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Development of a dynamic pressure generator based on a loudspeaker with improved frequency characteristics

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ABSTRACT

This paper presents the development and analysis of a measurement system with a dynamic pressure generator that is designed for the purpose of investigating the frequency characteristics of pressure connecting tubes. The developed dynamic pressure generator (DPG) consists of an electrodynamic loudspeaker that generates stable and adjustable sinusoidal pressure pulsations inside the air chamber within the generator housing. As the frequency characteristics of the DPG are defined by the properties of the loudspeaker diaphragm, the air chamber and the connections of the reference pressure sensor to the DPG, the DPG dimensions were optimized with the help of physical–mathematical modeling. Experimental analysis of the developed DPG, which enables flush mounting of the reference pressure sensors, showed improved amplitude and phase-frequency characteristics in comparison with the previous configuration of the DPG based on two loudspeakers.

1. Introduction

With progress over the past few decades technical processes have become more rapid, which has increased the requirements for more accurate measurements of time-varying pressures. Due to spatial, temperature or other constraints pressure sensors often cannot be mounted directly on the measurement object, therefore, the use of connecting tubes between the measured object and the pressure sensing element is required. Due to dynamic characteristics of the connecting tube, the magnitudes of the dynamic measurement errors can be significantly increased. For investigations of the dynamic characteristics of pressure connecting tubes an appropriate dynamic pressure generator (DPG) that can generate periodic or aperiodic pressure pulsations in a specific amplitude and frequency range is required [1–5]. For generating periodic or aperiodic pressure pulsations a DPG based on a loudspeaker can be used. The movement of the loudspeaker diaphragm inside the air chamber can generate pressure pulsations limited to small amplitudes (up to 2 kPa) and frequencies up to 3 kHz [1,4,6–9]. The advantage of a DPG based on loudspeakers is its relatively simple design and the ability to generate periodic pressure pulsations with adjustable amplitudes and frequencies. The studies showed that by using a periodic signal instead of an aperiodic signal, a better signal-to-noise ratio at higher frequencies can be achieved and also the uncertainty and spectral leakage inherent in the frequency analysis of aperiodic signals are avoided. Therefore, the transfer function is expected to be determined with better accuracy when generating pure periodic pressure pulsations. The main limitation of periodic DPG is the difficulty in achieving undistorted periodic pulsations at higher amplitudes and frequencies, especially in a gaseous medium due to the nonlinearities that result from the gas dynamics.

The purpose of this paper is to present a newly developed, sinusoidal DPG based on one loudspeaker that can be used for investigations of the frequency characteristics of pressure connecting tubes. The developed DPG enables flush mounting of the pressure sensors and therefore measurements of the generated pressure pulsations directly in the air chamber. With the use of flush mounted pressure sensors the amplitude and phase-frequency characteristics of the DPG are improved in comparison with the previously developed DPG based on two, face-to-face-orientated electrodynamic loudspeakers [4]. The dimensions of the DPG were optimized in order to retain a relatively high gas stiffness and therefore a relatively high natural frequency of the DPG and the small effects of the air chamber of the DPG on the DPG static sensitivity, and to minimize the effects of the air chamber volume on the determination of the frequency characteristics of the connecting tubes. The employed physical-mathematical model of the DPG is based on linear lumped models of mechanical and acoustical elements, and is presented in Section 2. Section 3 presents the measurement system used for the experimental evaluation of the frequency characteristics of the developed DPG. The analysis of the measurement results for the developed measurement system with the sinusoidal DPG are presented in Section 4. The capabilities of the developed pressure measurement system are also compared with the capabilities of the previous DPG

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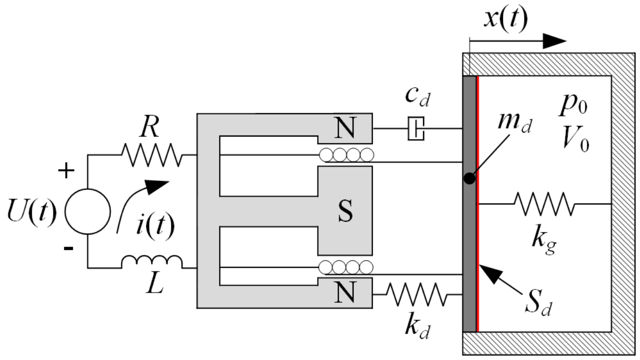

Fig. 1. Model of the DPG based on an electrodynamic loudspeaker.

based on two loudspeakers.

2. Modeling and design

The developed dynamic pressure generator consists of an air chamber in which the electrodynamic loudspeaker generates sinusoidal pressure pulsations with defined characteristics. During the development of the DPG its dimensions were optimized with the help of physical-mathematical modeling in order to ensure a relatively high natural frequency of the DPG and small effects of the air chamber on the DPG static sensitivity, and to minimize the effects of the air chamber volume on the frequency characteristics of the connecting tubes. The main properties of the physical-mathematical model are presented in the next subsection, but see, for instance [10,11], for details of the derivation of similar mechanical and acoustical lumped-element models.

