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Modal analysis of a complete clarinet

M. Facchinetti^{a,c}, X. Boutillon^b and A. Constantinescu^c

^aLaboratoire d'Hydrodynamique, CNRS - Ecole Polytechnique, 91128 Palaiseau Cedex, France

^bLaboratoire d'Acoustique Musicale, CNRS - Université Paris 6 - Ministère de la Culture, 11 rue de Lourmel, 75015 Paris, France

^cLaboratoire de Mécanique des Solides, CNRS - Ecole Polytechnique, 91128 Palaiseau Cedex, France

A modal computation of a complete clarinet is presented by the association of finite-element models of the reed and of part of the pipe, and a lumped-element model of the rest of the pipe. This is a continuation of an initial work by Pinard and Laine (unpublished reports of the Ecole Polytechnique) on isolated reeds. The eigenmodes of the complete system are computed and the results lead to a discussion of the following points: flexion and torsion modes of the reed, their coupling to the acoustical field, plane wave hypothesis, equivalent volume approximation in the mouthpiece, and alignment of resonance peaks.

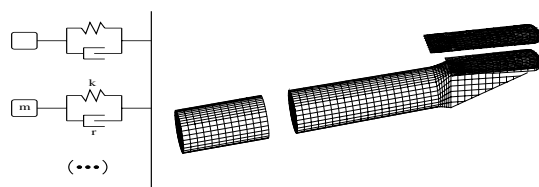


FIGURE 1. Lumped elements model for the pipe, FEM for the barrel, the mouthpiece, and the reed of the clarinet.

INTRODUCTION

The classical view of a clarinet associates a linear resonator - the pipe - and a nonlinear excitor - the reed. The purpose of our approach is to include the reed in the linear part and to restrict the nonlinear aspects to boundary conditions: the air flow from the mouth to the pipe through the reed-slit and contact forces between the reed and the curved lay of the mouthpiece. The present analysis deals with the linear aspects of the ensemble of the reed coupled to the pipe by means of a modal investigation of the instrument.

The simplest reed model - a spring - has been approached experimentally [1, 2, 3] and used in numerical simulations which were successful in describing basic features of the dynamics of a clarinet [4, 5, 6]. The further step in complexity is that of a single oscillator with various possible sophistications [7, 8, 9, 10]. Modeling the reed as a true continuous system is the current state of research. Several examples of modal analysis of isolated clarinet reeds have been presented over the recent years using holographic interferometry [11, 12, 13, 14]. Two examples of finite-element modeling based on measurements of the mechanical properties of cane have been reported [15, 16]. The present model treats the reed as a complex continuous system in association with the air-column: fluid and solid finite element models (FEM) for

the reed and the beginning of the pipe associated with a lumped elements model for the main part of the pipe (Fig. 1).

MODELS AND RESULTS

The reed geometry has been carefully measured. Reed cane is considered as an elastic transversely isotropic, homogeneous material. Since we are concerned with individual modes of the reed, losses are ignored. They would have to be taken into account in the actual dynamics of the instrument. Five parameters are needed to describe the material (in parenthesis, the values used in the computation): density ρ (450 kg/m^3), longitudinal and transverse Young's moduli E_L ($10\,000 \text{ MPa}$) and E_T (400 MPa), transverse to longitudinal shear modulus G_{LT} ($1\,300 \text{ MPa}$), and longitudinal-transverse Poisson coefficient ν_{LT} (0.22). The reed is considered rigidly clamped on the section corresponding to the ligature and having a stress-free boundary elsewhere. This model has been implemented using linear Love-Kirchoff plate elements in the Castem finite-element code (www.castem.org:8001). Three of the first modes of a reed are presented in Fig. 2.

