Sensors and Actuators A: Physical 168 (2011) 149-154
doi: 10.1016/j.sna.2011.03.037

CHARACTERISTICS OF A DYNAMIC PRESSURE GENERATOR BASED ON LOUDSPEAKERS

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ABSTRACT

The dynamic pressure generator under discussion consists of two, face-to-face-orientated electrodynamic loudspeakers and the air chamber between. The aim of this paper is to investigate the static and dynamic characteristics of this pressure generator. Physical modelling and an experimental analysis were employed to demonstrate its capabilities and limitations. The generator's static sensitivity, which was defined by the ratio between the generated pressure and the excitation electric current, mainly depends on the ratio between the force factor and the effective area of the loudspeakers. The presented system has relatively good precision and stability, and a small sensitivity to changes in the internal volume. Its dynamic characteristics are defined by the properties of the loudspeaker diaphragm, the air chamber between the loudspeakers and the connection of the device under test to the pressure generator.

Keywords: pressure generator; pressure dynamics; loudspeaker

1. INTRODUCTION

Pressure is an important process variable in a wide variety of industrial and scientific applications. Whenever measurements and/or control of the changing pressure conditions are required, the installed sensors and other equipment should have suitable dynamic characteristics. As a result, the research and development of dynamic pressure generators are closely linked to the growing needs for dynamic testing and calibration of such equipment.

It is possible to choose from a variety of operating principles and configurations when it comes to dynamic pressure generators [1,2]. One of these operating principles relates to pressure generators based on loudspeakers, which are generally used for low-pressure amplitudes and acoustic frequencies. The accessible literature describes some of their potential areas of application: the dynamic calibration of low-range pressure sensors [3,4], the testing of the dynamic response of pneumatic transmission line systems [5-7], and the testing of hydrostatic pressure switches [8].

This paper deals with the loudspeaker-based pressure generator shown in Fig. 1. A similar configuration was introduced at the conference in 2000 [9], since when it has been successfully employed as a dynamic pressure generator in a variety of applications [6,8]. This pressure generator consists of two, face-to-face-orientated electrodynamic loudspeakers. On the circumference of the chamber between, there are evenly distributed points for connecting pressure sensors or other equipment under test. The employed loudspeakers were chosen on the basis of the large ratio between the force factor and the effective area, which determines the attainable magnitude of the generated pressure.

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Fig. 1. Pressure generator with two loudspeakers.

The aim of this paper is to investigate the static and dynamic characteristics of the loudspeaker-based pressure generator (see Section 2 and 3, respectively). Physical modelling and an experimental analysis were employed to demonstrate its capabilities and limitations. The physical model of the pressure generator, presented in Sections 2.1 and 3.1, is based on the linear lumped models of mechanical and acoustical elements [10,11]. The employed acoustical model assumes that the wavelength of the generated pressure oscillations is large compared to the longest linear dimension of the air chamber, which assures that the generated pressure inside is essentially uniform. Similar assumptions are often used in basic modelling of a loudspeaker mounted in a (medium sized) closed box [12,13]. In Section 2.1, the acoustical load of the loudspeaker diaphragm due to the gas stiffness is briefly rederived to properly consider a simultaneous motion of both loudspeakers. The experimental work, presented in Sections 2.2 and 3.2, was designed to discuss the main characteristics of the pressure generator, such as the static sensitivity, the precision and stability, and the frequency range. A particular attention is focused on the influence of changes in the pressure-generator internal volume, which can occur in some applications. The findings of this paper will be useful for the proper application and the further development of such devices.

2. STATIC CHARACTERISTICS OF THE PRESSURE GENERATOR

2.1 Static physical model

Both the loudspeakers of the pressure generator are modelled as being identical. The effective area S_d of their diaphragms is assumed to be constant within the range of the displacements $x \in [-x_{max}, x_{max}]$. The x displacement of both diaphragms with respect to one another results in a change of the internal volume $V = V_0 - 2S_d x$, where V_0 is the initial internal volume. In the closed system, such a change in the volume of a gas leads to an increase in the absolute pressure, from an initial value P_0 to $P = P_0 + p$. The gas volume is considered as an adiabatically closed system in which PV^{κ} is constant, with κ being the adiabatic index [11]. For relatively small changes the following relation between the pressure change and the diaphragm displacement can be derived:

$$p = 2\frac{\kappa S_d P_0}{V_0} x . \qquad (1)$$

(If the gas volume were to change relatively slowly over time with respect to heat transfer to the surroundings, it might be more reasonable to consider the system as isothermal, in which PV is constant; substitute the derived expressions with $\kappa \to 1$.)

