell are identified as possible locations, as shown in Figure 5. From the results of simulations, a notable influence of the local excitation location on the impedance is suspected. There exist distinct differences between the three types of sheet metals. Since flat sheet metals do not have any structural elements there are no local excitation locations. Also there is no effect expected on the vibration behavior of the flat sheet metal at the change of the global excitation location as long as it is far enough away from the edge. For structured sheet metals, however, the connection between structure position and local excitation location must be analyzed intensively. The spatial position of the sheet metal at positive structure position within the experimental setup, as shown in Figure 2, does not allow reaching every local excitation location that was determined beforehand. Thus, the impact of an external force on the web or the web corner cannot be realized because of the small distance between the honeycombs.

The factors of the experiment and their factor levels are summarized in Table II. All determined factors are qualitative variables that cannot be changed, except for thickness of the sheet metal and the wrench size. The sheet metals can only be delivered with a certain thickness which makes a linear adjustment of the sheet metal thickness impossible. Due to production conditions the width across flats can only be produced for certain levels for which press tools already exist. A subsequent evaluation by using the regression analysis is therefore not possible and an analysis of variance is needed.

Table II: factors of sheet metal types

sheet type	factors	#	level 1	level 2	level 3	level 4	factor type
flat sheet metal	sheet type	3	DC04	X5CRNi18-10	Al	-	qualitative
	sheet thickness	3	0.5mm	0.7mm	1mm	-	quantitative, not linear distributed
structured sheet metals	sheet type	3	DC04	X5CRNi18-10	Al	-	qualitative
	sheet thickness	3	0.5mm	0.7mm	1mm	-	quantitative, not linear distributed
	wrench size	3	33	43	51	-	quantitative, not linear distributed
	structure position	2	positive	negative	-	-	qualitative
	local excitation	4	honeycomb	web	web corner	shell	qualitative
	global excitation	2	sheet center	outside of symmetry axes	-	-	qualitative
structured sandwich sheet metals	sheet type	3	DC04	X5CRNi18-10	Al	-	qualitative
	join type	3	spot welding each honeycomb	Spot welding each second honeycomb	sticking	-	qualitative
	wrench size	3	33	43	51	-	quantitative, not linear distributed
	local excitation	4	honeycomb	web	web corner	shell	qualitative
	global excitation	2	sheet center	outside of symmetry axes	-	-	qualitative

2.4. Experimental effort before the design of the experiments

For every type of sheet metal an experiment room is spanned according to the identified factors. As shown in Table III, the maximum number of factor combinations for flat sheet metals is nine, for structured sheet metals it is 432 and for structured sandwich sheet metals it is 216.

Thus, 657 experiments arose only by the different combinations of parameters and level possibilities. The experiments do not include repetitions of the experiments and contain factor combinations that are not executable. Repetitions of the experiments are, however, important for the determination of the standard deviation and the assessment of the significance (Kleppmann, 2013). Furthermore, the balance of the experimental design is no longer given due to the combination of factors with a different number of factor levels. For the evaluation of such experimental designs it is important to keep in mind that factors with a higher number of factor levels can be varied less often. The accuracy of the calculated effects for parameters varies therefore depending on the quantity of levels.
Since the performance of 657 experiments with an estimated time of 5 minutes per experiment without repetition would take about 55 hours, the factor examination has to be reduced to the necessary and reasonable minimum. As a result, the experimental scope should be reduced and the flexible adaption to real needs should be enabled. This includes for example the elimination of components or a different evaluation of the importance of the factors. As described already, most of the identified factors enter the experimental design only as a two level parameter. This means that only linear dependencies between the different levels can be detected. If inconsistencies are found during the experiments existing experimental design must be expanded or new ones must be used.

