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Analysis of Nonlinear Characteristics of the Clarinet Exciter Obtained via a New Measurement Method

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ABSTRACT

A new method for measuring the nonlinear characteristic of the clarinet exciter, which binds the air flow entering into the clarinet with the pressure drop (Δp) across the reed, is described. It uses a clarinet mouthpiece equipped with a reed and an artificial lip whose position ψ is controlled by a micrometer screw. The mouthpiece is connected to a bottle in which a moderate vacuum is generated at the beginning of the experiment. After a short time lapse, the opening of the reed occurs. The thermodynamics of the volume in isochoric conditions enables the calculation of the volume velocity entering the mouthpiece from the pressure measurement. 13 reeds with 10 different embouchures are measured. The measurements enabled the estimation of the equivalent aeraulic section $S(\Delta p, \psi)$. We propose a model of S as a convex function of Δp and ψ, defined as the sum of two 1D stiffening springs plus a porosity constant. The mean standard error of the model is 0.2%.

1. INTRODUCTION

Since the invention of the instrument, about 300 years ago, the clarinettists complain about the difficulty to find musically suitable reeds (reeds with a "good vibration"). Many scientific studies are devoted to this topic, for instance [1, 2, 3, 4]. Some authors measure the nonlinear characteristics of the clarinet exciter (reed+mouthpiece+lip), for instance [5]. This paper describes a new, precise measurement method of these characteristics. We are convinced that the main musical differences between clarinet reeds are related to the quasistatic aeraulic behavior. The "vibration" of the reed is probably not the major point, but the ability of the reed i) not to interfere negatively with the sound production of the clarinet, ii) to enable an efficient sound control by the lip and iii) to allow an operating blowing pressure which is comfortable for the clarinettist.

This paper is organized as follow: in Sec. 2 the setup of the measurement method is described and its thermodynamical behavior is modeled in Sec. 3. Sec. 4 illustrates an application of the method to clarinet reeds and proposes a quasistatic model of the aeraulic section as a function of the pressure drop and the lip pressure.

2. DESCRIPTION OF THE SETUP

The measurement is divided in 2 phases: 1) calibration of the diaphragm, 2) measurement of the nonlinear characteristics of the reeds. The underlaying thermodynamic problem must be solved for each phase.

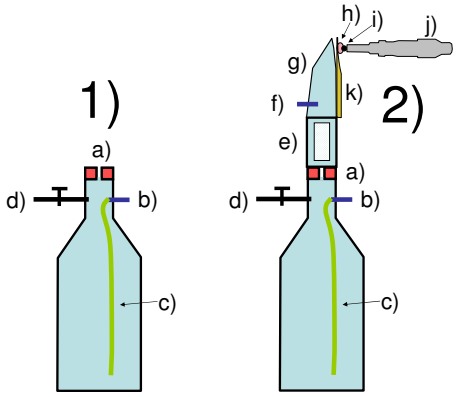


Figure 1. Schematic setup of the problems 1) and 2). a) diaphragm, b) piezoelectric pressure sensor (bottle), c) thin tube (about 1 mm inner diameter), d) cock valve, e) adaptation barrel with absorbing foam (damping the acoustic oscillations), f) piezoelectric pressure sensor (mouthpiece), g) clarinet mouthpiece, h) artificial lip (silicon 10 mm thick), i) steel beam (diameter 3 mm) glued to the artificial lip, j) micrometer screw (controlling the position ψ of the artificial lip), k) clarinet reed

2.1. Problem 1): discharge through a diaphragm

A diaphragm is connected to a hermetically closed, rigid volume (bottle, 3.178 liters, well isolated thermally and opaque to the light). A moderate vacuum (about 15-20 kPa) is generated in the bottle trough a cock valve at the beginning of the experiment (while the diaphragm is closed). After about 1 minute (allowing the observation of the heat exchange with the bottle), the diaphragm is quickly opened and the discharge starts (the air comes back into the bottle). The pressure in the bottle is measured with a piezoelectric sensor (Endevco). See Fig. 1.

The purpose is to determine the effective aeraulic section of the diaphragm S_{dia} from the pressure measurement (via the computation of temperature and flow rate).

