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Evaluation of machinery acoustic properties using the acoustic radiation efficiency parameter

Kozupa Michal[1], Kmita Grzegorz[2], Platek Robert[3]
ABB Corporate Research
Starowislna 13 A Str. 31-038 Kraków, Poland

Matys Magdalena[4]
AGH University of Science and Technology
al. Mickiewicza 30, 30-059 Krakow, Poland

ABSTRACT

Acoustic radiation efficiency is a parameter which characterizes the sound radiation effectiveness of a vibrating surface. It can be useful in describing the coupling between a vibrating element and the origin of its structure-borne noise. This paper discusses the possibilities of using acoustic radiation efficiency parameter as an indicator applied to assess the noise emitted by power machinery. Acoustic methods, including intensity scanning, Laser Doppler Vibrometry (LDV) and numerical analyses, were used to determine the vibration velocity and, subsequently, calculate and evaluate the radiation efficiency values. Results of measurements and FEM simulations are presented along with comparison of the methods.

Keywords: Acoustic radiation efficiency, Laser Doppler Vibrometry
I-INCE Classification of Subject Number: 14

1. INTRODUCTION

Radiation efficiency (other names: radiation factor, radiation ratio, radiation index) is a quantity that characterizes the efficiency of a given vibrating surface as a sound radiator [1]. It is a fundamental parameter to describe the coupling between structural waves propagating in a vibrating element with the structure born noise [2] [3].

The radiation efficiency σ is given by the formula [1]:

$$\sigma = \frac{W_{rad}}{\rho_0 c_0 S \langle \bar{v}^2 \rangle} \tag{1}$$

where:

W_{rad} – sound power radiated from one side of a vibrating surface, having the area S [*W*]
$\rho 0$ – density of the medium [kg/m^3]
c – speed of sound [*m/s*]
S – area of the vibrating surface [m^2]
$\langle \bar{v}^2 \rangle$ – squared vibration velocity magnitude in [*m/s*] and averaged over area *S*.

[1] michal.kozupa@pl.abb.com
[2] grzegorz.kmita@pl.abb.com
[3] robert.platek@pl.abb.com
[4] mw.matys@gmail.com

The concept of radiation efficiency is present in many fields of engineering where noise control is an important issue. It is extensively used to characterize the radiation ability of vibrating plates carrying bending waves [4] – this problem appears in construction of machinery, buildings, electroacoustical devices, airplanes, cars [5].

2. DESCRETE CALCULATION METHOD

The physical idea behind DCM consists in dividing the examined sound-radiating structure into rectangular elements each of which is further assumed to radiate sound as a rigid hard-baffled circular piston with the surface area equal to this of the corresponding virtual element (Figure 1). It is assumed that each rectangular element contributes to the total sound radiation power. The advantage of the method over conventional sound radiation efficiency measurement techniques comes in the fact that instead of acoustic pressure values, source (plate) vibration velocity amplitude values are measured in a selected number of regularly distributed points. In many cases, this allows to determine the sound radiation efficiency with sufficient accuracy, especially for the low frequency regime.

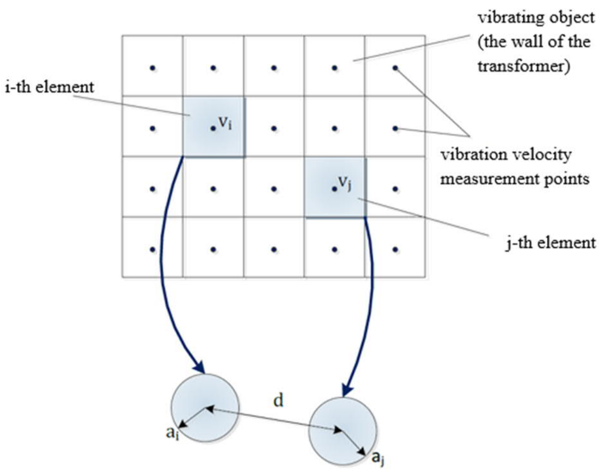

Figure 1. The idea of Discrete Calculation Method

This virtual division opens up the possibility to use analytical expressions for a vibrating circular piston in order to calculate radiation efficiency of our vibrating. The radiation impedance related to each individual DCM element and each mutually interacting pair of elements is derived with the help of Sir Rayleigh formula for impedance of a rigid piston vibrating in an infinite rigid baffle [2]. The expressions are presented below:

Self radiation impedance:

$$z_{ii} = \rho c s_i \left[1 - \frac{J_1(2ka_i)}{ka_i} + j\frac{S_1(2ka_i)}{ka_i}\right] \tag{2}$$