Table III: maximum number of factor combinations for different sheet types

sheet type	factors	levels	number of factors	maximum number of factor combinations
flat sheet metals	material sheet thickness	3 3	2	9
structured sheet metals	material sheet thickness wrench size structure position local excitation global excitation	3 3 3 2 4 2	6	432
structured sandwich sheet metals	material join type wrench size local excitation global excitation	3 3 3 4 2	5	216

3. Full and fractional factorial experimental designs for impedance measurement on flat sheet metals, structured sheet metals and structured sandwich sheet metals

3.1. Experimental design for the impedance measurement on flat sheet metals

The impedance determination of flat sheet metals takes places in order to create a basis of comparison for later experiments on structured sheet metals and structured sandwich sheet metals. The previously identified important factors will be planned in separate experiment parts. The experiment with flat sheet metals is based on the information presented in Table IV. The actual experimental design includes the order of the experiments and the factor combination which should be set up.
To generate references data for further experiments, a full factorial experiment with two factors and three factor levels is targeted. The combination of the parameters leads to 3^3=9 experiments. Applying the experimental design, there is the question of how large the sample size n for each experiment should be. This depends on how likely differences between the sample means should be detectable. The general formula for the determination of the sample size is 2^{k-p}-experimental designs using the t-test (Scheffler, 1997):

$$\mathrm{n} = n_1 + n_2 = 4\frac{\sigma^2}{\delta^2}\left[t(v;P_\alpha) + t(v;P_\beta)\right]^2 \quad \textbf{(2)}$$

With the corresponding formulas for the degree of freedom and the probabilities P_α, P_β

$$v = 2n - 2 \quad \textbf{(3)}$$

$$P_\alpha = 1 - \frac{\alpha}{2}\ (\text{two-way})\ \text{or}\ P_\alpha = 1 - \alpha\ (\text{one-way}),\ P_\beta = 1 - \beta. \quad \textbf{(4)}$$

Table IV: factors, levels and constants for experiments of flat sheet metals

flat sheet metal				
objective	achieving comparable values for structured and structured sandwich sheet metals			
experiments	9			
constants	global excitation sheet center			
factors	levels	level 1	level 2	level 3
sheet type	3	DC04	X5CRNi18-10	Al
sheet thickness	3	0.5mm	0.7mm	1mm

The standard deviation is labeled with σ and the deviation which is detectable between the mean values is labeled with δ (Montgomery, 2013). Here, the t-test is based on the case that at the same standard deviation $\sigma_1 = \sigma_2$ a difference between the mean values of the upper and lower factor levels $\mu_1 \neq \mu_2$, should be detected. If the standard deviation is known to the population the freedom degrees *v* are infinitely large. If the standard deviation *s* is only an estimated value because it is determined by a sample, the freedom degrees are used from the determination of *s* (Scheffler, 1997). The significance level α which is used in the rear part of the formula, states the probability of the failure type 1 and β the probability of the failure type 2 (Kleppmann, 2013). 455

Table V: sample size depending on α, β, σ and δ (Scheffler, 1997)

β = 0.05					β = 0.10				
d	P				d	P			
	0.99	0.975	0.95	0.90		0.99	0.975	0.95	0.90
0.10	1578	1300	1083	857	0.10	1302	1051	857	657
0.20	395	325	271	215	0.20	326	263	215	165
0.30	176	145	121	96	0.30	145	117	96	73
0.35	129	107	89	70	0.35	107	86	70	54
0.40	99	82	68	54	0.40	82	66	54	42
0.45	78	65	54	43	0.45	65	52	43	33
0.50	64	52	44	35	0.50	53	43	35	27
0.55	53	43	36	29	0.55	44	35	29	22
0.60	44	37	31	24	0.60	37	30	24	19
0.65	38	31	26	21	0.65	31	25	21	16
0.70	33	27	23	18	0.70	27	22	18	14
0.80	25	21	17	14	0.80	21	17	14	11
0.90	20	17	14	11	0.90	17	13	11	9
1.00	16	13	11	9	1.00	14	11	9	7
1.20	11	10	8	6	1.20	10	8	6	5
1.40	9	7	6	5	1.40	7	6	5	4
2.00	4	4	3	3	2.00	4	3	3	2

Since the freedom degrees for the calculation of the standard deviation is not available during the experimental design, there is an alternative possibility for the determination of the experimental scope. After the determination of α, β, σ and δ the sample size can be read out from Table V. This is possible because *d* was defined as follows:

$$d = \frac{\delta}{\sigma\sqrt{2}} \quad (5)$$

if two mean values μ_1 against μ_2 should be examined with the same standard deviation $\sigma_1 = \sigma_2$ (Scheffler, 1997).

