25th International Congress on Sound and Vibration
8-12 July 2018 HIROSHIMA CALLING
ICSV25

NUMERICAL MODELING OF A LUMPED ACOUSTIC SOURCE ACTUATED BY A PIEZOELECTRIC STACK DEVICE THAT IS DRIVEN BY A SWITCHING AMPLIFIER

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This paper studies an acoustic source with a relatively small thickness and high bending stiffness. Piezoelectric actuators are used to drive the moving component of the acoustic source. In the current study, a lumped model is used to represent the acoustic source that is excited by a piezoelectric stacked actuator. The equivalent electrical circuit of the lumped acoustic source can directly be connected to the electrical circuit of a switching amplifier. Various methods are used to estimate the radiation impedance of the acoustic source. The effectiveness of these methods is investigated when they are used in combination with the equivalent electrical circuit of the lumped acoustic source, the actuator and the amplifier. Finally, result of a numerical finite element simulation is compared with the results of the fully-lumped equivalent electrical circuit.

Keywords: thin acoustic source, radiation impedance

1. Introduction

Thin acoustic sources operating at low frequencies can have specific applications. For instance, they can be used as sources with severe space constraints, in active sound absorption or active noise control. A thin acoustic source is introduced in Ref. [1] and is implemented in Ref. [2]. In this acoustic source, a high bending stiffness is obtained by attaching the source to a sandwich structure. The face of the sandwich structure internal to the source is perforated to increase the acoustic compliance. The acoustic source has to operate in the low frequency, quasi-static regime. In Ref. [3], piezoelectric actuators are investigated as the excitation parts of this acoustic source. A lumped model is used to simulate piezoelectric actuators and the acoustic source [3] .

In the current study, an equivalent electrical circuit, which was used in Ref. [3], is shown to simplify the lumped model of the acoustic source that is actuated by a piezoelectric stacked actuator. The equivalent electrical circuit is an effective approach to combine the lumped model with the electrical circuit of a switching amplifier in an ongoing research.

The main focus in this research is on improving the equivalent electrical circuit to represent the radiation impedance of the thin acoustic source that is actuated by a piezoelectric device. Various methods are used to estimate the radiation impedance of the acoustic source at a point on the symmetry line normal to the radiating surface. The effectiveness of these methods can be investigated when they are used in combination with the equivalent electrical circuit of the lumped acoustic source, the actuator and an appropriate switching amplifier.

A 3D numerical finite element analysis is also carried out. The coupled numerical simulation takes into account the effect of fluid-structure interaction in the acoustic source, and the interaction between electrical and mechanical domains in the piezoelectric device. The complete coupled FEM model is able to predict the sound pressure field on the radiating surface of the acoustic source. Finally, the result of the numerical simulation is compared with the results of the fully-lumped equivalent electrical circuit to choose the method that is best in agreement with the numerical results.

2. Flat acoustic source

The structure of the acoustic source is shown in Fig. 1. It consists of a radiating surface, a honeycomb structure, a perforated surface, an air cavity, and piezoelectric actuators. The details of this acoustic source is described in Ref. [3].

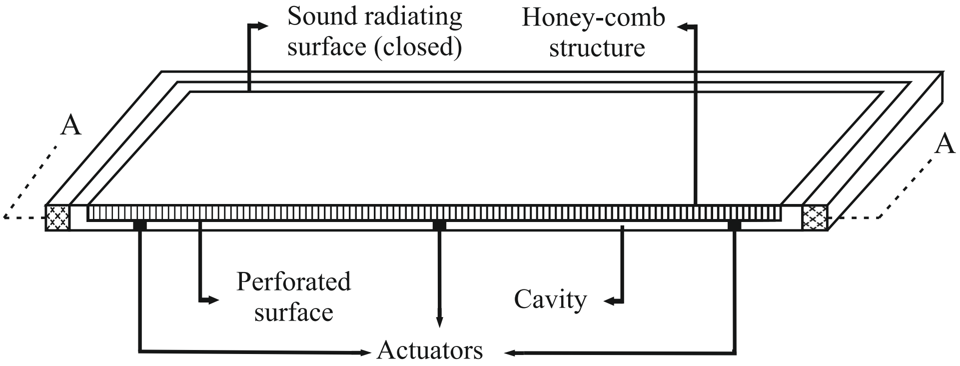


Figure 1: Cross section of the flat acoustic source.

