The clarinet: How blowing pressure, lip force, lip position and reed "hardness" affect pitch, sound level, and spectrum

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Using an automated clarinet playing system, the frequency f, sound level L, and spectral characteristics are measured as functions of blowing pressure P and the force F applied by the mechanical lip at different places on the reed. The playing regime on the (P,F) plane lies below an extinction line $F(P)$ with a negative slope of a few square centimeters and above a pressure threshold with a more negative slope. Lower values of F and P can produce squeaks. Over much of the playing regime, lines of equal frequency have negative slope. This is qualitatively consistent with passive reed behavior: Increasing F or P gradually closes the reed, reducing its equivalent acoustic compliance, which increases the frequency of the peaks of the parallel impedance of bore and reed. High P and low F produce the highest sound levels and stronger higher harmonics. At low P, sound level can be increased at constant frequency by increasing P while simultaneously decreasing F. At high P, where lines of equal f and of equal L are nearly parallel, this compensation is less effective. Applying F further from the mouthpiece tip moves the playing regime to higher F and P, as does a stiffer reed.
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I. INTRODUCTION

The pitch played by reed instruments such as clarinet, saxophone, oboe, and bassoon is controlled primarily by the configuration of open and closed holes on the bore of the instrument, which is in turn controlled by which keys are pressed: What players call a fingering. The fingering determines the passive acoustic properties of the bore and thus the downstream acoustic impedance spectrum that loads the reed. In normal playing, the frequency of the note played using a particular fingering is close to the frequency of one of the strong peaks in this impedance spectrum. Because each impedance spectrum has several peaks, it is often possible to play more than one note on a given fingering, whether intentionally or accidentally. The played frequency of any given note may be varied over a modest range using a collection of control parameters including the pressure P of the air in the mouth, the force F applied by the lip to push the reed toward the mouthpiece, and the position at which this force is applied. Pedagogues observe that playing more loudly (which usually requires higher P) is often associated with lower pitch and that biting harder (greater F) tends to raise the pitch (Thurston, 1977; Rehfeldt, 1977; Gingras, 2004). Properties of the reed and mouthpiece are also important. The configuration of the vocal tract can play a significant role in pitch bending but appears to be rather less important in normal playing in the normal range (Chen *et al.*, 2009, 2011). Thus whether conscious of it or not, a good player must learn that if she decreases the air pressure in the mouth so as to play at a very low sound level, she will often have to adjust control parameters (including, e.g., the lip force) to avoid the changes in pitch that would otherwise result (Pay, 1995).

The clarinet has become a standard object of study in the acoustics of wind instruments, and a number of theoretical and modeling studies predict the range of playing parameters and the pitch played under a variety of conditions (e.g. Gilbert *et al.*, 1989; Dalmont and Frappé, 2007). Blowing machines have been used to study reed behavior, flow-pressure relations, and, over some parts of the space of control parameters, the dependence of playing frequency on pressure in the "mouth" (Wilson and Beavers, 1973; Bak and Domler, 1987; Idogawa *et al.*, 1993; Mayer, 2003; Dalmont *et al.*, 2003; Dalmont *et al.*, 2005; Dalmont and Frappé, 2007; Ganzengel *et al.*, 2007). These papers have clarified much about the operation of the instrument and tested theoretical models. The present paper has somewhat different aim: It uses a blowing machine in conjunction with an artificial "mouth" to investigate, under controlled conditions and over the available range of playing parameters, how the fundamental frequency, the sound level, and the sound spectrum vary with pressure in the mouth, the force on the reed and the position at which it is applied, and the stiffness of the reed. The primary purpose is to understand how players must vary the control parameters for musical effects, such as playing a *crescendo* or *diminuendo* at constant pitch.

This artificial mouth used here is part of an automated clarinet-playing system. Sound files and video recordings of its performance are given elsewhere (Music Acoustics, 2008)

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as well as sound files from this experiment. When playing parameters are well adjusted, its sound is tolerable rather than good. The system is convenient for scientific measurements. However, it differs considerably from a human player in that the shape of the "vocal tract" is different and is made of rigid materials. The artificial "lip" and its attachment to the reed have elastic and damping properties that probably differ from those of human lips in this application. Further, because lip geometry varies considerably among people, lip damping and elasticity probably do, too. Inevitably, then, the results will differ quantitatively from those one might aim to measure on a (particular) player. Qualitatively, however, they should show similarities. Further, the quantitative differences should be small and perhaps of the same order as the differences among players and their preferred playing setups.

The variations among reeds and mouthpieces, and some of the relations between them, are well known to clarinetists. Reeds are commonly classified by a single parameter called "hardness," which roughly describes their stiffness as a cantilever spring and to which reed makers give a value from about 1.5 to 4.5, without units. The reed, however, is not a simple cantilever: Its thickness varies along its length, and some players adjust it to their taste by judicious scraping with a sharp knife. Further, players report that the hardness of a reed usually decreases the longer it is played. The shape of the lay, the surface toward which or against which the reed bends, and especially the opening at the mouthpiece tip are important parameters: Playing with a more open mouthpiece has some similarities to playing with a harder reed in that both require a larger lip force F (e.g., Dalmont and Frappé, 2007). The damping of the reed by the lower lip is also important: Squeaks (high frequency tones of undesired pitch) are produced if the force is applied to the reed by the teeth. To avoid this, the player places the lower lip between the lower teeth and the reed. Previous studies have used a balloon filled with water or another liquid (e.g. Bak and Domler, 1987; Gazengel *et al.*, 2007) as an artificial lip. In the experiments reported here, the lip is replaced by a slab of synthetic damping material, chosen because it avoided squeaks over a large range of parameters and produced a tolerable sound. This arrangement also allows for a well-defined position of the "teeth" and thus a relatively localized application of F.

