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## Correlation Analysis of Air Transfer and Sound Wave Transfer

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*Abstract:* - The basic goal of this paper is that the two phenomena, air transfer and sound wave transfer, are correlated. The correlation of Air infiltration flow (Q) using different Window Types (WT) for different Reverberation Time (RT) corresponding to 1 KHz Frequency and Global Weighted Noise Level Difference ( $\Delta LA$ ) has been analyzed in this study. This correlation has been studied for the specific application (building air infiltration) and the relationship between the physical parameters corresponding to the two phenomena.

*Keywords:* - Air transfer, sound wave transfer, correlation analysis.

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## 1. INTRODUCTION

People spend over 80% of their time indoors, therefore the quality of the indoor environment is of utmost importance for human health. The indoor environment can be characterized by several type of indoor comfort types: pollution level indoors, thermal comfort, noise level indoors, relative humidity and visual comfort. The control of the indoor environment

quality represents the key to a healthy building and to a well being indoors. However, indoor environment characteristics are highly influenced by the outdoor environment, by its pollution level [1], noise level [2], outdoor air temperature and relative humidity. The indoor environment quality is directly influenced by the outdoor environment due to the direct change of pollutant mass or noise through window joints or any façade leakage areas. Thus, the building façade

permeability represents the key element linking up the two environments; therefore, determining with good precision the building façade permeability represents an extremely important aspect for any indoor environment quality control strategy.

Today, the assessment of this building property is one of the most researched fields and we can find in the literature several ways to determine this parameter: prediction models and experimental measurements. The prediction models [3, 4, 5] present the advantage that without any building intrusive measure they can provide the value of the air permeability (prediction of normalized air leakage [4, 5] or air leakage coefficient [3]) based of different building characteristics: age, height, structure type, climate zone, energy efficiency, number of stories and floor area. Despite their easy to use and fast prediction of the building permeability, these prediction models are characterized by average prediction errors of about 30% and maximum errors of about 159%. Such high errors are not acceptable for neither any indoor environment quality control strategy nor building energy consumption estimation.

The experimental methods surmount this low precision disadvantage of the building air permeability prediction models. The standardized experimental methods concentration decay curve [6] and fan pressurization method [7, 8] are characterized by errors less than 5%. However, these methods present other disadvantages: sensitive to climate parameters, the high cost of the experimental equipment, the technical/scientific background of the user and time consuming. New experimental methods are developed. The method based on infrared tomography [9] was never tested for real windows and thus its applicability for different types and geometries of joints is questioned. The acoustic method [10] proved the existence of a very good correlation between the air transfer and the sound energy transfer through the same window joints. This method overcomes all disadvantages of the previously presented methods; it is a fast and inexpensive method characterized by a very good precision given it is an experimental method, independent to the climatic parameters variation. However, this correlation between the air transfer and the sound energy transfer, even though observed on real buildings, however it was never studied properly under laboratory condition that satisfies the airborne noise phenomena.

The purpose of this study is to understand if the two transpher phenomena are corelated and the results are relevant. Further we wish to understand if this new acoustic experimental method would

represent a viable solution for a fast and precise estimation of the leakage air flow.

## 2. EXPERIMENTAL APPROACH

This study represents the first study properly carried out inside of an airborne experimental stand. This approach is needed in order to study the phenomenon under controlled environment for different window types, for different window openings, without other outdoor noises (that represent error sources), meeting the airborne noise international measurement protocols. Several situations of window joints were experimented for different types of windows. The noise level difference was measured by means of airborne noise experiments and the leakage air flow was determined by means if a blower door experimental stand. The correlation between the two phenomena is further analyzed.

### 2.1. Problem conditions

In order to study the intensity of the relationship between the measured variables, the correlation analysis [11, 12], which can be expressed by the parametric coefficients if their distribution is normal, will be used. The Kolmogorov - Smirnov - Lilliefors (K-S-L) test was used to perform the normality test. The principle of verifying the normality of a distribution based on a test is to compare the actual cumulative frequencies with the theoretical cumulative frequencies extracted from the Gauss table. We accept the normality hypothesis if, at the calculated maximum difference, we find in the K-S-L table a higher critical value than this, for a given volume and a tolerated risk.