When the diaphragm is moved, due to the pressure change the internal gas acts on the diaphragm as an added stiffness force, which can be expressed as follows using Eq. (1):

$$pS_d = k_{f,d} x , \quad k_{f,d} = 2\frac{\kappa S_d{}^2 P_0}{V_0} , \qquad (2)$$

where $k_{f,d}$ is the gas stiffness. The movement of the loudspeaker diaphragm results from the magnetic force BLi acting on the voice coil, where L is the effective length of the voice coil wire in the magnetic field B and i is the excitation voice coil current [10]. Within the framework of the static model there should be a balance between the excitation force and the combined influence of the gas stiffness force (2) and the suspension stiffness force $k_{susp} x$. This results in:

$$x = \frac{BLi}{k_{f,d} + k_{susp}} . \qquad (3)$$

Substituting Eq. (3) into Eq. (2) leads to the linear static characteristic of the pressure generator. This can be expressed in terms of the static sensitivity K_{PG}, which is defined by the ratio between the generated pressure change and the excitation electric current:

$$K_{PG} = \frac{p}{i} = \frac{BL}{S_d} \frac{1}{1 + k_{susp} / k_{f,d}} . \qquad (4)$$

The generator's static sensitivity depends linearly on the ratio between the force factor BL and the effective area S_d, but the last fraction represents some decreasing effect of the ratio between the suspension and the gas-related stiffness.

2.2 Static measurements

Fig. 2 presents a scheme of the measurement system where the experiments on the pressure generator were carried out. In the case of static measurements, the loudspeakers (Beyma, 5"MP-60/N) were electrically excited from a voltage amplifier connected to the analog output of a DAQ board (National Instruments, DAQPad-6020E, max. input range ± 10 V, resolution 12 bit, max. sampling frequency 100 kHz). The excitation current was determined by measuring the voltage drop across a known resistor. The generated pressure was measured by a single variable-reluctance pressure transmitter (Validyne, P855, measuring range ± 1400 Pa, output voltage ± 5 V, accuracy 0.15 % of upper range limit, frequency range 0 to 250 Hz (–3 dB)). The signal acquisition and processing were realized in the LabVIEW programming environment. In some experiments an additional volume V_{ADD} of $0.5\ \mathrm{dm}^3$ or $1\ \mathrm{dm}^3$ was connected to the pressure generator with the volume $V_0' \approx 0.26\ \mathrm{dm}^3$, so the total internal volume was increased to $V_0 = V_0' + V_{ADD}$.

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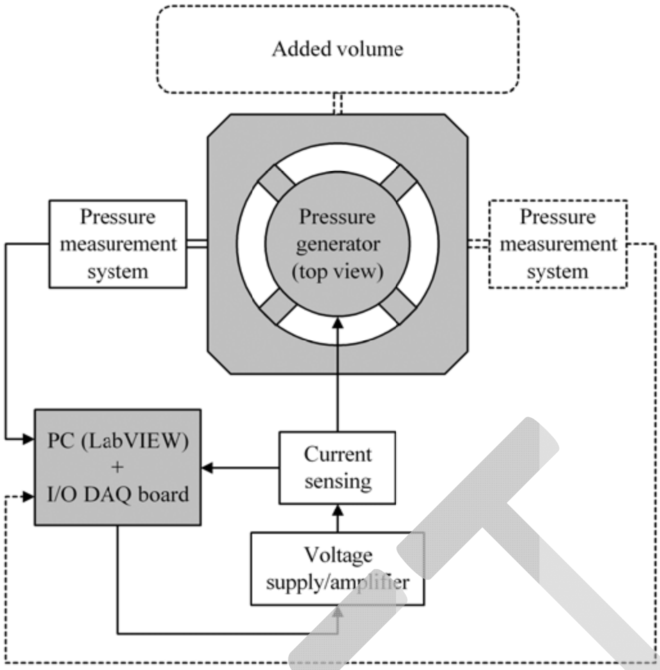

Fig. 2. Block diagram of the measurement system.