Each standard fingering on the clarinet is named for the note that is produced with that fingering under normal playing conditions. Even when appropriate damping is used, not all combinations of mouth pressure and lip force can produce that note, however. Typically, for a given lip force, the reed does not oscillate at very low mouth pressures P, and thus the instrument does not produce a note. When the mouth pressure reaches a certain value called the oscillation threshold P_{osc}, an acoustic oscillation can be maintained in the bore. At and above a much higher value, the mouth pressure bends the reed sufficiently to close it permanently on the mouthpiece lay: This is the extinction threshold P_{ext}. Without the oscillating movement of the reed, the sound production necessarily stops. P_{ext} exceeds the static pressure needed to hold the reed closed against the lay, called the beating threshold, P_b, because the acoustic energy contained in the oscillation of the air column can still make the reed oscillate between open and closed states. The values of these pressure limits depend on the lip force, F, and also on its point of application, on the reed hardness, and on mouthpiece geometry. A sufficiently high value of the lip force will close the reed even with zero mouth pressure. If losses are neglected, the curves of $P_{osc}(F)$ and $P_{ext}(F)$ meet at this point as shown in Fig. 1. At the lower limit of lip force, the two curves do not necessarily join because it is possible to have an oscillating regime without applying a mechanical force to the reed. In practice, zero lip force implies zero lip damping, so this case produces higher regimes such as squeaks (Wilson and Beavers, 1973), which are of limited interest.

The oscillations of the reed come in many flavors: In one, which is used most often in music, the reed oscillates at a frequency close to one of the maxima of the impedance spectrum of the resonator—usually the largest. (Impedance spectra of the clarinet for the standard and some nonstandard fingerings are given by Dickens *et al.*, 2007.) However, the impedance spectrum can have several peaks almost as strong as the absolute maximum, and consequently the reed can sometimes oscillate at a frequency corresponding to a different peak, often a note belonging to what players call a different register. Sometimes the reed oscillation is not driven by a resonance of the bore, and the instrument produces a loud, high-pitched sound, the frequency of which is only weakly related to features of the impedance spectrum of the bore. This *high regime* is not stable because it depends strongly on P, F, and possibly the configuration of the mouth.

Different P, F, and lip position, as well as different reeds and mouthpieces, produce different sound spectra. In this paper, the spectral centroid, *SC*, is used as a simple quantification of the spectrum. *SC* is the power weighted average frequency of the spectrum, and it is strongly correlated with timbral brightness (Grey and Gordon, 1978; Schubert and Wolfe, 2006).

Much of the area on the (P, F) plane lying between $P_{osc}(F)$ and $P_{ext}(F)$ is the normal playing region: The regime in which the musician can adjust P and F to achieve the desired sound level, intonation, and timbre of the note. This paper focuses on how the frequency f, sound level L, and the

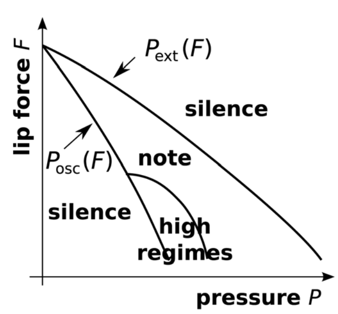

FIG. 1. A schematic of the regimes on the (P,F) plane. Above the extinction curve $P_{ext}(F)$ and below the threshold $P_{osc}(F)$, there is no periodic sound. Between the two lies an area in which the intended note is produced. A second smaller area is often present in which various high-frequency regimes such as squeaks are produced.

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spectral centroid vary over the (P,F) plane in this region. Trajectories of constant f in the (P,F) plane and the variations in L they produce are of particular interest because these are presumably what clarinetists learn while practicing *crescendi* and *diminuendi* on the instrument: What gestures may be used to keep the note in tune while changing its sound level or timbre. Most of the results in this paper are therefore presented as contours of constant f, contours of constant L, and in one case contours of spectral centroid measured on the (P,F) plane under controlled conditions. Sets of measurements are reported for three different fingerings, including that for one of the easiest notes on the instrument, for two different reed hardness values and for three different lip force positions.

II. MATERIALS AND METHODS

The clarinet (Yamaha model YCL250) is a commonly used, mass-produced student model made of resin rather than wood. It was fitted with a resin mouthpiece (Yamaha model CL-4C) that has a facing length of 19.0 mm and a tip opening of 1.05 mm. The clarinet is mounted horizontally with the mouthpiece oriented upside down so that the reed is at the top (Fig. 2). The mouth end is sealed in a chamber (volume, 50 ml) connected to a hose of internal diameter 22 mm that replace the musician's mouth and throat. A rectangular prism of polyurethane foam (Sorbothane, Kent, OH), 4 mm thick and 20 mm × 20 mm, is glued to the reed so it covers an area from about 4 mm to 24 mm from the tip. Mechanical effects of the glue are minimized by only gluing a small strip of the "lips" at the end distant from the tip of the reed. A steel tube, 1.5 mm in diameter, sits on this piece at one of three positions engraved on the rubber. A loop of thread passes through this tube and exits via two small holes at the bottom of the mouth. The two ends of this thread support a frame carrying masses that are varied to exert a known, constant force on the reed. (The lip, thread, and frame have a total mass of 0.85 g).

Cane reeds need to remain humid to work as intended. Because this experiment was conducted in dry air, and to ensure greater reproducibility, synthetic reeds (Legere,

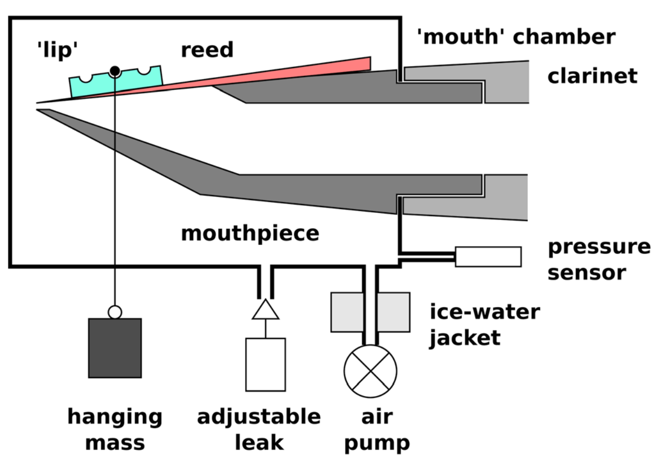

FIG. 2. (Color online) Schematic sketch (not to scale) of the clarinet mouthpiece inside the artificial mouth indicating the positions used for the application of lip force.