The read out, tabulated necessary sample value is additionally slightly increased when σ is replaced by s. The adjustment takes place because only one estimated value with a limited number of freedom degrees is used for the calculation (Scheffler, 1997). This means in detail that

$$\alpha = 0{,}05 \rightarrow n = \text{table value} + 2 \quad (6)$$

$$\alpha = 0{,}01 \text{ (one-way)} \rightarrow n = \text{table value} + 3 \quad (7)$$

$$\alpha = 0{,}01 \text{ (two-way)} \rightarrow n = \text{table value} + 4. \quad (8)$$

Which values α and β should assume within the experiment is objectively dependent on the consequences of a false decision and subjectively on the view of the decision maker. The reduction of both influential factors leads to a great increase of the number if experiments and is therefore often not realizable. If α is large, the significant effects can be detected faster because of the early rejection of the null hypothesis (Scheffler, 1997). For β a value of 5% or 10% is mostly found in literature and for α 1% or 5% [7, 9]. For the experiment planned here the value of β is assumed with 10%.

Differences are therefore identified with a chance of 90%. The chosen probability of error α is 1%. Since the deviations should be detected in both directions a two-way test has to be used additionally. As further parameters to determine the sample size, additional values for σ and δ have to be assumed. Since the determination of the variance σ^2 is in practice not possible without experiential values, an earlier experiment series or a preparatory experiment (Montgomery, 2013), an assumption is made for the standard deviation. The same applies for the detection of the difference δ. On condition that the standard deviation s and the detectable differences δ are equal in size, the result is a value for d of approximately 0.7.

Thus the read out sample size is 27, see Table V. Since a two-way test should be carried out and s instead of σ is used, the sample size rises up to $n_1 = n_2 = 27 + 4 = 31$. Therefore $n_1 + n_2 = 62$ experiment should be carried out. Adjusted to experimental designs with two steps the next higher power of two is 64. Therefore $n_{ges} = 64$ experiments are necessary in total. Afterwards, this amount of experiment points will be distributed among the experimental design and the repetitions with

$$\boldsymbol{n_{ges}} = \boldsymbol{cN}, \text{ where} \quad (9)$$

c = the number of repetitions,

N = the total number of experiments of an experimental design (Scheffler, 1997). The resulting repetition numbers can be found in Table VI.

Table VI: realizations depending on the number of factors (Kleppmann, 2013)

number of factor with two stages	realizations
1	30
2	15
3	8
4	4
5	2

Through the shown number of realizations it is assured that an actually existing difference is made clear with a probability of $1-\alpha$ and a not significant result proves the existence of a difference $\leq \delta$ with a probability of $1-\beta$ (Scheffler, 1997). Falling below the upper read out sample sizes increases β, which increases the confidence interval of the average value when α is steady. Exceeding the necessary number of experiments, leads to a reduced risk β or the decrease of the detectable difference δ.

The number of characteristics for flat sheet metals is lower than for other kinds of sheet metals. As a consequence, significant differences can only be found for a considerably higher number of experiment executions. However, for flat sheet metals the study focus is not the determination of influential factors but the determination of comparative values. Regarding aspects of cost-effectiveness for the experimental procedure, a four-time realization of experiments is recommended in contrast. Thus the experiment consists of 36 experiments.