2.1. Physical-mathematical model

Fig. 1 shows a schematic representation of the simplified model of the DPG based on an electrodynamic loudspeaker, which can be described as a second-order dynamic system. The loudspeaker diaphragm is modeled as a solid body with one degree of freedom that acts like a harmonic oscillator driven by an electrodynamic force proportional to the electric current flowing through the loudspeaker coil [10]. If we consider an ideal gas, an adiabatic process, a spatially homogenous pressure of the air in the generator chamber, small diaphragm displacements $x(t)$ and neglect the heat transfer, the gas contained in the generator chamber can be modeled as an additional one-dimensional spring and therefore the equation of motion for the loudspeaker diaphragm can be written as:

$$m_d\ddot{x}(t) + c_d\dot{x}(t) + (k_d + k_g)x(t) = Bli(t), \tag{1}$$

where m_d, c_d and k_d are the effective mass, the damping coefficient and the spring constant of the loudspeaker diaphragm, respectively, and k_g is the gas stiffness [11]:

$$k_g = \frac{\kappa S_d^2 P_0}{V_0}, \tag{2}$$

where κ is the adiabatic index, S_d is the effective area of the diaphragm and P_0 and V_0 are the average absolute pressure and the average volume of the gas in the generator chamber, respectively. The movement of the loudspeaker diaphragm results from the magnetic force $Bli(t)$, where l is the effective length of the loudspeaker coil wire in the magnetic field B and $i(t)$ is the excitation electric current. The electrical circuit model of the electrodynamic loudspeaker contains a coil with a resistance R and an inductance L that surrounds the permanent magnet and is excited by the electric voltage $U(t)$. Due to the fact that the inductance of the coil is often negligibly small, the excitation electric current can be written as [10]:

$$i(t) = \frac{1}{R}(U(t) - Bl\dot{x}(t)), \tag{3}$$

where the last term represents the induction of the electric voltage due to the motion of the coil in the electromagnetic field. The DPG static sensitivity K_{DPG} is defined as the ratio between the generated pressure change p and the excitation current change, which holds true for sufficiently low excitation frequencies:

$$K_{DPG} = \frac{p}{i} = \frac{Bl}{S_d}\frac{1}{1 + \frac{k_d}{k_g}}. \tag{4}$$

That ratio can be significantly changed as we approach the natural frequency of the DPG, which can be written as:

$$f_{0,DPG} = \frac{1}{2\pi}\sqrt{\frac{k_d + k_g}{m_d}}. \tag{5}$$

2.2. Optimization of the dimensions of the dynamic pressure generator

The electrodynamic loudspeaker was chosen on the basis of achieving the highest possible amplitudes of the generated pressure pulsations and, therefore, the largest ratio Bl/S_d, see Eq. (4). Simulations of the effects of the inner height of the generator housing h (see Fig. 2) were performed for the dimensions and the effective mass of the diaphragm of the loudspeaker and the internal volume of the pressure sensor used in the experimental study described in the next section, see Table 1.

In order to ensure a relatively high natural frequency of the DPG and the small effects of the internal gas volume of the DPG on the DPG static sensitivity, a relatively high gas stiffness has to be achieved, see Eqs. (5), (4) and (2). In order to increase the gas stiffness, the volume of the air chamber has to be decreased. But on the other hand, the volume of the air chamber has to be large enough in order to minimize its effect on the determination of the natural frequency of the connecting tubes that will be investigated with the use of this DPG. In the investigations of the frequency characteristics of the connecting tubes a pressure sensor 2 connected to the DPG with a connecting tube, shown in Fig. 2, represents a fluid oscillator [11]. Such a pneumatic pressure measurement system can be described as a discrete Helmholtz resonator with two unequal volumes, where the fluid in the connecting tube acts as the oscillator mass, while the compressible fluid in the internal volumes of the pressure sensor 2 and the DPG air chamber acts as the oscillator springs. The general assumptions in the analysis of Helmholtz resonators are the fluid velocity in the internal volumes being significantly smaller than the fluid velocity in the tube, the absence of

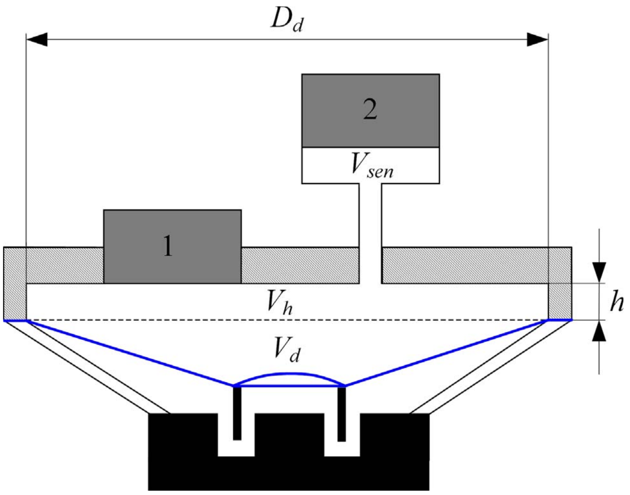

Fig. 2. Schematic representation of the DPG with connected pressure sensors 1 and 2.