Barrie, ON) were used instead of cane reeds. Reeds of two hardnesses (2 and 3.5) were used. Although each reed was fitted with a different lip made from polyurethane foam, the lips were of similar geometry and glued at the same position.

The pressure and air flow into the mouth chamber are produced by an electrical pump (positive airways pressure model R261-708, ResMed, Sydney, Australia) and measured with a sensor (model 24PC, Honeywell, Morristown, NJ). Pressure is controlled using a PID loop designed for a clarinet playing robot (Music Acoustics, 2008; Almeida *et al.*, 2010). Because the air flow through the instrument depends on the average reed opening, the maximum pressure value reached in the mouthpiece can vary from 6.5 to 7.5 kPa. The pump heats the air to several degrees Celsius above ambient and consequently temperature in the clarinet bore could vary with air flow rate and thus with mouth pressure and lip force. To reduce this source of variability, the air duct connecting the pump to the mouth traverses a chamber filled with iced water with a length that lowers the temperature close to ambient. The air arriving at the clarinet during experiments has a temperature of 19 °C ± 1 °C for a room temperature of 20 °C.

For each measurement, the mouth pressure is increased from a low value below the oscillation threshold, increased as quickly as possible to a constant value that is kept for 6 s, then released back to the low value, extinguishing the oscillation. A trial consists of a sequence of such measurements where the value of the constant pressure starts just below the oscillation threshold and continues until either to the maximum value of the pump or the maximum oscillation threshold, whichever is lower. The mass hanging from the reed is then changed, and the pressure sequence repeated. Usually, masses are adjusted in steps of 25 g, with a minimum value of 25 g, which usually determines the lower limit of F studied here. Some lower values were used for the series in which the force was applied at the "tip" position of the reed. The threads applying the force to the lip pass through the wall of the mouth via holes larger than the threads, so as to minimize friction. This introduces a small leak, which does not affect pressure measurements.

The playing system can play from written E3 (the lowest note) to about D6, although playing the highest notes depends very sensitively on the parameters. Three different fingerings were used: Those for written G3, G4, and G5 (nominally sounding F3, F4, and F5: The clarinet is a transposing instrument). The finger holes are closed using a plastic molding/adhesive compound (Blutak), and the appropriate keys are held with tape.

For each value of pressure and lip force, the sound produced by the instrument is recorded on the axis in front of the bell at a distance of 50 mm.

The frequency of the played sound is extracted using a Fast Fourier Transform (FFT)-based algorithm from a 2 s sample where no transients occurred. Intended notes and higher regimes are distinguished by ear. In some cases, the instrument may produce a tone at a frequency (usually higher) that is very different from that expected for the particular fingering used. This can correspond to a note in a higher register or to a squeak where the vibration regime is

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determined largely by a resonance of the reed. These typically occurred at a frequency around 1000–1200 Hz. In later figures in this paper, playing regimes are indicated by shading and differentiated from higher regimes. These experiments studied most of the range of the lip force F, from close to zero up to the value that closed the reed against the lay. The minimum weight of the hanging mass that applies force to the lip limited the range studied here. The lower range of mouth pressure P could always be studied, but the large values of P required to close the reed at low F could not always be reached because of the upper limit of the pump used (about 7 kPa, the exact value depending on the flow rate). Most of the pressure range available to and used by players, however, was studied.

In Figs. 4–8, polynomials of the form $f = f_r + b_f P + c_f P^2 + d_f F + e_f F^2 + g_f PF$ and similar polynomials for sound level and spectral centroid were fitted to data sets like those shown in Fig. 3 by minimizing the residual sum of squares.

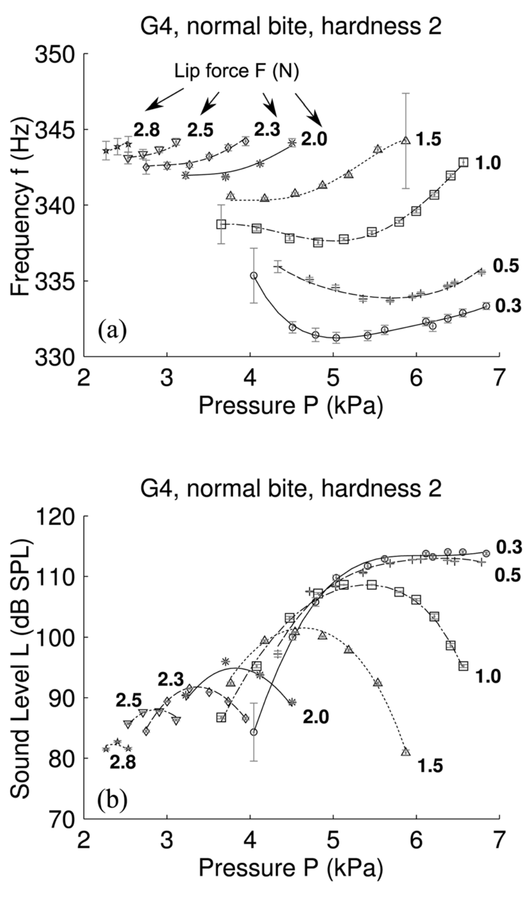

FIG. 3. Measured frequency f and sound level L as a function of mouth pressure P for each value of the lip force F (shown in newtons). The reed has hardness 2, and the teeth are at the middle position (see Fig. 2). The fingering is that for the note (written) G4. On this plane, a *crescendo* or *decrescendo* at constant pitch would be a horizontal line and so would require varying F. For the forces of 0.25 and 0.5 N, the clarinet sound is not extinguished below the pressure of 6.7 kPa (the highest that can be achieved with the current system). The error bars that indicate the variability in frequency or sound level in the entire recorded sound sample (approximately 1.5 s) are shown in gray for all points. These are usually too small to be clearly visible. However, three points show atypically large error bars: The low P limit of the $F = 0.25$ and 1.0 N curve and the high P limit of the 1.5 N curve. This is the result of hysteresis, instability, and sometimes turbulent noise at the perimeter of the playing regime.