The generator's static characteristic was measured at nine points, equally divided over the chosen testing range, including both increasing and decreasing pressure. Fig. 3 shows one example of the time variations of the excitation current and the generated pressure. For each testing point, the excitation voltage was set to some constant value for a stabilization time of about 10 s. The variation of the excitation current (and proportionally of the generated pressure) during the stabilization time, which is more evident at higher excitation voltages, results from the changing temperature of the loudspeaker coils. An increasing coil temperature leads to an increasing coil resistance and, consequently, to a decreasing current at a constant voltage supply.

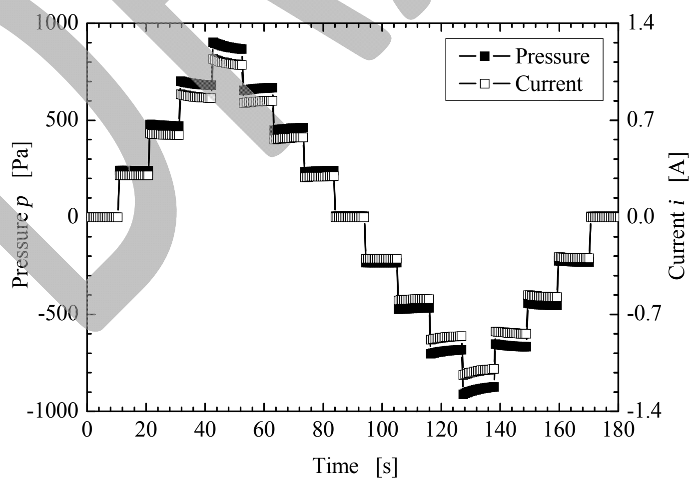

Fig. 3. Time variation of the excitation current and the generated pressure for measurements of the generator static characteristic.

The resulting static characteristic that relates to the last measured values at each testing point (after the stabilization time) is presented in Fig. 4. The measurements are approximated by a linear regression line through the origin, the slope of which represents the static sensitivity

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K_{PG}. Such estimated sensitivities are collected in Table 1 for three different values of the added volume V_{ADD} and three repetitions in each configuration. The pressure generator's sensitivity is about 800 Pa/A. As expected from the physical model in Eqs. (2) and (4), the sensitivity shows some decrease with the increasing internal volume. An approximation of the results in Table 1 with the physical model shows that k_{susp} in the pressure generator under discussion is relatively small in terms of $k_{f,d}$: $k_{susp}/k_{f,d} \approx 0{,}01$ without the added volume and $k_{susp}/k_{f,d} \approx 0{,}04$ for the V_{ADD} of $1\ \text{dm}^3$.

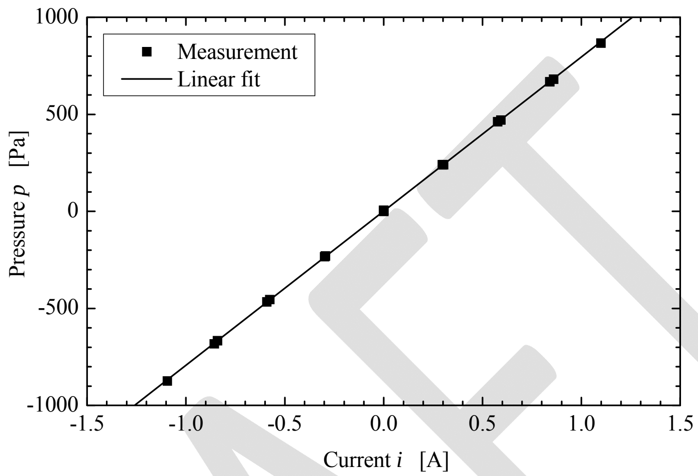

Fig. 4. Static characteristic of the pressure generator.