Mutual radiation impedance:

$$z_{ij} = \frac{\rho c k^2 s_i s_j}{2\pi}\left[2\frac{J_1(ka_i)}{ka_i}\right]\left[2\frac{J_1(ka_j)}{ka_j}\right]\left(\frac{\sin kd}{kd} + i\frac{\cos kd}{kd}\right) \tag{3}$$

Radiated sound power:

$$W_i = \mathrm{Re}(z_{ii})|v_i|^2 + \sum_j Re(z_{ij} v_i v_j^*) \tag{4}$$

where

ρ – air density [*kg/m*^{3}]

c – speed of sound [*m/s*]

s_i, s_j – area of the *i*-th element, area of the *j*-th element [*m*^{2}]

J_1 – first-order Bessel function

k – the wave number of sound
a_i – equivalent radius of the i-th element when the rectangular element is appropriated by a circular element, $a_i = \sqrt{s_i/\pi}$ $[m]$
S_1 – Struve function
d – distance between the centers of two circular elements $[m]$
$\mathrm{Re}(\dots)$ – real part of a complex number
v_i, v_j – complex vibration velocities of the i-th and j-th elements, obtained as spectra by Fast Fourier Transform analysis of the measured velocity waveform
S – area of the vibrating surface $[m^2]$
$\langle \bar{v}^2 \rangle$ – mean square of the vibration velocity in $[m/s]$ averaged over S

3. RESEARCH ON VARIOUS CASES OF DCM ALGORITHM USAGE

3.1 DCM in numerical modelling

In order to assess the usefulness of DCM method in numerical modelling a preliminary research was carried out. Applied methodology consisted of following steps:

- In Abaqus CAE environment there were four models of a plate designed which were stiffened in different ways. In each case dimensions of the plate were 0,3 m x 0,3 m x 0,01 m. Particular stiffening's were modelled as beams of cross-section dimensions 0,01 m x 0,01 m.
- There were two models designed for each plate – „vibration" model and „air" model. The plates were excited by concentrated harmonic 10 N force of 100 Hz frequency (applied in the centre of the plate).
- Results of real and imaginary part of vibration velocity at nodes („vibration" model) were exported in order to use the DCM algorithm. To do this, mandatory scripts for file conversion and calculation were implemented in MATLAB environment.
- „Air" models were used for validation of results by exporting acoustic pressure values on the nodes placed on the surface of the hemisphere.

Deflection shapes of designed plates excited with the force described above along with their acoustic radiation are shown in Figure 2. Results of DCM calculation and "air" model pressure modelling are presented in Table 1.

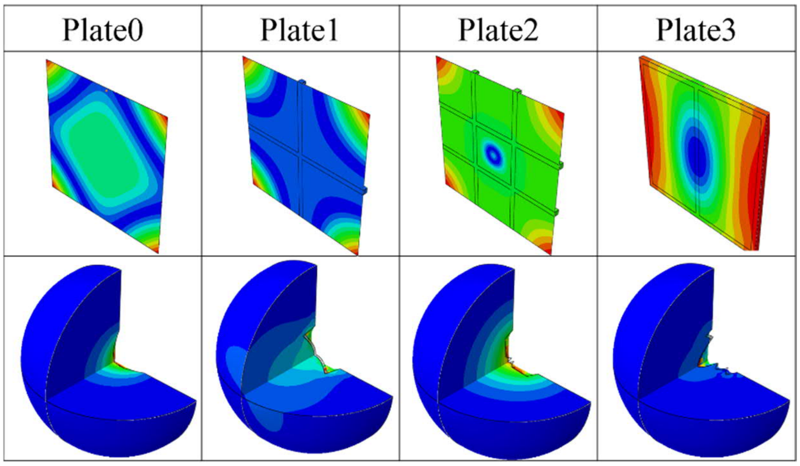

Figure 2. Deflection shapes and acoustic radiation of defined plates

Table 1. Sound power/pressure level comparison.

	„Vibration” model - DCM		„Air” model	
	L_w [dB]	$Lp_{0,5m}$ [dB]	L_w [dB]	$Lp_{0,5m}$ [dB]
Plate0	98,9	93,9	92,7	87,7
Plate1	94,5	89,5	94,1	89,1
Plate2	91,7	86,7	85,7	80,7
Plate3	90,5	85,6	90,7	85,7

As we can see in Table 1, the differences between sound power obtained using these two methods differ up to about 6 dB, hence, further research is obligatory. However, taking into account the advantages that this method involves (mainly the simulation time reduction) it is a very promising approach.