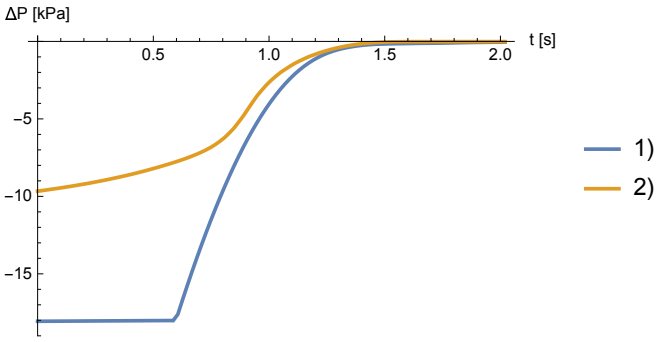


Figure 2. Typical measurements of ΔP during the discharge (zoom) for Problems 1) and 2): 1) diaphragm of 1.5mm diameter. 2) reed #J03 with embouchure $\psi = 7$ [arbitrary units]

2.2. Problem 2): discharge through a varying aeraulic section

The setup of Problem 1) is completed by a clarinet mouthpiece and a reed. An artificial lip (silicon) compresses the reed against the lay of the mouthpiece. Its position (normal to the table of the reed and denoted as ψ) is controlled by a micrometer screw. The reed is not moistened before measurement, in order to avoid a bias in the measurement due to drying.

The purpose is to determine the effective aeraulic section of the channel (slit between reed and mouthpiece) in quasistatic conditions from the pressure measurement inside the mouthpiece p and the aeraulic section of the diaphragm S_{dia} calibrated with Problem 1). The measurement of the pressure in the bottle serves only as a control for the computations. This way the delicate problem of pairing between sensors can be avoided and the precision and the reproducibility of the measurements is increased.

Typical discharge measurements for problems 1) and 2) are depicted on Fig. 2. The total duration of one experiment is about 90 s.

3. THERMODYNAMIC MODEL

3.1. Laws of thermodynamics

This subsection recalls some laws of thermodynamics, using mainly the traditional notations.

3.1.1. Constants and parameters

Ideal gaz constants : $R = 8.314 J/mol/K$
$\gamma = 1.4$ (for diatomic gazes), Density of air : ρ,
Pressure : P Atmospheric pressure : P_0
Pressure drop : $\Delta P = P - P_0$
Volume : V Flow rate : U Aeraulic section : S
$R\times$number of moles of gaz : $N = nR$
Absolute temperature : T Ambient temperature : T_0
Heat capacity at constant volume : $C_v = 1/(\gamma - 1)N$
Internal energy : E Work : W Heat : Q
Sample rate, time step : $f_s = 1/t_s$ (typically $f_s = 5000$ Hz)

Parameters with uppercase generally refer to values inside the bottle. In lowercase the same parameters refers to the value inside the mouthpiece.

3.1.2. Laws

Summary of thermodynamical laws: (1) Ideal gas law, (2) First principle of thermodynamics, (3) Newton's law of cooling (thermostat) and (4) Bernoulli's law:

$$\begin{aligned} P\,V &= N\,T && (1)\\ dE &= dW + dQ && (2)\\ dT_{th}/dt &= -r(T - T_0) && (3)\\ U &= \text{sign}(\Delta P)\,S\,\sqrt{2|\Delta P|/\rho} && (4) \end{aligned}$$

Remarks:
Newton's law of cooling: r is a positive constant, which has to be determined experimentally.
Bernoulli's law: valid for incompressible fluids and large ducts, comparatively to the aeraulic section S, for Reynolds numbers $Re \simeq U/(\nu\sqrt{\pi S}) > 2000$ ($\nu = 15.6 \times 10^{-6}$ for air at $25°C$). For compressible fluids the equation is approximately valid for the conditions at the output of the jet.