3. Equivalent electrical circuit

A fully-lumped model of the flat acoustic source is considered in this study. To simplify the computation, an equivalent electrical circuit of the lumped acoustic source is used in combination with the equivalent electrical circuit of piezoelectric stack actuators. The resulted circuit is represented in Fig. 2 where i_t and V_t are the total current and voltage, respectively, that are supplied to the electrical connected amplifier (*Amp.*). The current along and voltage across the piezoelectric element are respectively shown by i_{piezo} and V_{piezo}. Parameters i and e represent the output current and voltage of the electrical domain, respectively. Correspondingly, u and F_{in} show the input velocity and force to the mechanical domain, while F_{out} is the output force of the mechanical domain. In the acoustical domain the input volume velocity and pressure are namely represented by U_d and P_{in}. In the electrical domain C_0 shows the capacitance of the piezoelectric device. In the mechanical domain Z_T and Z_S are the compliance and effective mass of the piezoelectric actuator, respectively. M_s, C_s and R_s are correspondingly the mass, compliance and mechanical damping of the acoustic source. Parameters Z_{cavity}, Z_{hollow}, Z_{screen} and Z_{rad} represent the equivalent acoustical impedances of the cavity, hollows of the honeycomb structure, the perforated plate, and the radiation impedance of the acoustic source. U_1 and U_2 are the volume velocity along the cavity and hollows of the honeycomb panel, respectively. The parameters α and A are the conversion coefficients between domains, where the later is the surface area of the acoustic source. All the parameters in this fully-lumped model are described in detail in Ref. [3].

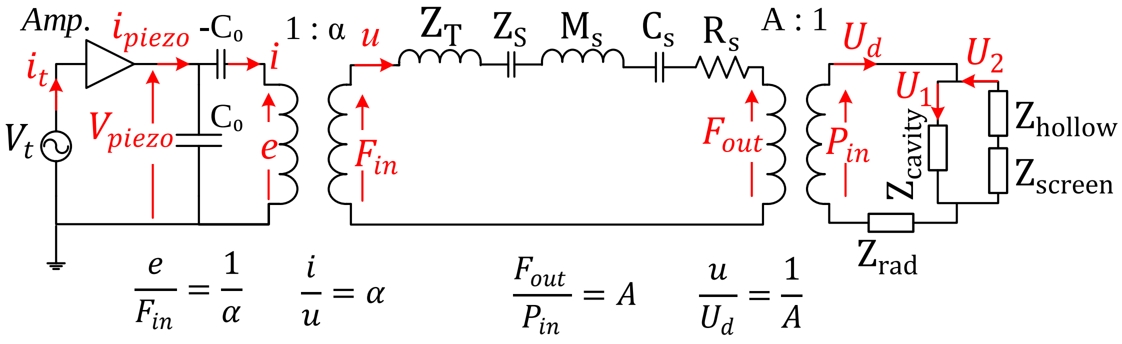


Figure 2: Complete equivalent electrical circuit of the acoustic source and piezoelectric actuators that can be connected to a switching amplifier.

4. Radiation impedance

In this paper, on-the-plane radiation impedance of the rectangular thin acoustic source is desired. In order to avoid computationally expensive Finite Element Method (FEM) or Boundary Element Method (BEM), an equivalent unit representing the radiation impedance of the lumped acoustic source, Z_{rad} in Fig. 2, is required. This equivalent unit has to be consistent with the proposed equivalent electrical circuit of the lumped source.

According to the equivalent electrical circuit of the lumped acoustic source, various methods are used to estimate the on-the-plate sound pressure level at a point on the symmetry line normal to the radiating surface. These methods are introduced in the following section by considering an equivalent circular surface area for the rectangular acoustic source. The equivalent radius of the circular radiator is determined by assuming an identical surface area for both geometries.