III. RESULTS AND DISCUSSION

Figure 3 is a plot of $f(P)$ and $L(P)$ at eight different values of applied reed force F. The reed has hardness 2, the point of lip force application is the middle position (Fig. 2), and the fingering is that for the (written) note G4. On a clarinet played at room temperature with warm, humid breath, the nominal frequency of this note is 349 Hz (for tuning A = 440 Hz). The cool (19 °C) dry air of the blowing machine accounts for most of the difference in pitch: A 10 °C reduction in temperature is expected to lower that frequency to 343 Hz. Unexpected higher notes (including squeaks) did not occur in these measurements.

The low pressure limit shown here is a limitation of the method: These experiments were all done without the use of a tongue and without feedback to P and F based on the sound produced. Further, the pressure was varied in discrete steps to sample all of the available parameter space. In contrast, human players can start the first note of a phrase by tonguing: They either close or displace the reed with the tongue, produce a pressure excess in the mouth, then release the reed with a displacement transient. With careful adjustment of all control parameters, clarinetists can initiate and sustain notes with very low sound levels, using feedback from the sound to control P and F.

Figure 3(a) shows that in the low range of F, the values of $f(P)$ at constant F first decrease then increase with increasing P, an observation that can be readily demonstrated by a human player. The positive slope of $f(P)$ at constant F is consistent with the results of Bak and Domler (1987). The very low lip force range is of little practical interest to clarinetists because it plays flat. In the more typical higher F range, $f(P)$ at constant F increases with increasing P.

Larger values of P and larger values of F both tend to close the reed by bending it along the lay. This is expected to reduce both its effective length and area and thus to reduce its equivalent acoustic compliance. In the simple model of Benade (1985), the passive equivalent compliance of the reed is in parallel with the input impedance of the bore, and a smaller compliance increases the frequency of this parallel combination (Nederveen, 1998; Dickens *et al.*, 2007). This is consistent with the positive slope of $f(P)$ at constant F at all but very low values of F. Bending it against the lay also shortens the vibrating length; this increases the natural frequency of the reed as a cantilever.

Figure 3(b) shows that sound level L increases relatively rapidly with increasing P at low values of P when the reed-mouthpiece aperture is open. However, for usual values of lip force, and above a certain value of the mouth pressure, both P and F act to close the reed against the lay and admit little air, so that increase in the sound level due to increased P are offset by reductions due to the smaller acoustic flow. Reducing F gives a greater range of sound level than does increasing P. Fortunately for clarinetists, while lowering F lowers the pitch, increasing P raises it, making *crescendi* at constant pitch easier than would otherwise be the case. This is more easily displayed, however, by plotting f and L on the same graphs.

Hereafter, results are shown as contours of equal frequency and sound level f and L on the (mouth pressure, lip force) or

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(P,F) plane. Such plots show the regimes available for playing and also those that produce squeaks or other unexpected sounds. To produce these plots, the sets of measured points $f(P,F)$ and $L(P,F)$ for any note and mouthpiece configuration are fitted to a polynomial surface. [The curves in Fig. 3 are an example of sections of these surfaces in the (P,f) and (P,L) planes for each given lip force F.] Values of frequencies interpolated along these surfaces are used in the following figures.

Values of minimum and maximum pressure producing the expected note are also extracted from data curves similar to those shown in Fig 3. These are interpolated for different forces to obtain the playing regime (the limits of the sound level gray-scale map in Fig. 4). Moreover, the minimum and maximum values producing a squeak or other periodic sound are also extracted, so the (F,P) plane is divided into three areas: No periodic sound, the expected note, and other periodic sound (usually a squeak), when present. The solid line thus shows the limit of any periodic sound. Because of the pressure limitations of the pump, our measurements do not go above about 7 kPa, so the pressure extinction line cannot be shown for low values of F and the limit of our measurement is shown, on the right side of the plot, as a dashed line.

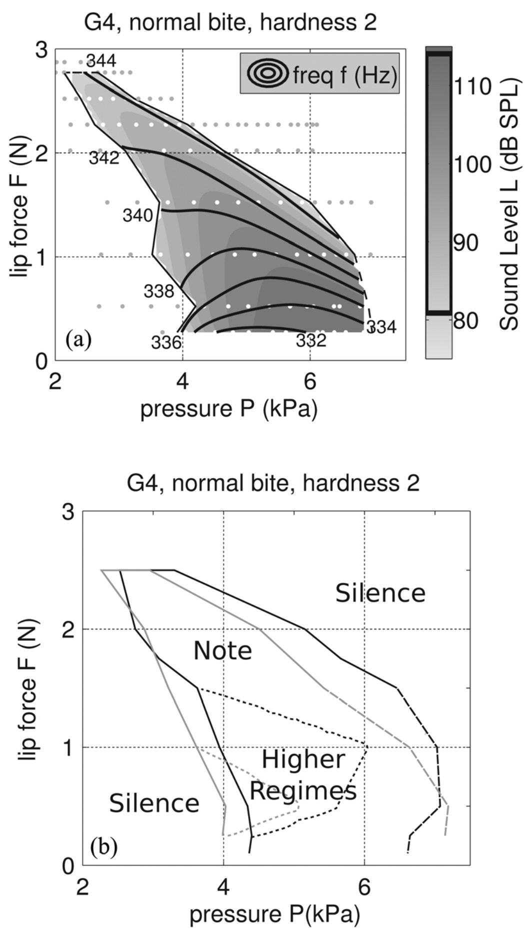

FIG. 4. (a) (top) is a frequency contour plot of the note G4 played with a reed of hardness 2 and the lip force applied at the middle position. Measurement points are shown as dots. The shaded area in (a) and the bounding lines in (b) (bottom) indicate the region where the instrument plays a note. The black lines in (a) are contours of equal frequency with values in hertz. Contours of the sound level are indicated by the gray scale. (b) shows hysteresis in two consecutive experiments conducted under conditions similar to those in (a). The black lines show the playing regime for one trial played in the same conditions as (a), and the gray lines show the playing regime measured in a later experiment, using the same reed and lip force position. In both cases, solid lines demark the range over which a periodic sound was produced, while dotted lines indicate the boundary of the regions where the instrument played a frequency far from the expected (a higher regime). Outside of these two areas, no pitched sound was produced.