Acoustical studies of the clarinet have so far represented the mouthpiece of a wind instrument by its equivalent volume. To go beyond this approximation and to compute the 3-D distribution of the pressure in the upper part of the instrument, a coupled fluid-solid model has been used. The air volume inside the mouthpiece and the barrel is modeled with linear tetrahedric and prismatic finite elements of compressible elastic fluid. The acoustic pressure at points of the open air surfaces is considered to be zero as well as the normal derivative of the acoustic pressure (corresponding to air flow) on the walls of the mouthpiece and the barrel. The boundary condition coupling the reed and the mouthpiece involves the stress in the solid and the velocity of the fluid. The precise for-

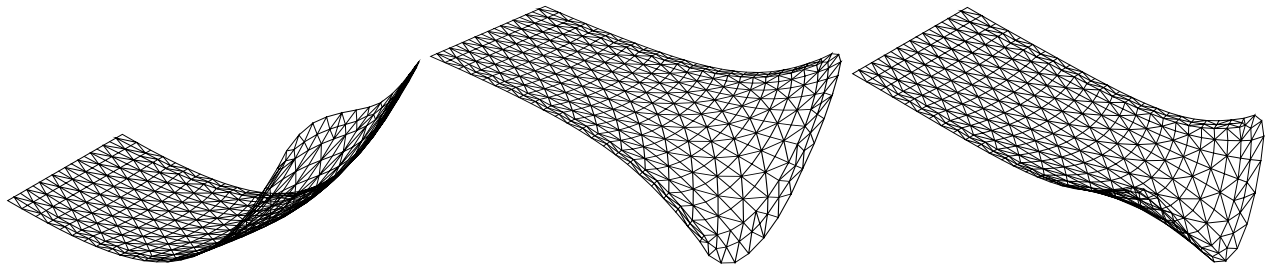


FIGURE 2. Modes at 2417, 4158, and 7020 Hz of an isolated reed.

mulation is given in [17]. Computed modes in the coupled situation match well the modal shapes on real reeds as measured by holographic interferometry. The modal acoustic pressure at an eigenfrequency of 4119 Hz is displayed in Fig. 3. In this mode, the reed undergoes torsion with a characteristic distance smaller than the half the wavelength in air at that frequency ($\lambda \approx 10$ cm); the resulting acoustical short-circuit prevents any efficient coupling of the reed to the air in the mouthpiece. This explains the fairly uniform acoustic pressure for this mode, except very near to the reed.

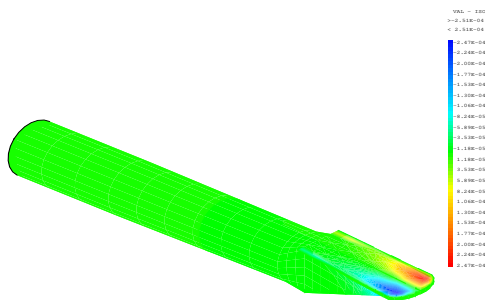


FIGURE 3. Computed eigenmode at 4119 Hz in a mixed solid-air situation - Acoustic pressure inside the mouthpiece and barrel.

In order to simulate the modal behavior of the complete clarinet, the FEM of the top of the pipe is associated with lumped elements representing the rest of the pipe. Simulations such as presented in Fig. 3 show that the acoustical field consists essentially of plane waves. The rest of the pipe can therefore be adequately represented by its acoustic input impedance. The lumped-element oscillators are coupled to the finite elements by means of a rigid plate with negligible mass. We used measurements provided by Vincent Gibiat. Each impedance peak is associated with an oscillator represented in its generic form in Fig. 1. The eigenmodes and eigenfrequencies have been computed for several fingerings of the instrument. We have then revisited the classical question of the harmonicity of the eigenfrequencies. The traditional model of the mouthpiece is that of a cylinder of equivalent vol-

ume. It appears that variations in eigenfrequencies due to the model change are significant with regard to the alignment of resonances, *even at low frequencies*. In other words, the misalignment of peaks in either model is of the same order of magnitude as the frequency shifts due to the presence of the reed and the prismatic shape of the mouthpiece.

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