Table 1. Measurement results of the pressure generator sensitivity for three values of the added volume

Number of measurement	Sensitivity of the pressure generator K_{PG} [Pa/A]		
	$V_0 = V_0'$	$V_0 = V_0' + 0.5\ \text{dm}^3$	$V_0 = V_0' + 1\ \text{dm}^3$
1	794.9	782.1	772.1
2	794.2	781.7	771.1
3	793.8	781.8	771.4

Maximal deviations of any measured static characteristic of the pressure generator from its best straight line do not exceed 10 Pa, or about 1 % of the generated-pressure upper range limit. These estimated deviations combine the effects of nonlinearity and hysteresis and the remaining temperature dynamic effects after the stabilization time of 10 s. Other possible contributions may be also related to non-ideal performances of the employed measurement instruments. Three repetitions of measurements in each configuration of the system can be used for estimating the repeatability (the short-term stability) of the pressure generator; a maximal relative deviation of the repeated estimations of the static sensitivity in Table 1 is about 0.15 %. The long-term stability of the static characteristic may be expected to depend on the duration and the magnitudes of the generator's loading and its effect on the properties of the rubber diaphragms. We performed the following test: the pressure generator was operating twelve hours generating the sinusoidal pressure with the amplitude of 500 Pa and the frequency of 100 Hz (more than 4 million of vibration periods in total). After each hour of operation the static sensitivity was measured. The results showed relative deviations smaller than 0.5 %, without any characteristic trend. That means the observed loading did not cause any noticeable systematic effects in the presented pressure generator.

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Fig. 5 presents the time variation of the generated pressure in the case of a step change of the internal volume. A hand-operated valve was built in between the pressure generator and the added volume of 0.5 dm^3; this valve was opened as quickly as possible at some moment during the pressure generation and the internal volume was increased in the ratio of about 1:3. As would be expected, the generated pressure shows a decrease due to the smaller static sensitivity with the larger internal volume. However, it is important to realize that the pressure decrease would be much greater without the electrodynamic operation of the pressure generator, as is also predicted for the comparison in Fig. 5.

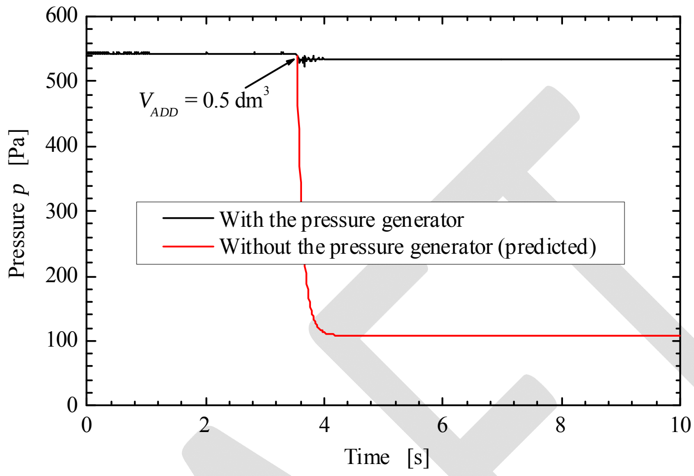

Fig. 5. Time variation of the pressure showing the effect of the sudden increase of the pressure generator's volume.

Small influences of the volume changes on the generated pressure can be advantageous for applications where volume changes occur during the testing, e.g., when testing the switching pressure of hydrostats. Fig. 6 presents the time variation of the pressure during the switching action of the hydrostat that was tested on the linear pressure input. The measured pressure in the hydrostat cavity changes due to progressive deflections of the hydrostat diaphragm and the final switch of the hydrostat mechanism. On the other hand, the measured pressure in the pressure generator shows the ability of generating the linear pressure input without observable influences of the hydrostat volume changes. If one pressure generator is used for simultaneous testing of more hydrostats, such characteristic would be of high importance to prevent their mutual interaction.

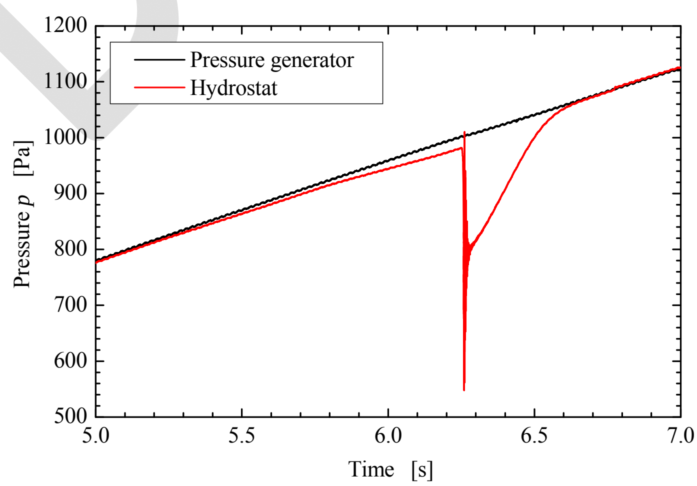

Fig. 6. Time variation of the pressure during the switching action of the tested hydrostat.