3.2 DCM in measurement approach

To assess the usefulness of DCM method in measurement approach a test setup was designed. Experimental model used in the research is presented in Figure 3. A set of tests was carried out which consisted in vibration velocity measurement (for DCM algorithm to be further applied) using Laser Doppler Vibrometer and sound power measurement using intensity probe (at distance 0,3 m). Comparison of results both methods is presented in Figure 4.

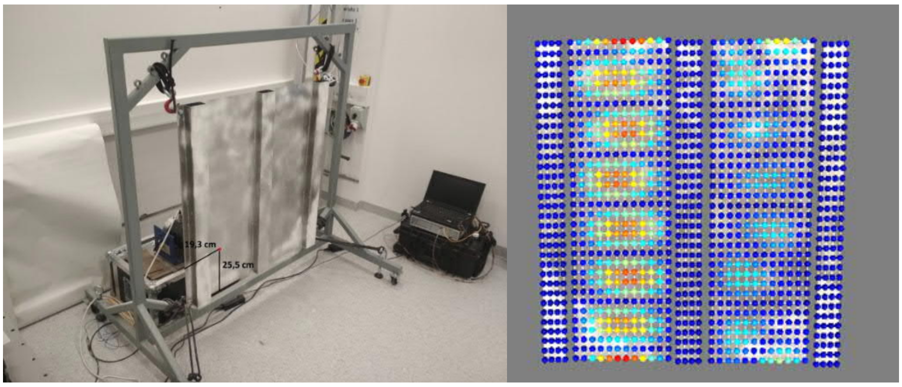

Figure 3. Experimental model

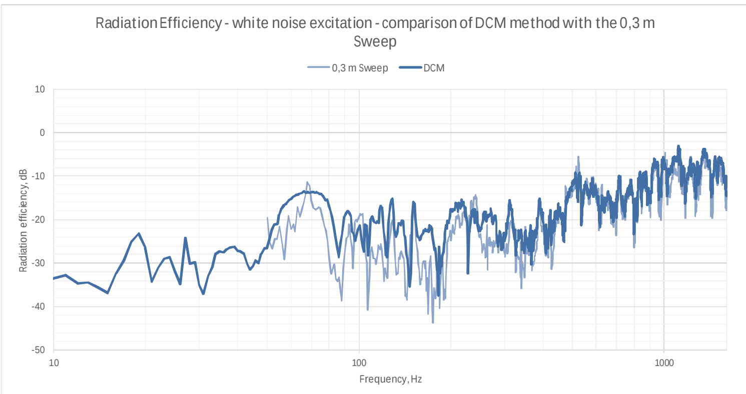

Figure 4. DCM and acoustic method comparison

Figure 5 shows the results of the numerical harmonic analysis performed in the ANSYS software using excitation at one of the resonant frequencies identified during the test. The model was excited numerically by the force applied to the node corresponding to the location of force in the physical vibration test, and the vector of this force was oriented perpendicularly to the vibrating surface of the model. The left part of the picture shows the velocity imported from the laser vibrometric measurement, while the right part presents the sound pressure level contour distribution that was used to calculate the SPL value and sound intensity at a 0,3 m distance from the model.

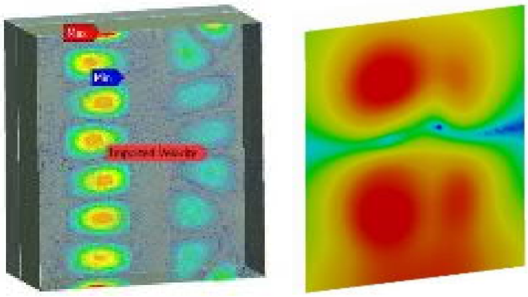

Figure 5. Numerical model representation with the velocities imported from the LDV measurement and the corresponding sound pressure contour calculated 0,3m from the model, based on the test input data

The results show that the use of DCM provides a very good correlation between the data returned by both numerical and physical tests. The SPL values predicted by the numerical analysis were about 80 dBA, which was almost exactly the value reported during physical measurement of sound.

4. CONCLUSIONS

The paper describes the possibilities of using acoustic radiation efficiency parameter as an indicator applied to assess the noise emitted by power machinery. The DCM method was presented and verified by measurements and numerical simulations. Knowledge that this algorithm provides corresponding effects to acoustic measurement leads to the next step which is to transfer it into numerical simulations.

Advantages of the method:

- Drastic simulation time reduction by eliminating the acoustic medium which in most cases (when the propagation of sound emitted by an object is examined) has many more elements than the vibrating object itself,
- Ease of calculation,
- Radiation efficiency is a valuable information which may serve as an evaluation parameter for comparison of acoustic properties of vibrating plates.

Disadvantages of the method:

- Further research is mandatory due to a mismatch of results from „vibration" model and „air" model,
- There is a need for results export from simulation environment.

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