3.2. Isochoric model

The heat variation due to the thermostatic effect of the bottle is:

$$dQ = C_v\,dT_{th} \quad (5)$$

The work of small air volume dV leaving the jet outgoing the diaphragm with a temperature T_{jet} and a pressure P is $dW = dV\,P = dN\,T_{jet}$. On the other side, the variation of energy is $dE = 1/(\gamma - 1)((N + dN)(T + dT) - (dN\,T_{jet} + N\,T))$. Applying Eqs. 1, 2, 3 and 5, we obtain the equation of our thermodynamic model in isochoric conditions (*i.e.* at constant volume):

$$dN = \frac{dP\,V + N\,r\,(T - T_0)dt}{\gamma\,T_{jet}} \quad (6)$$

Considering an adiabatic expansion in the jet, the temperature of the air leaving the jet is $T_{jet} = T_0\,(P/P_0)^{\frac{\gamma-1}{\gamma}}$.

3.3. Discrete time scheme for Problem 1

During an experiment, the pressure in the bottle $P[t]$ is measured with time steps t_s : $P_m = P[m\,t_s]$. We have to deduce from the equations above the temperature T_m and the number of moles ($\times R$) of air in the bottle, N_m.

Initialization

At time step $m = 0$ (before generating the vacuum), the air in the bottle is at ambient temperature T_0 and atmospheric pressure P_0. Applying Eq. 1, the initial quantity of air in the bottle is: $N_0 = P_0 V/T_0$.

Iterations for $m > 0$

$$\begin{aligned} dN &= \frac{V(P_m - P_{m-1}) + N_{m-1}\, r\, t_s\, (T_{m-1} - T_0)}{\gamma\, T_{jet}} \\ N_m &= N_{m-1} + dN \\ T_m &= P_m V / N_m \\ U_m &= dN\, T_m / (P_m\, t_s) \end{aligned} \tag{7}$$

3.4. Validation with known diaphragms

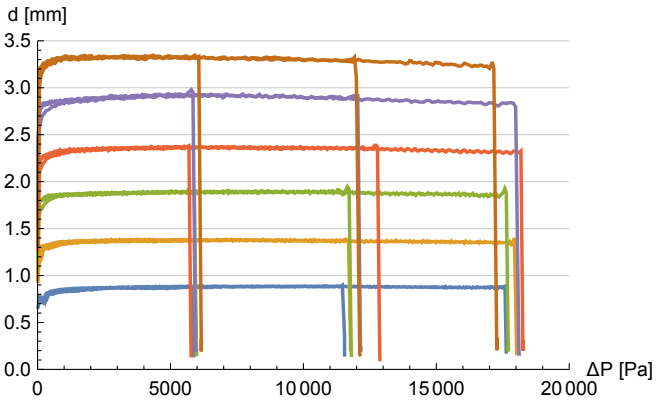


Figure 3. Color lines: aeraulic diameter of the tested diaphragms computed with the isochoric scheme Eq. 7. Each diaphragm is measured 3 times with different initial conditions. Thin dark lines: nominal diameter of the diaphragms.

A validation of the model was performed with a series of chamfered diaphragms of nominal diameters 1, 1.5, 2, 2.5, 3 and 3.5mm. Eq. 4 allows the computation of the equivalent aeraulic section S from U, ρ (in the bottle) and Δp, from which we deduce the equivalent aeraulic diameter of the diaphragms.

Fig. 3 depicts the results. The following values of r were determined by optimization (among 3 tests with different initial depressions for each diaphragm): 0.25, 0.32, 0.39, 0.46, 0.54, 0.61, for the diameters 1 to 3.5mm. This accounts approximately for the greater heat exchange with the bottle when the flow rate through the diaphragm is high. Before the discharge $r = 0.20$ (measured value in static conditions).

The aeraulic section of the diaphragm S_{dia} used in Problem 2) is calibrated with this method (in our case 2.9mm). The adaptation barrel with absorbing foam (damping the acoustic oscillations) belongs formally to the diaphragm (like every aeraulic resistance downstream the mouthpiece sensor).

3.5. Discrete time scheme for Problem 2

This problem is subdivided in 2 subproblems:
A) compute the net mass flow dn entering into the mouthpiece
B) compute the net mass flow dN entering into the bottle

The total mass flow entering trough the channel is $dN_{ch} = dn + dN$, from which $U_{ch} = T_0\,(p/P_0)^{\frac{\gamma-1}{\gamma}}\; dN_{ch}/(p\,dt)$ and its corresponding aeraulic section S_{ch} is deduced with Eq. 4.

