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Sound radiation of panel-form loudspeaker using flat voice coil for excitation

C.H. Jiang, T.Y. Kam *, Y.H. Chang

Mechanical Engineering Department, National Chiao Tung University, Hsin Chu 300, Taiwan

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ABSTRACT

A novel panel-form loudspeaker in which the panel of the speaker is excited by the forces generated through the flat voice coil of a rectangular electro-magnetic type exciter for sound radiation is presented. The exciter when properly designed has the advantage of exerting appropriate loads to the panel so that the major sound pressure level (SPL) dips of the speaker can be suppressed or even eliminated. For designing such panel-form speaker, a method formulated on the basis of the classical plate theory (CPT), Ritz method, and first Rayleigh integral is proposed for predicting the SPL curve of the speaker. An experimental investigation was performed to verify the feasibility of the proposed method. The effects of some system parameters on the major SPL dips of the proposed panel-form speakers are investigated by means of several numerical examples. The optimal locations of flat voice coils for exciting several panel-form speakers are determined to illustrate the important role of excitation location for enhancing sound quality of such speakers via the removal or suppression of the major SPL dips.

1. Introduction

Because of their advantages such as being slight and thin and having large range of directivity, flat-panel loudspeakers have recently found many applications in audio systems as well as consumer electronic devices. In general, for a conventional electromagnetic type panel-form sound radiator/speaker, the sound radiation is induced by the vibration of the plate which is flexibly restrained at its edges and excited using at least one circular-type exciter. Based on this panel-form speaker configuration, many researchers have devoted their efforts to develop different techniques to improve the sound radiation capability or quality of such speakers [1–7]. For instance, Guenther and Leigh [1] proposed the use of a composite sandwich sound radiation plate comprising carbon fiber-reinforced face sheets and honeycomb core in a flat-panel speaker for attaining improved performance at higher frequencies. Kam [5] proposed the use of a plural number of exciters to excite the composite plate of a panel-form sound radiator at some specific locations to produce a smooth SPL curve for the sound radiator. In recent years, some consumer electronic devices such as cell phone, TV screen, and NB computer have had the trend to be slimmer, thinner, and lighter. This trend has thus significantly squeezed the space left for installing speakers in these electronic devices. In order to accommodate the requirements of such trend, the audio industry has devoted a lot of efforts to develop new types of panel-form speakers which can be installed in the electronic devices without sacrificing the sound quality of the speakers. One of the major shortcomings of using a circular exciter in a conventional flat-panel speaker is that when the speaker becomes slimmer, for instance, the aspect ratio (length/width) is larger than 2, the diameter of the circular exciter will become much smaller. The use of a small exciter in exciting the plate for sound radiation will lower the sound quality of the speaker including the decrease of the SPL of the speaker due to the small excitation force generated by the exciter and increase of harmonic distortion caused by the unstable motion of the plate. To remedy this shortcoming, multiple circular exciters have been used to excite the plate of a long panel-form speaker. This remedial technique, however, may induce other problems such as cost increase, complication of fabrication process, increase of impedance, and reduction of production yield rate. Therefore, the search for much better ways to design cost effective panel-form speakers with high quality performance is still a challenging work to be tackled. Recently, Kam [8] has patented a slim rectangular exciter in which a flat voice coil can be used to exert multiple line or point loads to a plate used for sound radiation if the voice coil is attached to the plate in an appropriate pre-designed way. Based on such pre-design way, the excitation forces can be allocated at different locations over a large region to excite the plate in such a way that the vibration

* Corresponding author.
E-mail address: tykam@mail.nctu.edu.tw (T.Y. Kam).

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shapes of the plate are adjusted to produce an expected smooth SPL curve for the speaker. The rectangular exciter has the potential to find applications in the audio industry to fabricate long flat-panel speakers for consumer electronic devices. Therefore, it is worthwhile to have detailed and in-depth studies about the sound radiation of panel-form speakers consisting of rectangular exciters so that the advantages of rectangular exciters can be exploited for audio applications.

The analysis of plate sound radiation behaviour has been an important topic of research [9–19]. Many methods have been proposed to analyse the vibro-acoustic behaviours of plates with different boundary conditions and structural configurations subjected to various types of loads. The sound radiation analysis of panel-form speakers, though still new to the audio industry, has also attracted the research interest of some researchers. Several papers have been devoted to study the sound radiation characteristics of panel-form speakers [20–28]. For instance, a number of researchers [20–23] have studied the effects of attached masses on the sound radiation behaviours of plates with regular or flexibly restrained boundary conditions. Fujii et al. [24] established a design method of the flat-panel loudspeaker for generating inclined sound using a honeycomb sandwich panel excited by a circular electro-magnetic exciter. Regarding the effects of loading conditions on the sound radiation capability of panel-form speakers, several researchers studied the use of different numbers of circular exciters to excite the plates of panel-form speakers at different locations to attain better sound radiation performance [25–28]. For instance, Doare et al. [27] proposed a dynamical model for formulating the vibration and acoustic radiation of a circular clamped plate excited by a circular voice coil and two annular piezoelectric patches located at different locations. Kam et al. [28] presented a method to study the vibro-acoustic behaviour of shear deformable laminated composite flat-panel sound radiators and determined the optimal diameter of the circular voice coil for exerting the excitation force so that a relatively smooth SPL curve can be attained. Besides the use of circular voice coils, it seems no work has been devoted to the use of voice coils of other shapes for sound radiation analysis of panel-form loudspeakers, not to mention the design of the optimal excitation locations for such voice coils.

