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The effect of the size of the opening on the acoustic power radiated by a reed woodwind instrument

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ABSTRACT

For a given note, the maker of woodwind instruments can choose between different sizes for the toneholes under the condition that the location is appropriate. The present paper aims at analyzing the consequences of this choice on the power radiated by a hole, which depends on the coupling between the acoustic resonator and the excitation mechanism of the self-sustained oscillation, thus on the blowing pressure. For that purpose a simplified reed instrument is investigated, with a cylindrical pipe and a unique orifice at the pipe termination. The orifice diameter was varied between the pipe diameter and a size such that the instrument did not play. The pipe length was in each case adjusted to keep the resonance frequency constant. A simple analytical model predicts that, for a given mouth pressure of the instrumentalist, the radiated power does not depend on the size of the hole if it is wide enough and if resonator losses are ignored. Numerical solution of a model including losses confirms this result: the difference in radiated power between two diaphragm sizes remains smaller than the difference obtained if the radiated power would be proportional to the orifice cross section area. This is confirmed by experiments using an artificial mouth, but the results show that the linear losses are underestimated, and that significant nonlinear losses occur. The measurements are limited to the acoustic pressure at a given distance of the orifice. Experiments also show that rounding edges of the orifice reduces nonlinear losses resulting in an increase of the power radiated and of the extinction threshold, and resulting in a larger dynamical range.

1. Introduction

When designing a woodwind instrument, for a given note, the maker can choose between a large range of sizes and locations for the toneholes. If the choice is a very wide hole, the effect is close to that of cutting the pipe at the hole location, at least at low frequencies. However it is also possible to choose a narrower hole with a location chosen closer to the pipe inlet than a wider hole, because for a narrow hole the influence of the downstream portion of the main pipe is large.

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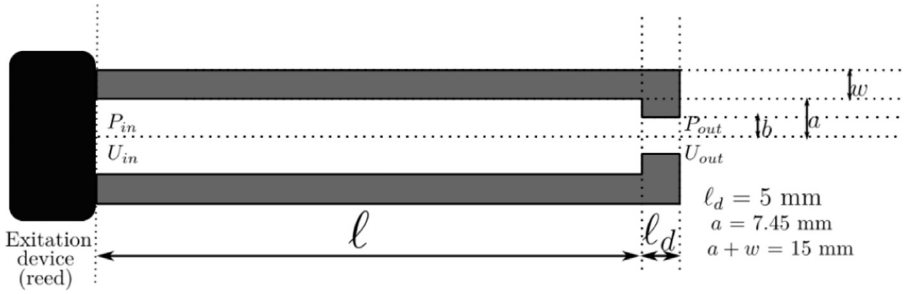

Fig. 1. Geometry of the tube with diaphragm. The length ℓ depends on the diaphragm radius b, with a fixed first resonance frequency $f_1 = 250$ Hz.

The present paper aims to investigate whether the above-mentioned choice is important for the amplitude of the radiated acoustic power. Obviously if the hole has a vanishing size, the acoustic power radiated by this hole approaches zero. But what happens when the size of the hole increases? To our knowledge, this question has not yet been treated in the literature. Models and measurements for toneholes and tonehole radiation can be found in several papers (see, e.g., [1–4]). However the power radiated by wind instruments in functioning, i.e., including the effect of the nonlinear coupling with an excitor, has rarely been treated in the literature (see [5]). Preliminary results of our study were described in a conference paper [6].

The answer to the above question is necessarily intuitive, because at low frequencies the real part of the radiation acoustic impedance (which is defined as the ratio of acoustic pressure to acoustic flow) does not depend on the size of the hole (see, e.g., [7]).

In the present paper we consider a simplified reed instrument: a cylindrical pipe terminated in only an orifice, and excited by a clarinet-like reed (with mouthpiece). The dependency of the radiated acoustic power on the blowing pressure is investigated. The effect of this simplification is discussed in Section 2.4. The scope of this paper is limited to the case of the notes corresponding to the first register, i.e., when the playing frequency is close to that of the first impedance peak.

The geometry is shown in Fig. 1. The radius of the pipe corresponds to the usual value of the output of a clarinet mouthpiece, $a = 7.45$ mm. The termination of the pipe is a cylindrical diaphragm of length $\ell_d = 5$ mm, which is approximately equal to the wall thickness of a clarinet, and of radius b, which is chosen among the following values: $b = 7.45$, 6, 5, 4, 3, 2 mm (The first value corresponds to $b = a$, a pipe without diaphragm). For a clarinet, the tonehole radius varies from 2.5 mm in the higher part of the instrument to 6 mm for the hole which is close to the bell. The length ℓ of the pipe is chosen in order to keep the first resonance frequency independent of the diaphragm radius and equal to 250 Hz. Thus ℓ depends on the diaphragm radius. Without diaphragm, if the sound velocity in free space at 20 °C is $c = 343.4$ m s^{-1}, ℓ is equal to 328 mm. With a diaphragm, the length ℓ is equal to 323, 317, 306, 286, and 237 mm for the widest to the narrowest radius (see Section 2.2). The pipe wall thickness is $w = 7.55$ mm (thus the external pipe radius is $a + w = 15$ mm).

In Section 2, a simplified model is proposed. Because losses are ignored, and the pressure signal is assumed to be mostly monochromatic, a simple result is obtained: under certain conditions imposed on the hole radius b, the radiated power is independent of this radius. In Section 3, losses are introduced, resulting in a slight modification of the simple result. Then in Section 4, numerical simulation of the sound production and radiation is carried out with an ab initio model, in order to obtain better precision. Finally, experiments are presented in Section 5 and compared to the theoretical results.

2. Elementary theoretical analysis

2.1. Simplified linear model of the resonator

For the calculation of the radiated power, two transfer functions of the resonator have to be determined in the frequency domain: the transfer admittance between the output flow rate U_{out} and the input pressure P_{in} (in the mouthpiece) for the radiation, and the input impedance $Z_{in} = P_{in}/U_{in}$ for the coupling with the excitation mechanism. For these transfer functions, the simplest model of the present section is based on standard formulas. It ignores the resonator losses. Assuming, however, that at low frequencies $kb \ll 1$ (k is the wavenumber) and therefore that the diaphragm radiates into infinite space as a monopole, the mean radiation power can be deduced from the knowledge of the flow rate U_{out}, calculated when ignoring losses:

$$\mathcal{P}_r = \frac{1}{2}\mathrm{Re}(Z_r)|U_{out}|^2, \quad (1)$$

where Z_r is the radiation impedance of a monopole:

$$\mathrm{Re}(Z_r) = \frac{k^2 \rho c}{4\pi}. \quad (2)$$