Subproblem A) The mouthpiece is treated with Eq. 7 in which the variables of the mouthpiece replace those of the bottle ($P \to p$, $U \to u$, and so on). An adiabatic approximation can be used for this case : $dQ = 0$, thus $r = 0$.

Subproblem B) the combination of Eq. 6 with Bernoulli's law Eq. 4 enables the calculation of the pressure in the bottle P_m (at discrete time m) from the corresponding measurement of the pressure in the mouthpiece, denoted p_m.

Initialization Like Problem 1), additionally: $p_0 = P_0$.

Iterations for $m > 0$

$$\begin{aligned} \delta p &= p_{m-1} - P_{m-1}, \quad \rho = (M\, N_{m-1})/V \\ dN &= \text{sign}(\delta p)\, P_{m-1}\, S_{dia}\, \sqrt{|2\delta p/\rho|}\, t_s / T_{m-1} \\ dP &= (N_{m-1}\, r\, t_s\, (T_0 - T_{m-1}) + dN\, \gamma\, T_{jet})/V \\ N_m &= N_{m-1} + dN \\ P_m &= P_{m-1} + dP \\ T_m &= P_m V / N_m \\ U_m &= dN\, T_m / (P_m\, t_s) \end{aligned} \tag{8}$$

with $M = 0.028965/R = 0.00348388$ for the air.

4. MEASUREMENTS OF CLARINET REEDS

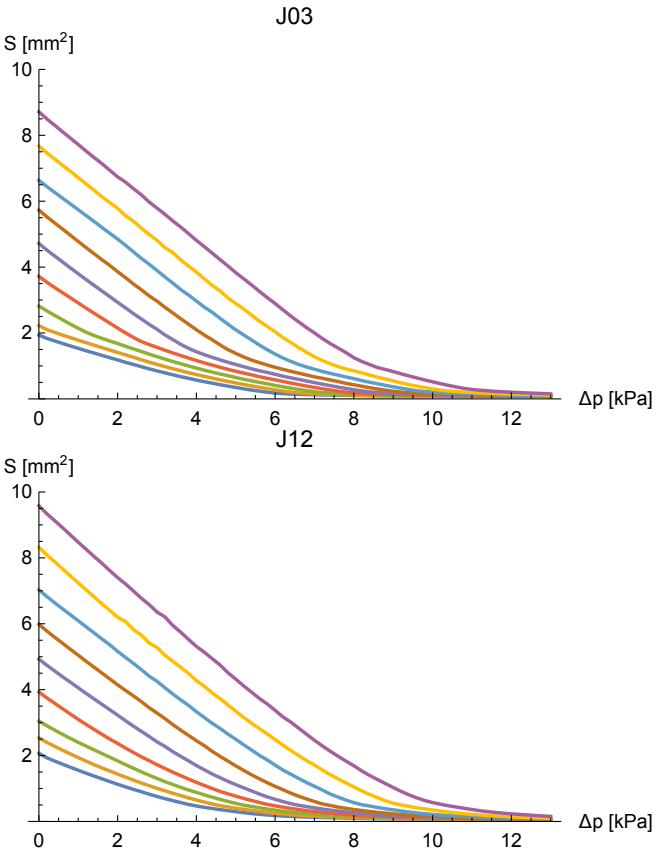


Figure 4. Aeraulic section $S(\Delta p, \psi)$ determined with Eq. 8 for the reeds J03 and J12, $\psi = 1 \ldots 9$ (color lines). Below the transition to turbulent flow, S is approximated from the optic sensors inside the mouthpiece.

A series of 14 clarinet reeds was measured with the described method (Rigotti and Rico, strength 3 and 3 1/2). 10