A. Frequency and loudness contours on the *F,P* plane

Figure 4(a) shows the playing area on the (F,P) plane. Contours of equal frequency f are indicated by lines, while the contours of sound level L are indicated by the gray scale. The sample measurements used to generate these contours are also shown as pale dots on the graph. The uncertainty in the boundaries of the playing range can be taken as half the distance between the measurement points, which differs for different values of F. The dashed line at right shows the maximum pressure achieved by the pump at that particular load. At sufficiently low pressures (below about 3–4 kPa, the value depending on F), there is no sound or squeaks. Above the extinction line, there is also no sound, this time because the reed is pushed closed against the lay by a combination of F and P. The slope of this line is negative and its magnitude is about 3 cm^2. This value, which depends on the lip position, could be interpreted as an effective area on which the pressure acts to close the reed. The relation of this area to a geometric area of the reed is complicated because the reed is most flexible at the tip, beyond the point of application of F. This effect tends to make the slope more negative.

The sound level L is greatest at the bottom right corner: When P is large and F is small. L is lowest on the low-pressure side of the playing range and not strongly dependent on F. Pitch increases with F over the whole playing range, and, at large lip force values, pitch increases with increasing mouth pressure P.

B. Repeatability tests and hysteresis

Reeds change: They become softer over time. Although the changes are slower in synthetic than in cane reeds, the long, sustained application of a lip force still caused the reed properties to vary. This is shown in Fig. 4(b). The two trials were made in similar conditions except that in the first, F was increased throughout the experiment, and in the other, it was decreased. Thirty minutes elapsed between the two, and for all measurements in the later experiment, the reed had previously been exposed to sustained forces sufficiently large to close the reed completely.

Figure 4(b) shows for an experiment conducted after that of 4(a), the regions of the (P,F) plane that produced the expected note (indicated by the label "Note") and regions that produced unexpected higher pitched sounds, including squeaks [labeled as "Higher Regimes" and not present in the experiment in Fig. 4(a)]. Outside the boundaries shown in Fig. 4, no periodic sound was produced. These regions have a qualitatively similar shape in the two experiments. However, the shapes are shifted toward lower pressures or lower force in the later experiment. Lines of equal frequency are shifted downward in the second trial by about 0.5 N (data not shown). Both of these observations are consistent with

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the reed becoming somewhat less stiff after being played for the duration of the experiment, which can be attributed to the viscoelastic time constant of about 15 min observed in synthetic materials used for reeds (Almeida *et al.*, 2007) or to plastic deformations. A repetition of the experiment 1 day later showed a further reduction in the lip force required to produce the same frequency, all else equal.

High regimes are defined as periodic sounds at pitches far above that expected for the fingering. The high regime (shown as a dashed polygon) is smaller in the second trial of Fig. 4(b) and absent in that of 4(a). In general, the squeak region appears at lower pressures and lower values of lip force, in part because larger force implies greater damping (Wilson and Beavers, 1973). The extent and shape of the high regime region is difficult to reproduce. Clarinetists would sympathize with this observation: The boundaries of this region in human playing are distressingly unpredictable. Overall, the low pressure side of the curves—the limit at which sustained notes ceased—were less reproducible than the high pressure side. (These unexpected higher pitched sounds usually had frequencies between between 1.0 and 1.2 kHz. They are useful in this experiment in that they give a lower limit to the natural frequency of the reed. However, the squeak frequency is presumably rather lower than the natural frequency of the reed because of the acoustic load of the bore and the mechanical constraint imposed by the lip, at least some of which moves with the reed).

C. Spectral centroids and sound level

In many musical instruments, increased loudness is correlated with a disproportionate increase in higher harmonics and therefore in timbral brightness. (This effect contributes to listeners' ability to tell from a recording played back at low sound level whether the original sound was loud or soft.) Larger amplitude vibrations produce higher sound levels, but they also produce more nonlinearities, which usually distort the sinusoidal vibrations and thus produce stronger higher harmonics (Benade, 1976). The spectral centroid is the weighted average frequency of a power spectrum, and it rises when the higher harmonics increase more rapidly than the low. It is strongly correlated with perceived brightness (Grey and Gordon, 1978; Schubert and Wolfe, 2006).

For these reasons, it is interesting to compare how sound level and spectral centroid depend on F and P. This is shown in Fig. 5 where the shading still represents sound level, but the solid lines now indicate contours with equal spectral centroid in hertz. This figure shows, over most of the playing area, a very strong correlation between sound level and spectral centroid, as expected.

Figure 5 suggests that the musician cannot easily use P and F to modify the timbre so as to increase the perception of loudness independently of sound level. Although not studied in the present work, an adjustment of the vocal tract may be required to provide a further enrichment of the spectrum.