In this paper, the design of a novel panel-form loudspeaker consisting of rectangular exciters is presented. A brief description of the configuration of the panel-form loudspeaker is given to illustrate the special features of the speaker. An efficient and simple method is established to analyse the sound radiation of the panel-form speakers. A number of numerical examples are given to determine the optimal excitation locations for producing relatively smooth SPL curves of the speakers in some specific frequency ranges using an optimization technique.

2. Configuration of panel-form speaker

One simple configuration of the new panel-form speaker consisting of a rectangular exciter is shown in Fig. 1. The speaker consists of four major parts, namely, a rigid frame, a plate for sound radiation, a rectangular exciter, and a resilient surround. The rigid frame is used to house the exciter and support the surround which in term supports the periphery of the plate. The exciter consists of three parts, namely, a magnetic assembly, a flat voice coil, and an elastic suspension system. The magnetic assembly consists of two units of which each unit comprises a long rectangular magnet and two washers placed, respectively, on the top and bottom surfaces of the magnet. There is an air gap in-between the two units of the magnetic assembly. The washers are used to transmit magnetic flux from one unit to the other to form two magnetic flux paths,

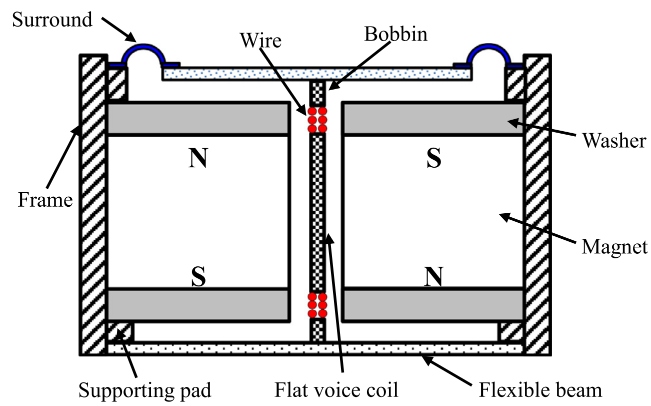

Fig. 1. Schematic description of panel-form speaker.

respectively, at the top and bottom of the magnetic assembly. The flat voice coil placed vertically in the air gap of the magnetic assembly consists of a thin rectangular hollow bobbin for housing a rectangular wire circuit. The top edge of the voice coil is adhesively attached to the bottom surface of the flat plate. The suspension system for supporting the voice coil may consist of one elastic beam of which its central portion is bound to the bobbin bottom while its two ends are bound to the rigid frame. The voice coil is positioned in the middle of the air gap in such a way that the top and bottom magnetic flux paths passing through the top and bottom long sides of the wire circuit, respectively. When an alternating current passes through the wire circuit, the Lorentz force generated by the wire will move the voice coil up and down to excite the plate. It is noted that the bobbin top edge shape can be designed in such a way that the required excitation forces can be generated to excite the plate to produce a relatively smooth SPL curve. For instance, two possible top edge shapes for the bobbin are shown in Fig. 2 in which the straight edge in Fig. 2a produces a long line load to the plate while the corrugated edge in Fig. 2b a set of short line loads to the plate. It is noted that if the length of a short line load is small, e.g., shorter than one fifth of the plate short side length, it is reasonable to approximate the short line load as a point load.

3. Sound radiation analysis of panel-form speaker

A mathematical model is established to analyse the sound radiation of the proposed panel-form speaker. In modeling the panel-form speaker consisting of N_b rectangular exciters, with the flat voice coils being treated as stiffeners, the sound radiation plate is modeled as a stiffened thin plate subjected to N_b line loads. The adhesive layer between a stiffener and the plate surface is assumed to be so thin that its effects on the sound radiation behaviour of the flat-panel speaker can be neglected. The stiffened rectangular plate of size a (length) $\times$ b (width) $\times$ h_p (thickness) with $a \geqq b$ is elastically restrained along the plate periphery by distributed translational and rotational springs with spring constant intensities K_{Li} and K_{Ri}, respectively, and at the center of each line load by a spring with spring constant K_{ci} ($i = 1, \ldots, N_b$) as shown in Fig. 3. It is noted that the peripheral and interior springs are used to model, respectively, the surround of the speaker and the flexible supports of the voice coils. The x-y plane of the global x-y-z coordinate is located at the center of the plate mid-plane. It is noted that the stiffeners on the bottom plate surface may be arranged symmetrically with respect to the plate center in x and/or y directions. Herein, for illustration, only 3 stiffeners in the y-direction are shown in Fig. 3. The displacement field of the stiffened thin plate modeled on the basis of the classical plate theory [29] is expressed as