It is important to pay attention to a number of conditions during the performance of the experiment in order to gain evaluable results. That means, all values should be representative; measured values of groups should be normally distributed and the standard deviation should be steady (Kleppmann, 2013). During the experimental design it is important to regard the representation of the values through randomization and the creation of blocks. The other two criteria will be determined subsequently to the experiment by comparison (e.g. Mann-Whitney-Wilcoxon or χ2-Test).

3.2 Experimental design for the impedance measurement on structured sheet metals

In comparison to the previously introduced experimental design, the experiment with structured sheet metals is divided into pre, main and post experiments. This allows on the one hand the exclusion of unrealizable factor combinations and can be used on the other hand to keep the total number of experiments low. The pre experiments should always result in the limitation of possible factor levels. The following main experiments are used to determine and quantify the effects. Possible post experiments should only be used to additionally examine insignificant factor combinations. Experimental designs can be changed purposefully if large discrepancies between the experimental design and the results of the main experiments occur during the performance of the experiment.

Table VII: factors, levels and constants for pre experiment of structured sheet metals

pre experiment - structured sheet metal					
objective	determining the optimal global and local excitation location				
experiments	16 (global excitation 4 levels) or 8 (2 levels)				
constants	negative structure position sheet thickness 0.5mm wrench size 33 sheet type DC04				
factors	levels	level 1	level 2	level 3	level 4
local excitation	4	honey comb	web	web corner	shell
global excitation	2	sheet center	outside of symmetry axes		

The pre experiment examines the correlation between local and global excitation location and should identify two local excitation locations that serve best for the main experiment, see Table VII. An optimal excitation location could be for example one point with minimal and one point with maximum impedance. The experiment can be carried out as full factorial 42-experimental design. However, this includes a more detailed determination of the effects of the global excitation location compared to the local excitation location because there are twice as many pairs of values for the calculation of the effect available. Thus, the principle of orthogonality is no longer guaranteed. In order to generate sufficient values for variance calculations, each measurement has to be repeated four times. Since this is a pre experiment which does not calculate final effects, a repetition of the experiment and a simple pairing of the two global factor levels with four local levels is recommended. Therefore, $2 \cdot 4 \cdot 2 = 16$ experiments are necessary.

Table VIII: factors, levels and constants for first main experiment of structured sheet metals

first main experiment - structured sheet metal			
objective	determining the correlations between factors, focus on structure position		
experiments	32 or 16		
constants	sheet type DC04		
factors	levels	level 1	level 2
structure position	2	negative	positive
sheet thickness	2	0.5mm	0.7mm
wrench size	2	33	51
local excitation	2	honeycomb	shell
global excitation	2	sheet center	outside of symmetry axes

The focus of the of the main experiment is the examination of the structure position in connection with possible correlation effects. The experimental scope of the main experiment is $2^5 = 32$ when carried out full factorial and $2^{5-1} = 16$ for a fractional factorial experiment. Performed as full factorial 2^5-experimental design, it can determine all correlation effects not mixed up. A repetition is sufficient for the calculation of the distribution, see Table VI. According to that, the experimental scope includes 64 experiments. A short version of the experimental design can be found in Table VIII. The separation into two main experiments is necessary because the structure position is being taken into account. This means, it is not possible to carry out experiments on all excitation locations of the sheet metal. For this reason, factor levels that were identified in the pre experiment can most likely not be applied in the first main experiment.

Table IX: factors, levels and constants for second main experiment of structured sheet metals

second main experiment - structured sheet metal			
objective	determining the correlations between factors, focus on local excitation		
experiments	32 or 16		
constants	negative structure position		
factors	levels	level 1	level 2
sheet type	2	DC04	X5CRNi18-10
sheet thickness	2	0.5mm	0.7mm
wrench size	2	33	51
local excitation	2	honey comb	web
global excitation	2	sheet center	outside of symmetry axes

The second main experiment takes up the local excitation points as identified in the pre experiment and points out which, at best, linear dependencies exist between factor changes and values of the target dimension. Due to the previous simulations, the honeycomb and the web are chosen excitation location in the experimental design. This can be changed depending on the situation. The experimental description is given in Table IX.