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In some published references, see, e.g., [3,5], the closed-volume pressure generators with one loudspeaker were used in contrast to the discussed configuration with two loudspeakers. If the static physical model presented in Section 2.1 was modified for such configuration with one loudspeaker, the only change would be twice smaller gas stiffness $k_{f,d}$. Therefore, their static sensitivity would become about twice more dependent on the internal gas volume changes. Such properties can represent an important benefit of the pressure generator with two loudspeakers when employed in applications with the varying volume.

3. DYNAMIC CHARACTERISTICS OF THE PRESSURE GENERATOR

3.1 Dynamic physical model

The simplified dynamic model of the loudspeaker-based pressure generator is set up within the framework of discrete, lumped-parameter oscillators. The pressure generator is assumed to consist of an internal volume V_0' between the diaphragms, to which the device under test with the internal volume V_0'' is connected using a tube with an internal cross-section S_t. Other assumptions follow Section 2.1.

The natural frequency of the diaphragms moving with respect to one another can be estimated as:

$$f_d = \frac{1}{2\pi}\sqrt{\frac{k'_{f,d} + k_{susp}}{m_d}}, \tag{5}$$

where m_d is the effective mass of the vibrating diaphragm, but its stiffness $k'_{f,d} + k_{susp}$ sums the contributions of the gas and the suspension springs, where $k'_{f,d}$ is defined by Eq. (2) using V_0'. For the pressure generator under discussion, $k_{susp} << k'_{f,d}$ (see Section 2.2), so the natural frequency of the diaphragms depends strongly on the properties of the internal gas volume. If the closed-volume pressure generator used only one loudspeaker, the effective gas stiffness $k'_{f,d}$ in Eq. (5) would become twice smaller (as already discussed at the end of the previous section). Therefore, when $k_{susp} << k'_{f,d}$, the pressure generator with one loudspeaker would have about the $\sqrt{2}$ smaller diaphragm's natural frequency compared to the discussed configuration with two loudspeakers.

If the dimensions of the internal gas volume between the diaphragms are relatively small, in comparison with the wavelength of the generated pressure oscillations, this fluid degree of freedom can be neglected in the dynamic model. Thus, the pressure change inside can be related to the diaphragm displacement by Eq. (1) using V_0'. The wavelength is defined as c/f, where c is the speed of sound (about 343 m/s for dry air at 20 °C) and f is the oscillation frequency [13]. For an internal diameter of about 12 cm, which represents the longest linear dimension in the pressure generator under discussion, such an assumption is appropriate for pressure oscillation frequencies of a few hundreds of Hz,.

However, the natural frequency of the diaphragm still does not represent the only dynamic limitation. The connecting tube of the device under test, together with the side volumes, forms

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the fluid oscillator called a Helmholtz resonator [11]. The natural frequency of this resonator can be written as:

$$f_f = \frac{1}{2\pi}\sqrt{\frac{k'_{f,t} + k''_{f,t}}{m_f}}, \qquad (6)$$

where m_f is the effective mass of the fluid in the connecting tube and $k'_{f,t} + k''_{f,t}$ is the combined influence of the gas springs of both side internal volumes V'_0 and V''_0:

$$k'_{f,t} + k''_{f,t} = \frac{\kappa S_t^{\,2} P_0}{V'_0} + \frac{\kappa S_t^{\,2} P_0}{V''_0}. \qquad (7)$$

If the pressure generator volume is much larger than the internal volume of the device under test, $V'_0 >> V''_0$, the natural frequency of the fluid oscillator only depends on the device under test and its connection to the pressure generator. In that case both identified oscillators can be treated as uncoupled.