D. Influence of lip position

The results shown in the previous section were all produced by a force applied at a distance of 10 mm from the reed

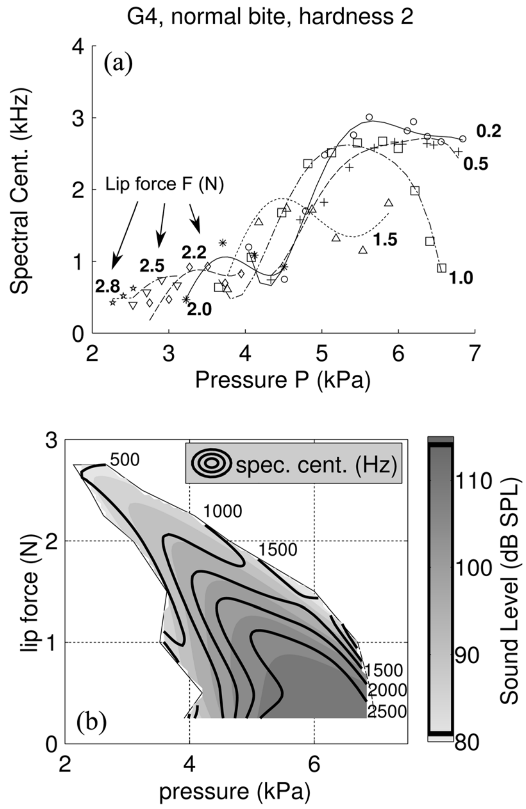

FIG. 5. Results of the experiment shown in Figs. 3 and 4, but this time plotting the spectral centroid rather than pitch as a function of pressure (a) and with contours of equal spectral centroid (b) on the pressure/force plane. The strong correlation between spectral centroid and sound level (gray scale) is evident.

tip (middle position). Some teachers recommend changing the position of the lower lip on the reed under different conditions (e.g., Brymer, 1976). Figure 6 shows measurements with a reed of the same hardness but with two different lip force positions: In Fig. 6(a), the lip force is moved 5 mm further from the tip; in Fig. 6(b), 5 mm closer to the tip, called "long bite" and "short bite," respectively, hereafter.

With the long bite embouchure, the playing regime extends to much higher lip forces, three to four times higher than in the middle position and, for this reason, a different scale is required on the F axis. This is as expected because to move the tip of the reed by a similar amount, a higher force is necessary when applied closer to the contact with the lay, where the lever arm is shorter and where the reed is thicker. Pressure and frequency ranges and trends are similar, but a wide region produces high regimes, probably because of reduced damping (Wilson and Beavers, 1973). The region where these appear (not present in Fig. 4) can be identified as the position inside the "tone region" (limited by a straight line) that is not covered by the grayscale map. Clarinetists would generally agree with the observation that it is harder to control the note produced by a given fingering when the lower lip and teeth are moved further than normal from the reed tip.

Figure 6(b) shows the opposite situation, where the lip was moved 5 mm from the middle position toward the tip so that the center of force is only about 10 mm from the tip. As expected, a lower force is required to close the reed. The

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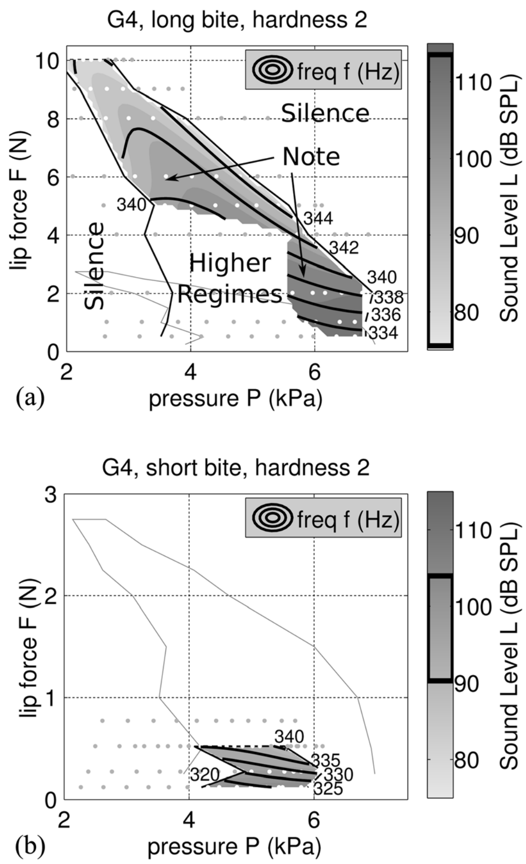

FIG. 6. Frequency contour plot for the note G4 played with a reed of hardness 2 and the lip in two different positions: (a) shows the results for the "long bite" position (point of lip force application moved further from the tip) and (b) those for the "short bite" position. The pressure axis and sound level scale are the same in both figures but because of the very different ranges of force applied, the force axis of Fig. 4(a) has been changed. For comparison, the limits of the "normal bite" [Fig. 4(a)] are shown as a dashed light gray line on both figures. Measurement points are shown as dots.

frequency ranges are considerably different as is the timbre produced by the instrument. With the short bite, the clarinet plays flatter with a dull sound, with weaker higher harmonics, and with a less stable frequency. Clarinetists rarely play with the lower teeth this close to the mouthpiece tip, in spite of the lower probability of squeaks, presumably because of the problems with pitch, timbre, and limited range of sound level.

E. Influence of reed stiffness

Lip force F and mouth pressure P are parameters that are varied by players while playing. The position at which F is applied may also be varied readily, although some clarinet teachers recommend against it. Much less rapidly, the stiffness of the reed may also be changed: The player may choose another reed with a different hardness rating or scrape the reed with a knife to change its profile. Further, reeds gradually become more compliant with use over time.