Table X: factors, levels and constants for post experiment of structured sheet metals

post experiment - structured sheet metal			
objective	determining the influence of aluminum		
experiments	4		
constants	negative structure position sheet type aluminum local excitation on honeycomb global excitation on sheet center		
factors	levels	level 1	level 2
sheet thickness	2	0.5mm	1mm
wrench size	2	33	43

If the experimenter is time-bound the full factorial plan can be split into two fractional factorial plans. This makes it possible to determine all correlations precisely without mixing. There is also the possibility to follow up the first full factorial main experiment with a fractional factorial second main experiment. After the performance of the main experiments an additional post experiment can be carried out to determine the influence of the material aluminum, see Table X. This is only necessary if the materials are available. If the material costs are too high at this point, it is advisable not to take the materials into account. According to the simulation only minor influences are expected from the material, therefore a repetition number of three is suggested. This is far less than the calculated minimum amount of repetitions of 14 but there must be a consideration between statistical accuracy and arising costs.

3.3 Experimental design for the impedance measurement on structured sandwich sheet metals

The overall experiment on structured sandwich sheet metals is divided in several part experiments as well. At the beginning, a pre experiment similar to the one on structured sheet metals should be carried out to determine the excitation location. Ideally, the local excitation locations of the structured sheet metal und the structured sandwich sheet metal are identical and enable a comparison. In Table XI the pre experiment is shown which consists of eight experiments.

Table XI: factors, levels and constants for pre experiment of structured sandwich sheet metals

pre experiment - structured sandwich sheet metal					
objective	determining the optimal global and local excitation position				
experiments	16 (global excitation 4 levels) or 8 (2 levels)				
constants	spot welding each honeycomb sheet thickness 0.5mm wrench size 33 sheet type DC04				
factors	levels	level 1	level 2	level 3	level 4
local excitation	4	honey comb	web	web corner	shell
global excitation	2	sheet center	outside of symmetry axes		

The experimental design is visualized in Table XII. Corresponding to the pre experiment for structured sheet metals, a repetition of the experiments is targeted. The experimental scope increases therefore to 16 experiments.

Table XII: design of pre experiment for structured sandwich sheet metals

default sequence	pass ranking	point type	blocks	local excitation	global excitation	impedance	wrench size to honeycomb height	wrench size to sheet thickness
8	1	1	1	shell	outside of symmetry axes			
10	2	1	1	honeycomb	outside of symmetry axes			
1	3	1	1	honeycomb	sheet center			
5	4	1	1	web corner	sheet center			
9	5	1	1	honeycomb	sheet center			
11	6	1	1	web	sheet center			
2	7	1	1	honeycomb	outside of symmetry axes			
4	8	1	1	web	outside of symmetry axes			
12	9	1	1	web	outside of symmetry axes			
16	10	1	1	shell	outside of symmetry axes			
7	11	1	1	shell	sheet center			

6	12	1	1	web corner	outside of symmetry axes
15	13	1	1	shell	sheet center
3	14	1	1	Steg	sheet center
14	15	1	1	web corner	outside of symmetry axes
13	16	1	1	web corner	sheet center

In contrast to the two main experiments on structured sheet metals, for the analysis of structured sandwich sheet metals one main experiment is sufficient due to the low amount of factors and factor levels. In addition, no mutually exclusive factor combinations occur. The experiments aim for the analysis of the complex correlations between the factors and its influence on the impedance values. A summary of the experiment can be found in Table XIII and an excerpt of the experimental design is presented in Table XIV.