The Pearson correlation coefficient was used, which is a parameter coefficient and noted with  $r_{xy}$  or  $r$ . This coefficient can be calculated using the relationship:

$$r_{xy} = \frac{\frac{1}{n} \cdot \sum_i (x_i - \bar{x}) \cdot (y_i - \bar{y})}{s_x \cdot s_y} \quad (1)$$

where:

$n$  – the size of sample for  $(x,y)$ ;

$x_i$  – the measures for  $x$ ;

$y_i$  - the measures for  $y$ ;

$\bar{x}$  - the arithmetic media for  $x$ ;

$\bar{y}$  - the arithmetic media for  $y$ ;

$s_x$  -  $x$  standard deviation;

$s_y$  -  $y$  standard deviation.

## 2.2. Experiments

The experimental stand (Figure 1) is composed of two chambers. The two chambers have their own foundation, independent structure from the other chamber and independent from the structure of the entire laboratory building.

This dissociation assures that the sound wave is not transmitted from one room to the other one through the walls. Each room has a double door towards the adjacent hall to the experimental stand. The experimental wall is placed between the two rooms on its own foundation different and dissociated from the foundations of the two rooms.

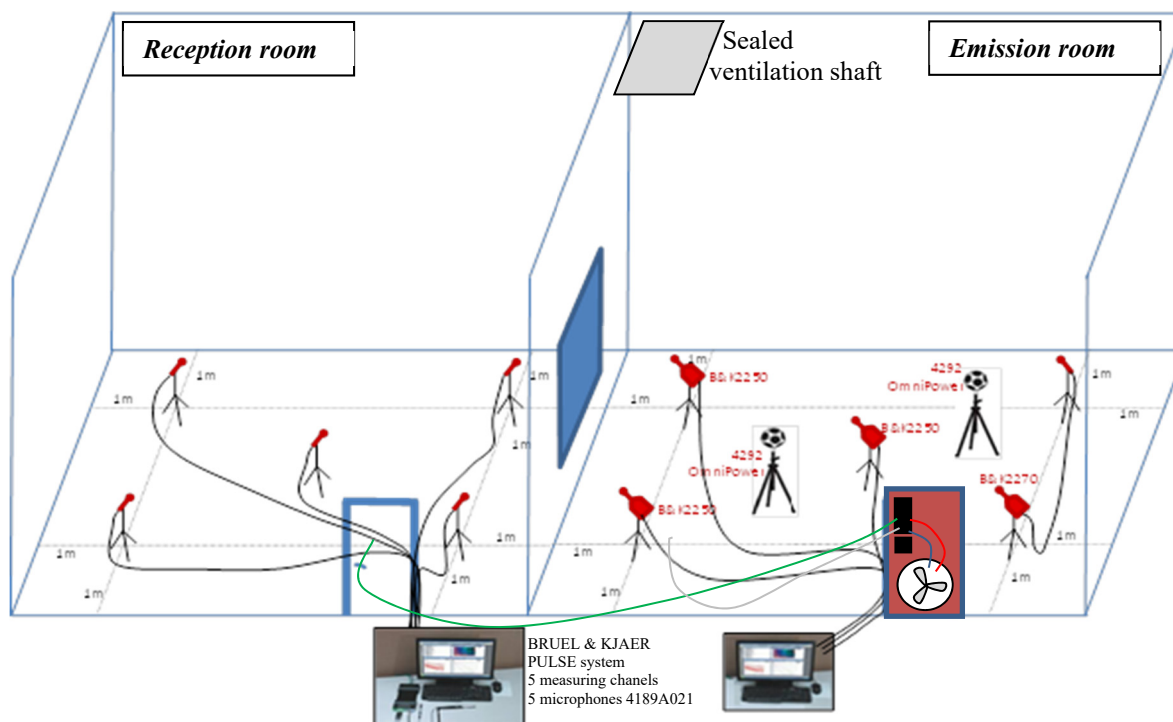


Figure 1. Experimental stand for airborne noise measurements

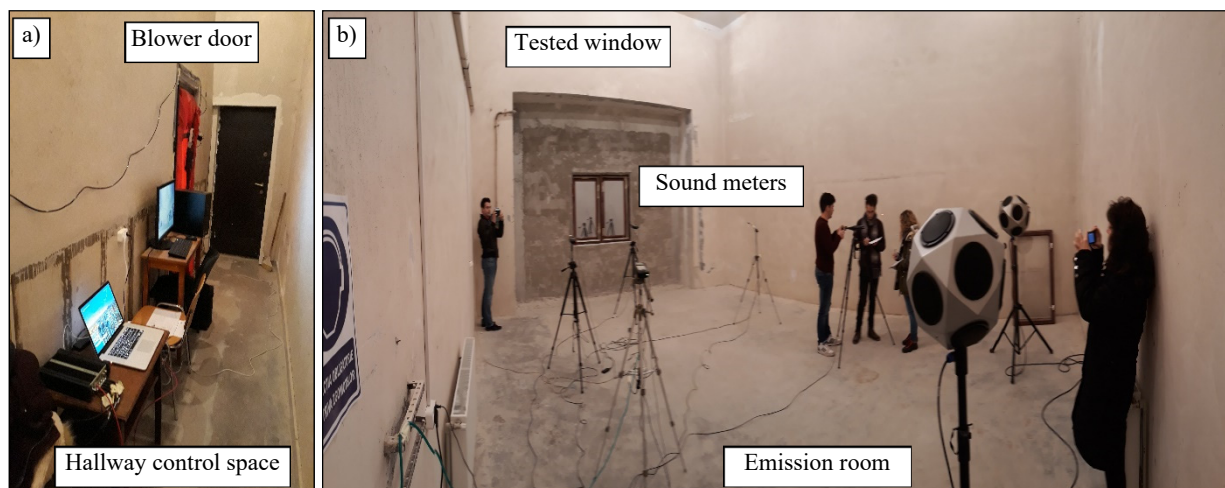
This wall is a five layer wall (cement plaster, brick, acoustic insulation, brick and cement plaster) assuring a very good acoustic insulation ( $R_w = 60\text{dB}$ ). Inside this wall, the experimental window fixed frame (1.25m x 1.5 m) was mounted, which dimensions correspond to the norm values for airborne noise measurement [13].