3.2 Dynamic measurements

In the case of dynamic measurements, the generated pressure was measured by two piezoelectric pressure-measurement systems, including the piezoelectric pressure sensors (Kistler, 7261, sensitivity 22 pC/kPa, cal. measuring range ± 4000 Pa, accuracy (best straight line) 0.25 % of upper range limit, resonant frequency without connecting tube 2500 Hz (see the measured resonant frequencies for different connecting tubes in [6])) and the charge amplifiers (Dewetron, DAQ-Charge, sensitivity 0.1 V/pC, output voltage ± 5 V, accuracy (best straight line) 0.05 % of upper range limit, frequency range 0.3 Hz to 50 kHz (–3 dB)). Pressure sensors have an internal volume of 1.5 cm^3 and were connected to the chamber of the pressure generator with short plastic tubes (length about 5 cm, internal diameter about 4 mm). The sinusoidal excitation of the loudspeakers was performed with a function generator (Goldstar, FG-8002) using a voltage-controlled frequency from the DAQ board. The sampling frequency of the DAQ board for the excitation current and the pressure signals was set to 20 kHz. The other details about the measurement system are described in Section 2.2 and schematically presented in Fig. 2.

The frequency characteristic was determined at excitation frequencies up to 1000 Hz, in steps of about 10 Hz. At each point the amplitudes and phases of the excitation current and the pressure signals were calculated after a stabilization time of about 5 s. Fig. 7 shows the amplitude and phase frequency characteristics between the generated pressure and the excitation current for both the oppositely connected pressure sensors (P1 in P2). Two resonant frequencies are evident – the resonance at about 400 Hz corresponds to the natural frequency of the diaphragm, but the resonance at about 600 Hz corresponds to the natural frequency of the fluid oscillator formed by the connecting tube and the pressure sensor volume (see the physical model in Section 3.1).

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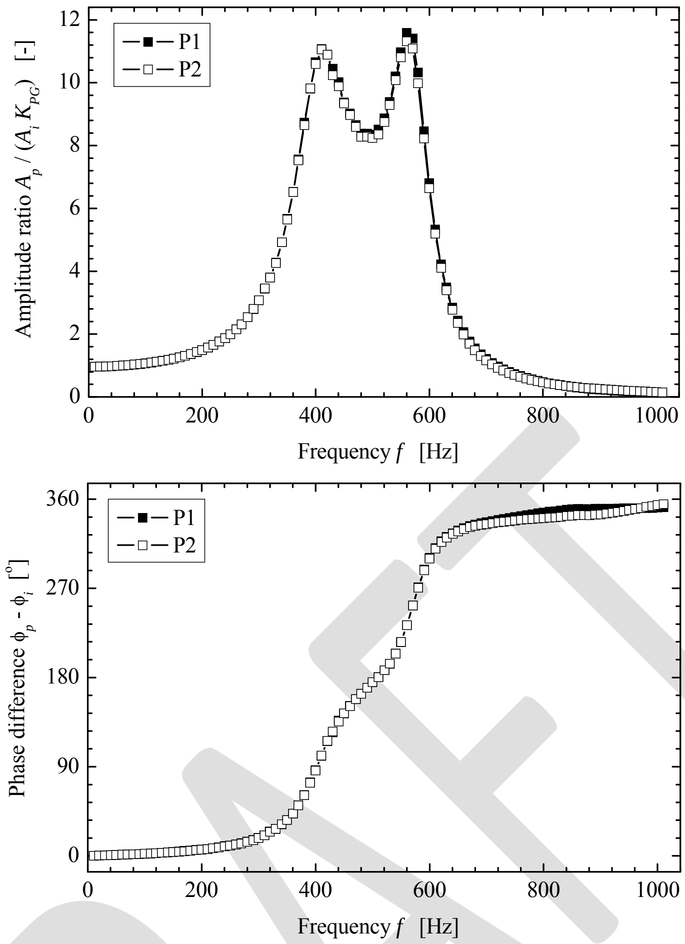

Fig. 7. Amplitude and phase frequency characteristics between the generated pressure and the excitation current for two pressure sensors (P1 and P2).