Table XIII: factors, levels and constants for main experiment of structured sandwich sheet metals

main experiment - structured sheet metal			
objective	determining the correlations between factors		
experiments	16		
constants	sheet type DC04 spot welding each honeycomb		
factors	levels	level 1	level 2
wrench size	2	33	43
sheet type	2	DC04	X5CRNi18-10
local excitation	2	honeycomb	shell
global excitation	2	sheet center	outside of symmetry axes

Table XIV: design of main experiment for structured sandwich sheet metals (excerpt)

default sequence	pass ranking	wrench size	sheet type	local excitation	global excitation	impedance	wrench size to honeycomb height	wrench size to sheet thickness
46	33	43	DC04	honeycomb	outside of symmetry axes			
43	34	33	X5CRNi18-10	web	outside of symmetry axes			
45	35	33	DC04	honeycomb	outside of symmetry axes			
48	36	43	X5CRNi18-10	honeycomb	outside of symmetry axes			
41	37	33	DC04	web	outside of symmetry axes			
37	38	33	DC04	honeycomb	sheet center			
36	39	43	X5CRNi18-10	web	sheet center			
35	40	33	X5CRNi18-10	web	sheet center			
38	41	43	DC04	honeycomb	sheet center			
39	42	33	X5CRNi18-10	honeycomb	sheet center			
40	43	43	X5CRNi18-10	honeycomb	sheet center			
47	44	33	X5CRNi18-10	honeycomb	outside of symmetry axes			
33	45	33	DC04	web	sheet center			
44	46	43	X5CRNi18-10	web	outside of symmetry axes			
34	47	43	DC04	web	sheet center			
42	48	43	DC04	web	outside of symmetry axes			
5	49	33	DC04	honeycomb	sheet center			
16	50	43	X5CRNi18-10	honeycomb	outside of symmetry axes			

Since only four parameters are included in the experiment the number of experiments is 16. For the generation of statistically reliable results it is necessary to repeat the experiments three times. The experimental scope amounts therefore to 64. If findings concerning the influential variable of the conjunction type should be collected a post experiment can determine the influence of different welding techniques or gluing, see Table XV.

3.4. Experimental effort after planning the experiments

With the help of the planned experiments all main actions and correlations which will be examined are to be calculated. The total number of proposed experiments is 111. If the repetitions are counted, the total effort amounts to approximately 276 experiments. This number represents a saving of 58% of the experiments, compared to the previous number of 657 experiments without repetitions.

Table XV: factors, levels and constants for post experiment of structured sandwich sheet metals

post experiment - structured sandwich sheet metal			
objective	determining the influence of join type		
experiments	2		
constants	negative structure position		
	sheet type DC04		
	local excitation on honeycomb		
	global excitation on sheet center		
factors	levels	level 1	level 2
join type	2	Spot welding each second honeycomb	sticking

At this place it should be once more indicated explicitly that the assumption concerning the values of α, β, σ and δ have been made. At least during the performance of the experiment with flat sheet metals or the pre experiments, the chosen parameters σ and δ can be checked for correctness. This could subsequently lead to an increase of repetitions. To avoid false decisions, the number of experiment repetitions must be adjusted immediately if larger deviations occur during the performance of the experiment.

5. Summary

Starting point of this study is the insufficient knowledge of the acoustic resistance of structured sheet metals and structured sandwich sheet metals. In consideration of the emerging costs and a minimal run time of the experiments, suitable experimental designs are created for flat sheet metals, structured sheet metals and structured sandwich sheet metals. In order to reduce the high number of experiments to determine the connection between the target value impedance and its influencing factors, the statistical experimental design is used. The full factorial experimental design developed for the analysis of flat sheet metal includes three factor levels. In contrast to the analysis of flat sheet metals, the respective impedance analysis of structured sheet metals and structured sandwich sheet metals is divided into three phases. This multi-stage approach is necessary because of unrealizable factor combinations. At the same time it is possible to keep the total number of experiments low. Therefore, the first phase consists of pre experiments that identify relevant factor levels. The defined factor level is used in the main experiment. The aim of this experiment is the determination of complex relations between parameters and the target value impedance. Further experiments can be conducted for optional analysis of additional factor levels or further influencing variables. This includes, for example, a different connection of the sheet metals such as gluing. By using full and fractional factorial experimental designs the necessary number of experiments of 657 experiments without repetition can be reduced to 276 experiments with repetition.

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