4.1 Helmholtz Integral

In the first approach, the resulting expression from Helmholtz integral [4] is used to evaluate the sound pressure level on the radiating plane of a circular rigid-piston radiator mounted in an infinite baffle. By using the following two equations:

$$Z_{rad} = \frac{\rho_0 c_0}{A}(R_{rad} + i\omega M_{rad}) \tag{1}$$

$$\begin{aligned} R_{rad} &= 1 - \frac{2J_1(2ka)}{2ka}, \\ M_{rad} &= \frac{1}{\omega}\frac{2K_1(2ka)}{2ka} \end{aligned} \tag{2}$$

the acoustical radiation impedance of vibrating circular pistons is estimated, where a is the radius of the equivalent circular piston, k and ω are namely the wave number and angular frequency, and J_1 and K_1 are Bessel and Struve functions of the first kind, respectively. In addition, ρ_0 and c_0 represent the density and speed of sound in the medium, respectively, and A is the facing surface of the piston which is in interaction with the medium.

This expression can be represented according to an equivalent electrical circuit shown in Fig. 3(a), where acoustical mass, M_{rad}, and resistance, R_{rad}, are arranged as the electrical elements in series.

(a) series. (b) Parallel.

Figure 3: Equivalent acoustical radiation impedance for series and parallel arrangements.

4.2 Approximation method

In order to use Helmholtz integral, estimating the Struve function, K_1, is crucial. However, it is not a straight-froward approach. As a result, in the second approach, the same assumptions shown in Fig. 3(a) and Eq. (2) are used. However, instead of using the Struve function, $K_1(2ka)$, an approximation:

$$H_1(2ka) = \frac{2}{\pi} - J_0(2ka) + (\frac{16}{\pi} - 5)\frac{sin(2ka)}{2ka} + (12 - \frac{36}{\pi})\frac{1 - cos(2ka)}{(2ka)^2} \tag{3}$$

is used according to Ref. [5], where J_0 is the Bessel function of the zero kind.

4.3 Parallel method

In a different approach, the acoustical radiation impedance of a baffled piston is obtained from the radiation impedance of a pulsating sphere, by substituting the the radius of piston to be 0.7 times of the radius of sphere [6]. The following equations are used by considering $r_{piston} = 0.7 \times r_{sphere}$:

$$\frac{1}{Z_{rad}} = \frac{1}{R_{rad}} + \frac{1}{j\omega M_{rad}} \tag{4}$$

$$\begin{aligned} R_{rad} &= \frac{\rho_{air} c}{4\pi r_{sphere}^2} = 0.51\frac{\rho_{air} c}{\pi r_{piston}^2}, \\ M_{rad} &= \frac{\rho_{air}}{4\pi r_{sphere}} = \frac{\rho_{air}}{2.8\pi r_{piston}} \end{aligned} \tag{5}$$

In Fig. 3(b), an equivalent electrical circuit is represented that consists of M_{rad} and R_{rad} in parallel according to this method.

5. Finite element model

A 3D finite element model in COMSOL Multiphysics software is used to numerically simulate the sound pressure field of the flat acoustic source. The piezoelectric actuator is modeled according an equivalent electrical model. This equivalent electrical circuit is combined with the mechanical and acoustical interfaces in the software. The coupled fluid-structure interaction problem is solved by considering the electrical, mechanical and acoustical interfaces available in COMSOL software package. Sound pressure level on the radiating surface of the acoustic source simulated by FEM is compared to the results of the fully-lumped model in the following section (Fig. 4).