The acoustic measurements were carried out in five different points in each room. In emission room the noise level was simultaneously recorded by means of three different 2250 and a double channel 2270 from Bruel&Kjaer. All sound meters were controlled via USB cable from a computer placed on the adjacent hallway. In reception room the noise level was simultaneously recorded by means of a five point pulse measurement system from Bruel&Kjar controlled from another computer placed also in the hallway. Two OmniPower sound sources were used in the emission room and their control was assured by one of the computers in the hallway way via a power amplifier placed in the emission room. The acoustic measurements were carried out according to [13].

Figure 2 presents the sound meters installed in the emission room and the measurements control computers located in the hallway.

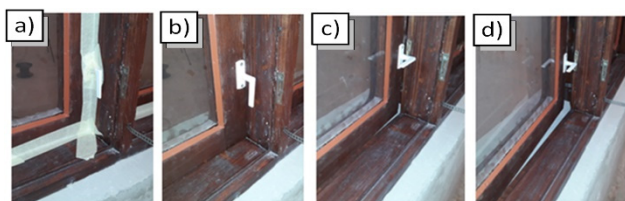
The permeability measurements were carried out by means of a Blower door system. The blower door was placed in the doorway of the emission room between the emission room and the hallway

The pressure tubes were placed at 1m height from the ground in both the emission and the reception rooms. The fan was controlled from the computer placed near by the system in the hallway. The permeability laws and estimated leakage area (ELA,  $\text{cm}^2$ ) were determined using the international standards [7, 8]. In order to simulate an infiltration, for a specific type of window, we cracked it open a little bit and kept it steady using a blocking system for the measuring period. One experiment is composed of two different measurements: the permeability measurement (in order to determinate the airflow crossing the window joint) and the acoustic airborne noise measurement (in order to determine the acoustic levels in both rooms).