As would be expected, a stiffer reed can support higher lip forces. Further, Fig. 7 shows that a stiffer reed restricts the range of frequencies that may be played with a given fingering (without the use of vocal tract effects). Also in the examples shown in Fig. 7, squeaks are produced for

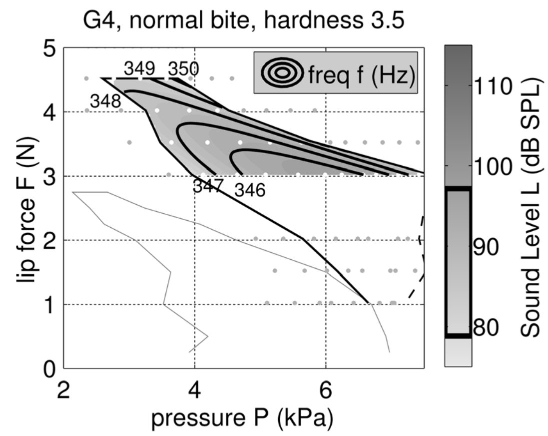

FIG. 7. Frequency contour plot for the note G4 played with a reed of hardness 3.5 and the lip in the "middle" position. For comparison, the limits for a reed of hardness 2 [from Fig. 4(a)] are shown by a dashed gray line. Measurement points are shown as dots.

moderate values of lip force, something that did not happen with the softer reed for this note. Two further adjustments available to players have effects somewhat similar to changing reed stiffness. Changing the position of the reed on the lay changes both the length of the cantilever and the thickness of the reed over the range of bending. Changing the curvature of the surface of the mouthpiece over which the reed opens (described by manufacturers as changing the opening) also changes the force required to bring the reed to a particular equilibrium position, though this is usually achieved with a new mouthpiece. Neither of these changes was studied here.

F. Comparison of different registers

The note G4 lies an octave and a minor third above the lowest note on the clarinet. It is in what clarinetists call the *throat* register and what physicists might call the first register because the fundamental frequency uses the first mode of vibration in the bore (one with no pressure node above the first of the series of open tone holes), i.e., its frequency lies near the first peak in the impedance spectrum. G4 is one of the easiest notes to obtain on a clarinet and is often the first note that a beginner plays: First, it requires no fingers because all finger holes are open and no keys are depressed. Further, it is relatively easy to sound and is less prone to squeaks or unwanted register transitions. Notes from two other registers were studied, G3 and G5. G3 is close to the lower end of the instrument's range, a minor third above the lowest note, and with only two tone holes open. A clarinetist calls this the *chalumeau* register, while a physicist might call it (also) the first register. G5, two octaves higher, plays using the second impedance peak, and uses the register key to weaken the first peak. Clarinetists call this the *clarino* register.

Figure 8 shows iso-frequency lines, sound levels, and playing regime in the (P,F) plane for the notes G3 and G5, played with the reed of "hardness" 2 (the less stiff reed) and with the lip force applied in the middle position. Comparing Fig. 8 (for G3 and G5) with Fig. 4 (for G4 using the same reed and lip position) shows that G3 plays over a narrower

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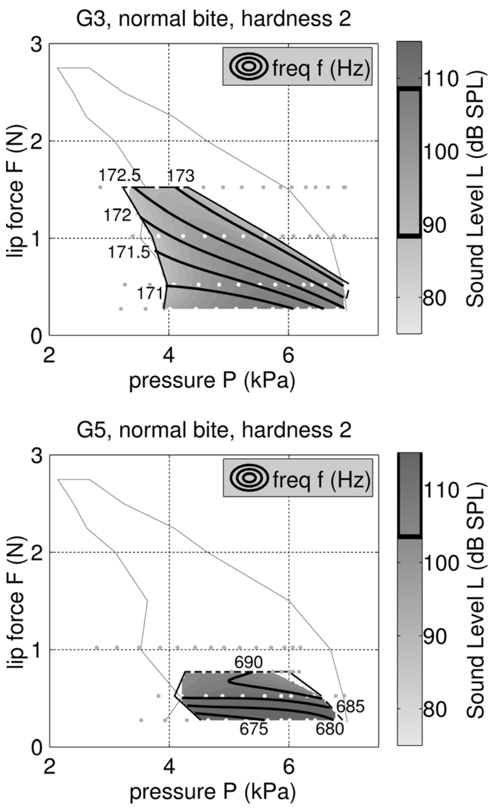

FIG. 8. Frequency contour plots for the notes G3 (top) and G5 (bottom) played with a reed of hardness 2 and the lip force applied in the "middle" position. To compare these with Fig. 4, which shows the note G4 for similar conditions, the outline of the playing regime from Fig. 4(a) is shown as a light gray line. Measurement points are shown as dots.

and lower range of lip forces than does G4. G5 also has an even smaller and lower range of F: For this note, squeaks were often produced with high lip forces. Both observations are consistent with the player judgment that G4 is an easier note. However, we have no certain explanation for the lower limit of F.

IV. GENERAL DISCUSSION

In all registers and embouchure configurations, and for the usual range of playing with relatively high F, lines of equal pitch usually have negative slope on the (P,F) plane. This is qualitatively consistent with the simple behavior discussed in the preceding text in which increasing either P or F reduces the effective compliance of the reed (and the compliance of the air in the mouthpiece) and thus raises the frequency of the parallel combination of bore and reed impedance (Nederveen, 1998).

Comparison with published theoretical models is not simple. Dalmont *et al.*, (2005) use a simple model for the clarinet playing regime called the Helmholtz model in which the instrument moves discontinuously between two states, rather like the stick-slip of the Helmholtz model of motion of a bowed string. This model assumes a reed of negligible mass and a perfectly cylindrical bore (i.e., no bell, no tone holes). A key parameter in this model is the losses. The acoustic losses in the bore are in principle available from measured impedance spectra. However, the peaks in these spectra are very sharp, so values are sensitive to small changes in frequency and thus to the parameters that produce changes in f.

Dalmont and Frappé (2007) plot the air flow U flowing past a clarinet reed into a bore with damped resonances as a function of the pressure difference between mouth and mouthpiece. On this plot, negative slope means negative acoustic resistance. Consequently, regions of sufficiently negative slope are capable of producing regeneration, so the peak of a curve for a given F gives the threshold, and locus of those peaks as F is varied gives the $F(P)$ threshold. In that study, the range of P and F are fairly close to that shown in Fig. 4 here, and the threshold line has a negative slope of a few tens of square centimeters as does the present study. The region of negative $U(P)$ slope in that study is somewhat larger than the playing regime reported here, possibly because of losses in the reed as a generator.