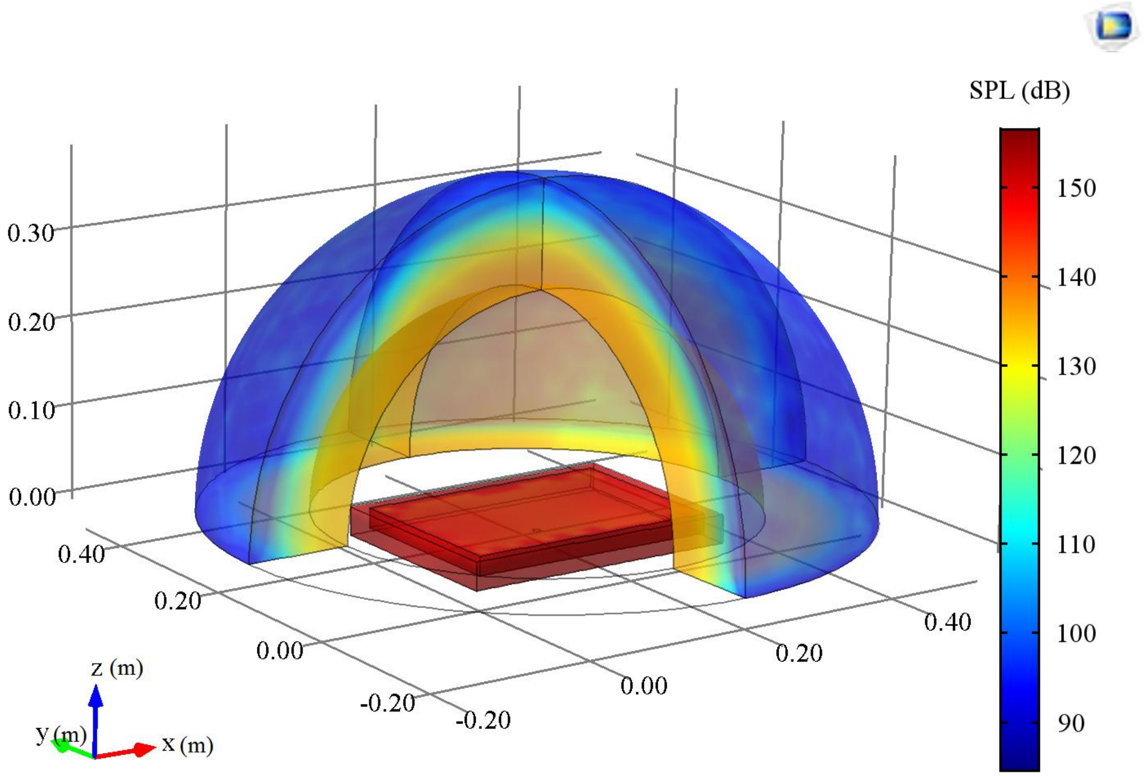


Figure 4: Sound pressure level of the acoustic source in dB, evaluated in COMSOL in the near-field domain.