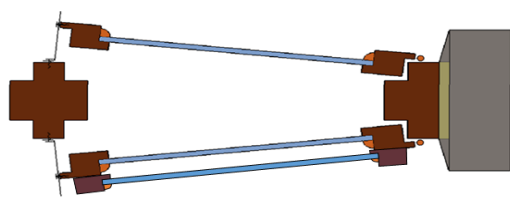
**Figure 2.** Photos of the hallway (blower door and computers) and emission room

This double measurement experiment was carried out for eight different window openings (Figure 3) and for nine different types of windows (simple wood frame window, coupled wood frame window, double wood frame window, triple wood frame window, aluminum double glazing window, double glazing wood frame window, PVC simple glazing window, PVC double glazing window and PVC triple glazing window) (Figure 4), resulting in a total of 72 different experiments.



**Figure 3.** Window openings for a simple wooden frame window  
 a) closed window, sealed joint; b) closed window;  
 c) closed window, small joint; d) closed window larger joint

Even if the entire experimental window is formed of two leaves, however during the experiment, we manipulated just one leaf in order to simulate an increasing infiltration limiting the error sources (Figure 4). Singled framed window opens towards the Reception room while the double and triple framed windows open towards both the Emission and the Reception rooms.



**Figure 4.** Experimental triple window, formed of one simple window and one coupled window

### 3. DATA ANALYSIS

Considering the fact that the units of measurement and the order of magnitude that characterize the analyzed parameters are very different, we will work in performing the statistical analysis with normalized values [14, 15] (Table 1-Table 2), where:

- Q [m<sup>2</sup>/h] – flow for the pressure 4Pa
- WT - Window Types (SL, DL, TL, DVL, DVAL, SVPVC, DVPVC, TVPVC)
- WO – Window Opening (0,1,2,3,4,5,6,7)
- RT[s] – Reverberation Time (0.60, 1.20, 1.80, 5.13)
- $\Delta LA$ [dBA] – corresponding to different degrees of opening of the windows (0, 1, ...7)
- $Q\_i\_j$ ,  $i \in \{0.60, 1.20, 1.80, 5.13\}$ ,  $j \in \{0, 1, \dots, 7\}$

To determine the correlation coefficient to be used in this study, the K-S-L normality test was performed using the IBM-SPSS Trial program, version 22.0.0, [16]. Table 3 shows that the significance degree, Sig., is greater than 0.05, indicating that the distribution of the variables does not differ significantly from the normal distribution pattern.

Table 4 contains the matrix of Pearson correlation coefficients. On both sides of the diagonal equal to 1 are the values of the correlation of each variable to itself.

The variables analyzed from the table 4 are strongly correlated, with many values of the Pearson Coefficient greater than 0.9 and the significance greater than 0.01 indicating the following:

- Reverberation Time (RT) does not influence Flow, Q, so it is sufficient to consider, for example, only the value of 5.13 s.
- The  $\Delta LA$  corresponding to the different opening degrees of the windows can only take the values corresponding to positions 1, 4, 5 and 6.

Further correlation analysis between the  $\Delta LA$  and RT proved these two parameters are strongly correlated (coefficient is greater than 0.97), which means that RT and  $\Delta LA$  are not independent variables.

#### 4. CONCLUSIONS

The results of the correlation analysis indicate the following:

- The infiltrated air flow depends of global weighted noise level difference noise  $\Delta LA$  and it is not influenced by the values of room reverberation time RT (see similar values in Tables 1 and 2),
- The global weighted noise level difference noise  $\Delta LA$  and room reverberation time RT are not independent variables,
- The infiltrated air flow can be determined as a  $\Delta LA$  function considering for example the

measured values for RT = 5.13 s (Table 2). The model can be determined using for  $\Delta LA$  only the values corresponding to the opening degrees of the windows in positions 1, 4, 5 and 6.

- A prediction method can be applied for the evaluation of the Flow depending of the  $\Delta LA$  using the Levenberg-Marquardt algorithm [17, 18].