In spite of the fact that the amplitudes and the phases of the generated pressure, in comparison with the excitation current, vary with the excitation frequency, there are relatively small deviations of the pressure oscillations at both connection points P1 and P2 on the circumference of the pressure generator. Fig. 8 shows the corresponding amplitude and phase frequency characteristics between the generated pressures up to 500 Hz. Although the loudspeaker's natural frequency is in the observed frequency range, the amplitude and phase deviations do not exceed 2 % and 1°, respectively. Such results indicate a relatively homogeneous distribution of the pressure in the chamber of the pressure generator up to 500 Hz.

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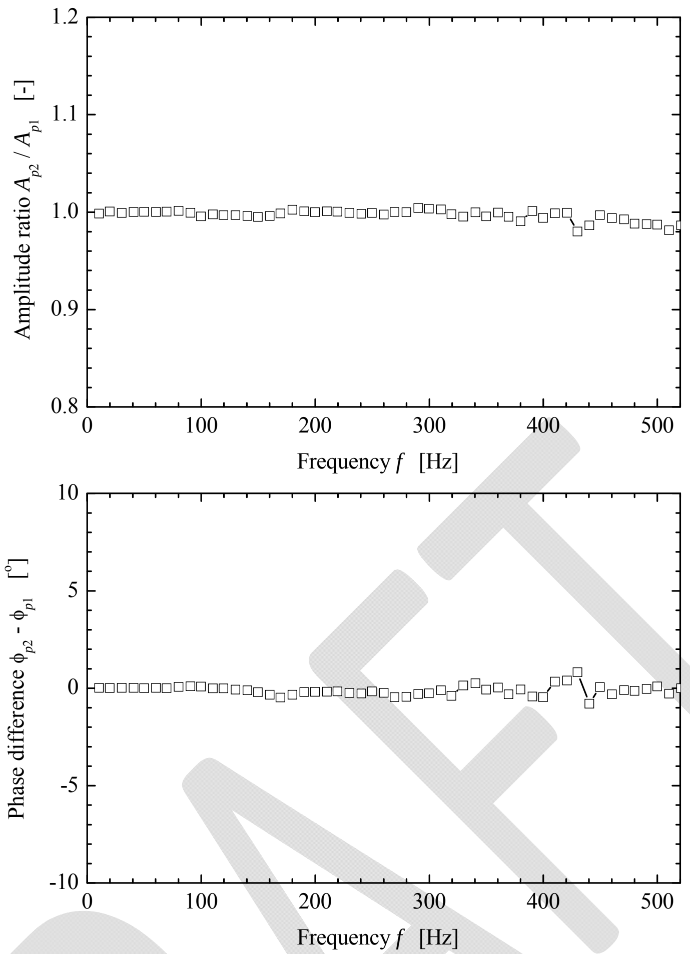

Fig. 8. Amplitude and phase frequency characteristics between the generated pressures measured by two pressure sensors (P1 and P2).

4. CONCLUSIONS

The physical modelling and experimental analysis presented in this paper offer an insight into the capabilities and limitations of a pressure generator based on electrodynamic loudspeakers. The generator's static sensitivity, which was defined by the ratio between the generated pressure and the excitation electric current, mainly depends on the ratio between the force factor and the effective area of the loudspeakers. The attainable magnitude of the statically generated pressure by the presented system is of the order of 1000 Pa. It is limited by the allowed electric current through the loudspeaker coil and the resulting temperature load. The estimated precision and stability of the pressure generator is of the order of 1 % of the upper range limit. The generator proves a small sensitivity to changes in the internal volume, showing only about 1.5 % decrease of the static sensitivity when the internal volume was increased three times.

The pressure generator is applicable in the frequency range of hundreds of Hz. Its dynamic characteristics are defined by the properties of the loudspeaker diaphragm, the air chamber between the loudspeakers and the connection of the device under test to the pressure generator. The measurement results for the generated pressures at the radially opposite connection points show the amplitude and phase deviations, which do not exceed 2 % and 1°, respectively, in the frequency range up to 500 Hz.

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The presented physical models show that the pressure generator under discussion, which is realized with two loudspeakers, has some advantages over an alternative configuration with one loudspeaker. The diaphragm gas-related stiffness is expected to be twice as high with two loudspeakers. Therefore, the effect of the internal gas volume on the generator's static sensitivity is smaller and the diaphragm's natural frequency is higher.

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