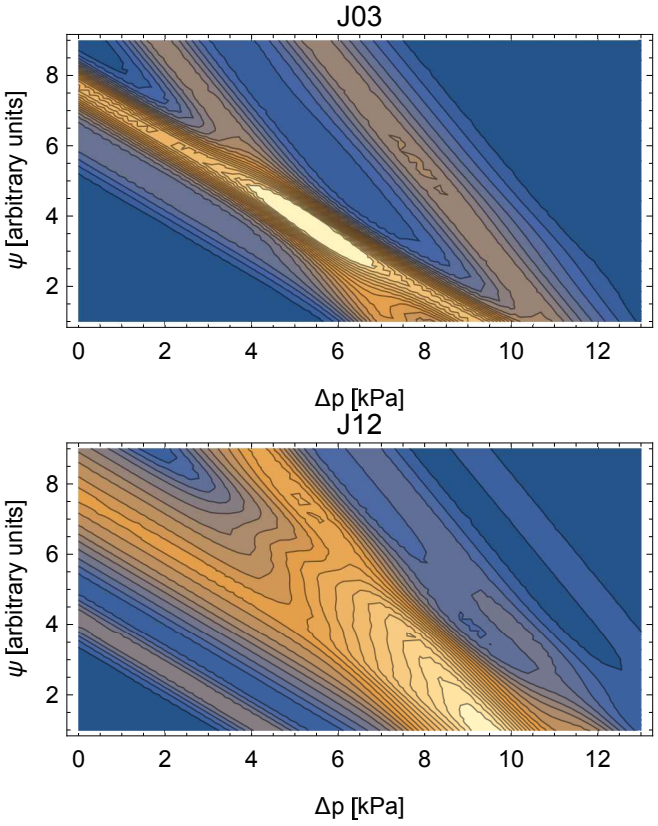


Figure 5. Contour plot of the second derivative of the aeraulic section $\frac{\partial^2 S}{\partial \Delta p^2}$ for the reeds J03 (Rigotti 3) and J12 (Rico 3 1/2), $\psi = 1 \dots 9$, according to the proposed model Eq. 9 (arbitrary color scale)

different positions ψ of the artificial lip were tested (in steps by 0.2 mm). Unfortunately our vacuum cleaner was not powerful enough for creating the vacuum in the bottle necessary to close some strong reeds with a loose embouchure. Complete measurements are available only for 13 reeds and 8 embouchures.

4.1. Measurements of the aeraulic section S

Fig. 4 depicts the results of the measurement of the aeraulic section $S(\Delta p, \psi)$ for 2 reeds. Fig. 5 illustrates $\frac{\partial^2 S}{\partial \Delta p^2}$ for the same reeds. An interesting feature is present for all reeds: we observe 2 different slopes along whom the second derivative is almost constant. The same observation can be done with $\frac{\partial^2 S}{\partial \Delta \psi^2}$. Along these slopes, Δp and ψ are partially decoupled.

The observed behavior can be approximated as a sum of 2 1D stiffening springs and a porosity constant:

$$S(\Delta p, \psi) \simeq S_1(\Delta p + k_1 \psi) + S_2(\Delta p + k_2 \psi) + k_p \quad (9)$$

The following values were determined by optimization for our setup : $k_1 = 1374.2$ and $k_2 = 670.3$ (same values for all reeds). The porosity constant k_p accounts for a residual flow which do not vanish for high values of Δp and must be determined individually for each reed.

This model implies that $S(\Delta p, \psi)$ is a convex function of Δp and of ψ. In other words, the second derivatives of S are non-negative. The stiffening springs can be implemented with non-negative, reproducing kernels (for instance gaussian kernel) as bandlimited functions. We used a kernel allowing a real-time implementation of the measured exciter for synthesis purpose (but this is beyond the scope of this paper).

The mean standard error of the model is around 0.02mm^2. This represents a height of 1.5 μm for a rectangular channel, 13mm wide, or 0.2% of the maximal measured aeraulic section.

5. CONCLUSIONS AND PERSPECTIVES

The precision of the method enables a detailed study of the nonlinear characteristics of clarinet reeds. A great variety of quasistatic behaviors could be measured, confirming the every-day experience of the clarinetists with their reeds and the importance of the non-linear contact between reed and mouthpiece. A comparison with 3D simulations about the dichotomic sensitivity of the reed to the lip pressure shows that k_1 accounts mainly for air coming from the middle of the channel while k_2 concerns mainly the air entering from the sides of the channel.

This short paper could only demonstrate the main features of the method, but could not investigate the musical consequences of the measurements for reed makers and clarinettists, explaining relationships with geometric and flexural measurements, nor demonstrate the ability of the model for a real-time simulation of the measured reeds.

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