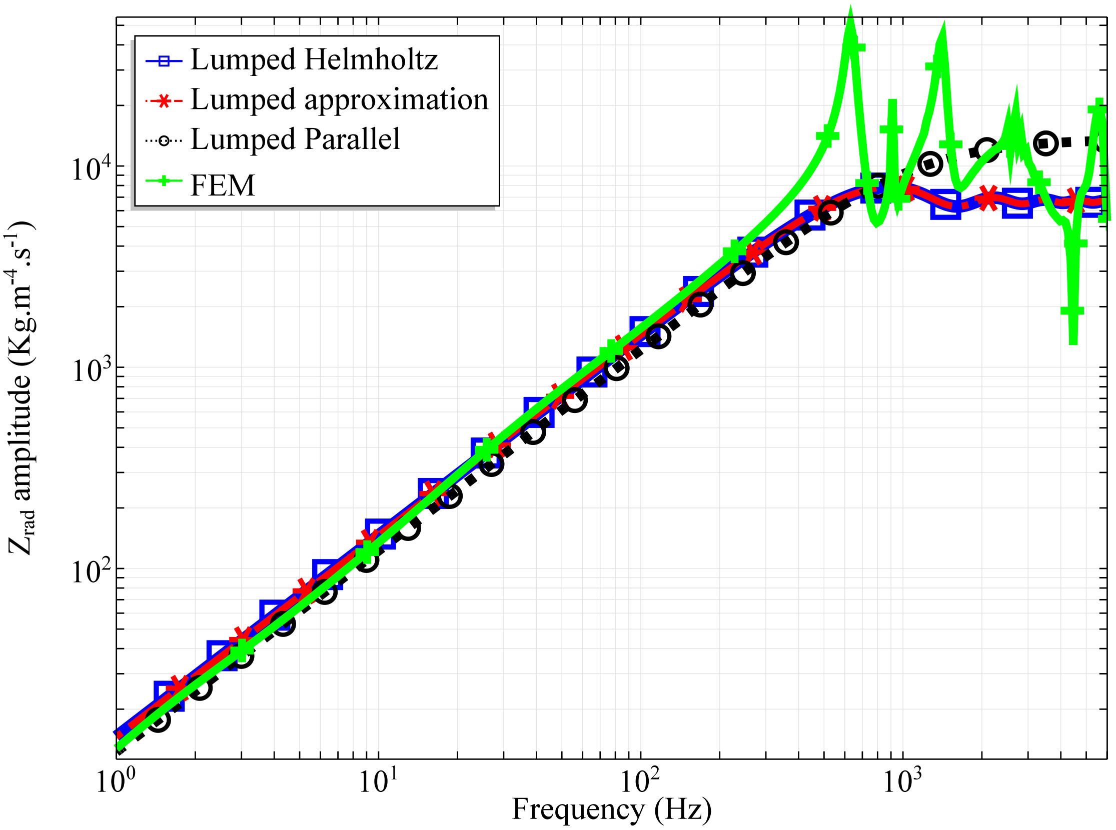
6. Results

Using three different approaches to estimate the acoustical radiation impedance of the lumped acoustic source, the effectiveness of these methods is evaluated when they are connected to the equivalent electrical circuit of the lumped acoustic source and actuators.

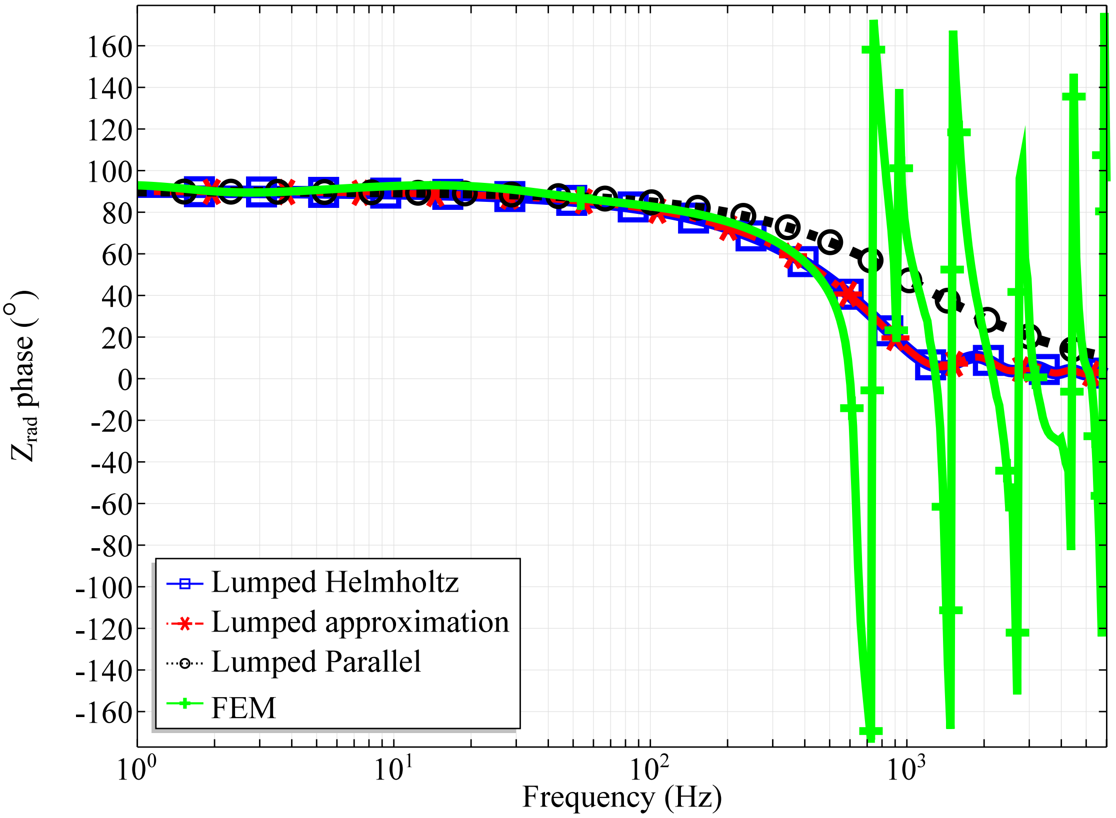
The acoustical radiation impedance is estimated by using various methods. Figure 5 represents the Bode diagram of Z_{rad}. According to Fig. 5, at low frequencies below 300 Hz, all three lumped methods are very close to the numerical result. On the other hand, the three methods combined with the lumped model of the acoustic source and actuators show deviation from the FEM model above 500 Hz.