Correlations are useful because if one can find out the type of relationship between two variables, then predictions can be made concerning the future behaviour for the experimental stand that we present in this article: the structure, the measurement devices, the experimental windows and their opening degrees.

The two transfer phenomena (air infiltration transfer through window joints and sound energy transfer) are correlated. Therefore we conclude that the infiltration air flow can be measured based on acoustic measurements.

**Table 1.** Normalized measured data of  $\Delta LA$ -global weighted noise level difference for RT-reverberation time for 0.60 s and 1.20 s; (WT – window type; WO – window opening)

RT WO WT	RT=0.60 s								RT=1.20 s							
	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7
SL	1.00	1.00	1.00	1.00	1.00	0.94	0.94	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.94	1.00
DL	0.26	0.17	0.56	0.67	0.63	0.68	0.71	0.82	0.26	0.17	0.56	0.67	0.63	0.68	0.71	0.82
CL	1.00	0.89	1.00	1.00	1.00	0.94	0.94	1.00	1.00	0.89	1.00	1.00	1.00	0.94	0.94	1.00
TL	0.26	0.21	0.56	0.67	0.63	0.68	0.71	0.82	0.26	0.21	0.56	0.67	0.63	0.68	0.71	0.82
DVL	0.00	0.00	0.00	0.27	0.30	0.55	0.53	0.76	0.00	0.00	0.00	0.27	0.30	0.55	0.53	0.76
DVAL	0.01	0.01	0.02	0.29	0.96	1.00	1.00	0.87	0.01	0.01	0.02	0.29	0.96	1.00	1.00	0.87
SVPVC	0.00	0.00	0.00	0.36	0.66	0.62	0.70	0.84	0.00	0.00	0.00	0.36	0.66	0.62	0.70	0.84
DVPVC	0.00	0.00	0.00	0.41	0.69	0.64	0.71	0.85	0.00	0.00	0.00	0.41	0.69	0.64	0.71	0.85
TVPVC	0.00	0.00	0.00	0.36	0.66	0.62	0.70	0.84	0.00	0.00	0.00	0.36	0.66	0.62	0.70	0.84

\* SL – wood frame simple window; DL - wood frame double window; CL - wood frame coupled window; TL - wood frame triple window; DVL - wood frame simple window double glazing; DVAL - aluminium frame simple window double glazing; SVPVC - PVC frame simple window simple glazing; DVPVC - PVC frame simple window double glazing; TVPVC - PVC frame simple window triple glazing;

**Table 2.** Normalized measured data (RT-reverberation time for 1.80 s and 5.13 s;  $\Delta LA$ -global weighted noise level difference; WT – window type)

RT WO WT	RT=1.80 s								RT=5.13 s							
	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7
SL	1.00	1.00	1.00	1.00	1.00	0.94	0.94	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.94	1.00
DL	0.26	0.17	0.56	0.67	0.63	0.68	0.71	0.82	0.26	0.17	0.56	0.67	0.63	0.68	0.71	0.82
CL	1.00	0.89	1.00	1.00	1.00	0.94	0.94	1.00	1.00	0.89	1.00	1.00	1.00	0.94	0.94	1.00
TL	0.26	0.21	0.56	0.67	0.63	0.68	0.71	0.82	0.26	0.21	0.56	0.67	0.63	0.68	0.71	0.82
DVL	0.00	0.00	0.00	0.27	0.30	0.55	0.53	0.76	0.00	0.00	0.00	0.27	0.30	0.55	0.53	0.76
DVAL	0.01	0.01	0.02	0.29	0.96	1.00	1.00	0.87	0.01	0.01	0.02	0.29	0.96	1.00	1.00	0.87
SVPVC	0.00	0.00	0.00	0.36	0.66	0.62	0.70	0.84	0.00	0.00	0.00	0.36	0.66	0.62	0.70	0.84
DVPVC	0.00	0.00	0.00	0.41	0.69	0.64	0.71	0.85	0.00	0.00	0.00	0.41	0.69	0.64	0.71	0.85
TVPVC	0.00	0.00	0.00	0.36	0.66	0.62	0.70	0.84	0.00	0.00	0.00	0.36	0.66	0.62	0.70	0.84

Given the high values of the correlation coefficients (above 0.9) we consider that the acoustic measurements represent a viable solution for the air permeability assessment with good precision.