In addition, the numerical sound pressure level on the vibrating surface of the acoustic source is evaluated and is compared to the result of numerical FEM simulation. Figure 6 reveals that at lower frequencies, equivalent methods are in good agreement with the numerical result. However, above 500 Hz, there is deviation from the result of numerical simulation. The fully-lumped models are not able to predict multiple resonances and anti-resonances of the acoustic source at higher frequencies. Figure 6 shows that at frequencies between 500 Hz and 4000 Hz, the lumped parallel approach gives slightly better approximation to the result of FEM than the series methods. At 2000 Hz for example, the evaluated sound pressure level by FEM, parallel, and series methods are respectively 137.9 dB, 138.1 dB, and 133.5 dB.

Another interesting result that can be seen out of Fig. 6 is that both series methods are almost identical over the entire frequency range of study.



(a) Amplitude.



(b) Phase.

Figure 5: Bode diagram of acoustical radiation impedance of the acoustic source.

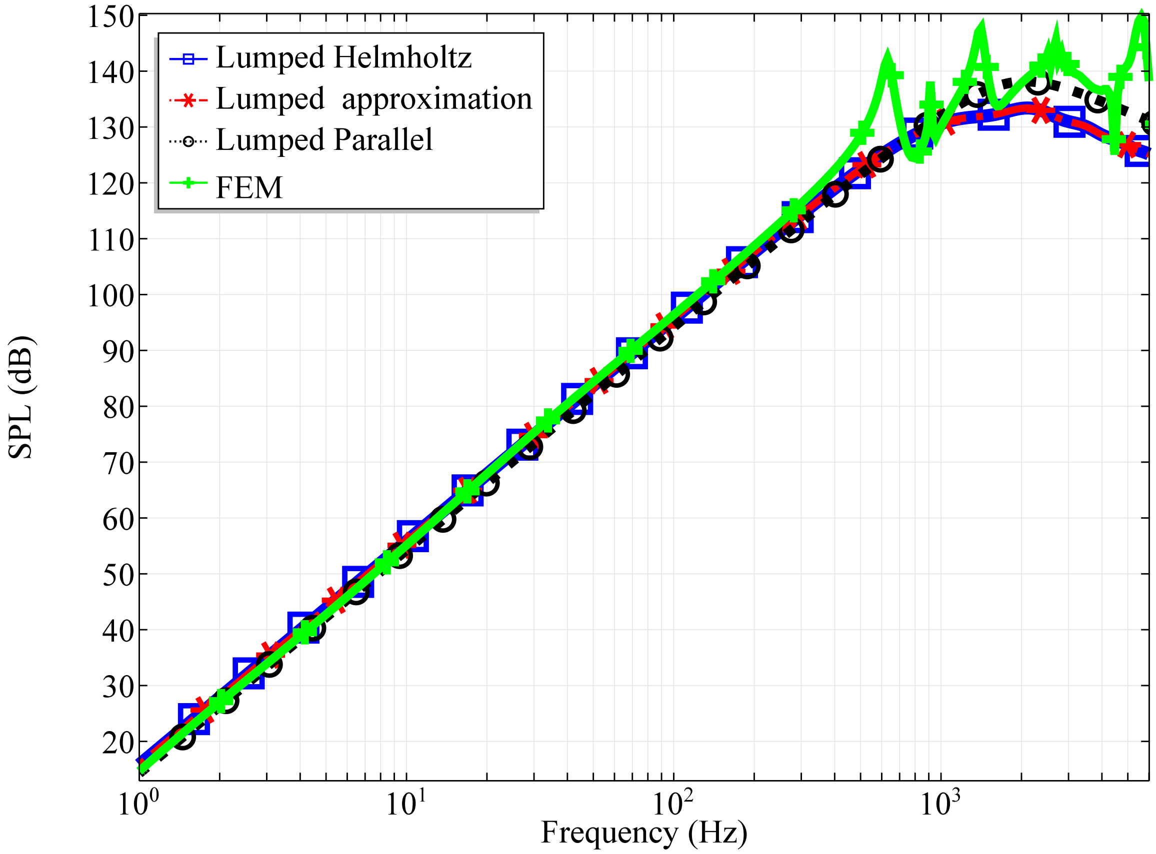


Figure 6: Sound pressure level on the vibrating surface of the acoustic source evaluated by using various methods, including lumped and FEM models.

7. Conclusion

In the current study, a lumped model is used to represent an acoustic source that is connected to a piezoelectric actuator. The equivalent electric circuit of the actuator and acoustic source unit is combined with an equivalent electrical element representing the acoustical radiation impedance of the lumped acoustic source. This fully-lumped equivalent circuit can directly be connected to a switching amplifier in another ongoing research. Three different methods are used to approximate the equivalent radiation impedance of the lumped acoustic source. The effectiveness of these methods is evaluated when the results are compared with the result of a numerical simulation.

The amplitude and phase of the acoustical radiation impedance of the acoustic source show that the approximation approaches are limited to frequencies below 500 Hz. A comparison between the equivalent methods and the numerical method is done to represent the acoustical radiation impedance of the acoustic source.

The study reveals that the parallel analogy is more in agreement with the result of FEM model to estimate sound pressure level on the radiating surface, especially at frequencies between 500 Hz and 4000 Hz. At lower frequencies on the other hand, all methods are in very good agreement with the numerical model.

Acknowledgment

The first and second author gratefully acknowledge the European Commission for its support of the Marie Sklodowska Curie program through the ITN ANTARES project (GA 606817).

REFERENCES

1. Berkhoff, A. P., *Sound generator*, US Patent, US20 100 111 351 A2 (2010).
2. Ho, J. and Berkhoff, A. P. Flat acoustic sources with frequency response correction based on feedback and feed-forward distributed control, *Journal of Acoustical Society of America*, **137** (4), 2080–2088, (2015).
3. Tajdari, F., Berkhoff, A. P. and de Boer, A. Numerical modeling of electrical-mechanical-acoustical behavior of a lumped acoustic source driven by a piezoelectric stack actuator, *Proceedings ISMA 2016*, Leuven, Belgium, 19–21 September, (2016).
4. Pierce, A., *Acoustics, an Introduction to Its Physical Principles and Applications*, the Acoustical Society of America, New York, (1989).
5. Aarts, R. M. and Janssen, A. J. E. M. Approximation of the Struve function H_1 occurring in impedance calculations, *Journal of Acoustical Society of America*, **113** (5), 2635–2635, (2003).
6. Leonard, R. W., Barone, A.,Truell, R., Elbaum, C. and Noltingk, B. E., *Generation and Measurement of Sound in Gases*, In: *Akustik II / Acoustics II. Handbuch der Physik / Encyclopedia of Physics*, Springer Berlin Heidelberg, 1–2, (1962).