However, the applicability of this method remains to be tested for different window and joints configuration, different building floor, and different wind exposures.

**Table 3.** Kolmogorov – Smirnov Test for different RT (0.6 s,1.2 s,1.8 s,5.13 s) and different WO (0,1,2,3,4,5,6,7)

		Q_0.6_0	Q_0.6_1	Q_0.6_2	Q_0.6_3	Q_0.6_4	...	Q_5.13_3	Q_5.13_4	Q_5.13_5	Q_5.13_6	Q_5.13_7
Normal Param.	Mean	.72	.74	.65	.60	.39	..	.60	.39	.57	.48	.55
	Std. Dev	.42	.40119	.43762	.39579	.32535	..	.39579	.32535	.37463	.32435	.33731
Most Extreme Difference	Absolut	.29	.321	.329	.253	.226	..	.253	.226	.315	.319	.274
	Positive	.25	.264	.213	.159	.226	..	.159	.226	.212	.214	.179
	Negativ	-.29	-.321	-.329	-.253	-.224	..	-.253	-.224	-.315	-.319	-.274
Kol.-Smir. Z		.89	.89	.962	.988	.758	..	.758	.678	.944	.956	.822
Asymp. Sig.		<b>.402</b>	<b>.402</b>	<b>.313</b>	<b>.283</b>	<b>.613</b>	..	<b>.613</b>	<b>.747</b>	<b>.335</b>	<b>.320</b>	<b>.510</b>

**Table 4.** The Correlation table for different RT (0.6 s,1.2 s,1.8 s,5.13 s) and different WO (0,1,2,3,4,5,6,7)

	Q_0.6_0	Q_0.6_1	Q_0.6_2	Q_0.6_3	...	Q_5.13_2	Q_5.13_3	Q_5.13_4	Q_5.13_5	Q_5.13_6	Q_5.13_7
Q_060_0	1	.99**	.95**	.96**	...	.95**	.96**	.65	.63	.59	.88**
Q_060_1	.99**	1	.93**	.94**	...	.93**	.94**	.66	.64	.59	.90**
Q_060_2	.95**	.93**	1	.98**	...	1.0**	.98**	.56	.55	.50	.76*
Q_060_3	.96**	.94**	.98**	1	...	.98**	1.0**	.59	.525	.504	.80**
Q_060_4	.65	.66	.56	.59	...	.562	.594	1.00**	.916**	.973**	.891**
Q_060_5	.63	.64	.55	.52	...	.555	.525	.916**	1.00**	.975**	.792*
Q_060_6	.59	.59	.50	.50	...	.506	.504	.973**	.975**	1.00**	.813**
Q_060_7	.88**	.90**	.76*	.80**	...	.760*	.808**	.891**	.792*	.813**	1.00**
...	...	...	...	...	...	...	...	...	...	...	...
Q_513_0	1.0**	.99**	.95**	.96**	...	.954**	.960**	.655	.639	.590	.887**
Q_513_1	.99**	1.0**	.93**	.94**	...	.931**	.942**	.665	.648	.599	.901**
Q_513_2	.95**	.93**	1.0**	.986**	...	1	.986**	.562	.555	.506	.760*
Q_513_3	.96**	.94**	.98**	1.00**	...	.986**	1	.594	.525	.504	.808**
Q_513_4	.65	.66	.56	.594	...	.562	.594	1	.916**	.973**	.891**
Q_513_5	.63	.64	.55	.525	...	.555	.525	.916**	1	.975**	.792*
Q_513_6	.59	.59	.50	.504	...	.506	.504	.973**	.975**	1	.813**
Q_513_7	.88**	.90**	.76*	.808**	...	.760*	.808**	.891**	.792*	.813**	1

\* good correlation; \*\* very good correlation

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