A difference between the present results and those of Dalmont and Frappé (2007) is the low pressure limit of the playing regime. The present results show a lower limit that decreases from almost 4 down to 2 kPa as the lip force is increased (and thus the reed opening decreases). Dalmont and Frappé found a lower limit of approximately 3 kPa that decreased only slightly with increasing lip force and state "Theory expects a slight decrease of the oscillation thresholds when the reed opening decreases which is not observed in the experiments." So the theory seems to fall between the two experiments. The difference between the experiments might involve the differences between the two lips: A water-filled latex tube in the former study and a sorbothane pad here. It might also be related to the shape of mouthpiece lay because this can strongly affect how the effective stiffness of the reed varies with increasing lip force.

V. IMPLICATIONS FOR PERFORMANCE

In all combinations of frequency, lip position, and reed, the highest sound levels (and the highest spectral centroids) are produced with high mouth pressure and low lip force for the reasons discussed in the preceding text. Low lip force is also usually the region where the playing frequency is most flattened, consistent with the observation, common among clarinet pedagogues, that the pitch tends to be lower at higher loudness levels (Rehfeldt, 1977; Gingras, 2004).

Over most of the range studied, and especially over the region of high pressure and high force, pitch increases with increasing pressure and with increasing lip force. Consequently, the slopes of lines of equal f on the (P,F) plane are negative. (The magnitude of the slope is comparable with that of the extinction line—a few square centimeters.) For constant lip force in the low force range and on the reed with low stiffness, frequency first decreases when the mouth pressure is increased, then increases until the extinction (Figs. 3 and 4). In the remaining measurements reported in the preceding text, however, the first effect of frequency decreasing with pressure is not observed, either because the oscillation threshold has high P or sometimes because squeaks hide this part of the tone region. Players tend to avoid very low F because of its low pitch and danger of squeaks, so this non-monotonic variation of pitch with increasing pressure might not often be noticed. Further, it

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is likely that players adjust several parameters simultaneously when playing, rather than just one, as the machine did in this experiment.

At low pressure, the sound level L increases with increasing pressure across the left hand side of the tone region. At pressures approaching the extinction line, the sound level usually decreases with increasing pressure. Thus at low to moderate pressures, the player can play a crescendo at constant pitch (increasing L at constant f) by increasing P and simultaneously lowering F, so as to follow one of the contour lines of equal f. On the high pressure side of the playing area, however, lines of equal f and of equal L are often nearly parallel. In this range, where the sound level is already moderately high, further increase in sound level requires either playing flat (i.e., lowering F more rapidly than a line of equal f) or adjusting a third control parameter, such as modifying a resonance of the vocal tract (Chen *et al.*, 2009).

In most cases, the tone region is limited by two lines. The extinction line is on the top right, where the reed is closed by either pressure or force. This has a negative slope of typically 3 cm^2. The threshold line, which bounds the playing region on the left, is steeper: The threshold pressure decreases more rapidly with increasing lip force.

The range of (P,F) that produces a periodic sound for the G4 fingering is larger than those for the higher and low notes. For G4, however, much of that range is at a fundamental frequency lower than the value (about 343 Hz) expected for this playing temperature: The low F part of the playing regime plays flat. There is the further complication, discussed in the preceding text, of compensating P and F to allow variations in loudness at constant pitch. That good players can play expressively and in tune, with a large range of sound level over a large range of notes, is testimony to their skill in reliably controlling a range of parameters, including those studied here.

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Almeida, A., Lemare, J., Sheahan, M., Judge, J., Auvray, R., Dang, K. S., John, S., Geoffoy, J., Katupitiya, J., Santus, P., Skougarevsky, A., Smith, J., and Wolfe, J. (**2010**). "Clarinet parameter cartography: Automatic mapping of the sound produced as a function of blowing pressure and reed force," in *International Symposium on Music Acoustics*, edited by J. Smith (Curran Assoc., New York), pp. 201–206.

Almeida, A., Vergez, C., and Caussé, R. (**2007**). "Experimental investigation of reed instrument functioning through image analysis of reed opening," Acta Acust. Acust. **93**(4), 645–658.

Bak, N., and Domler, P. (**1987**). "The relation between blowing pressure and blowing frequency in clarinet playing," Acustica **63**, 238–241.

Benade, A. H. (**1976**). *Fundamentals of Musical Acoustics* (Oxford University Press, New York) p. 442.

Benade, A. H. (**1985**). "Air column, reed, and player's windway interaction in musical instruments," in *Vocal Fold Physiology, Biomechanics, Acoustics, and Phonatory Control*, edited by I. R. Titze and R. C. Scherer (Denver Center for the Performing Arts, Denver, CO), Chap. 35, pp. 425–452.

Brymer, J. (**1976**). *Clarinet* (Macmillan, New York), p. 125.

Chen, J. M., Smith, J., and Wolfe, J. (**2009**). "Pitch bending and *glissandi* on the clarinet: Roles of the vocal tract and partial tone hole closure," J. Acoust. Soc. Am. **126**, 1511–1520.

Chen, J. M., Smith, J., and Wolfe, J. (**2011**). "Saxophonists tune vocal tract resonances in advanced performance techniques," J. Acoust. Soc. Am. **129**, 415–426.

Dalmont, J.-P., and Frappé, C. (**2007**). "Oscillation and extinction thresholds of the clarinet: Comparison of analytical results and experiments," J. Acoust. Soc. Am. **122**, 1173–1179.

Dalmont, J. P., Gilbert, J., Kergomard, J., and Ollivier, S. (**2005**). "An analytical prediction of the oscillation and extinction thresholds of a clarinet," J. Acoust. Soc. Am. **118**, 3294–3305.

Dalmont, J. P., Gilbert, J., and Ollivier, S. (**2003**). "Nonlinear characteristics of single-reed instruments: Quasistatic volume flow and reed opening measurements," J. Acoust. Soc. Am. **114**, 2253–2262.

Dickens, P., France, R., Smith, J., and Wolfe, J. (**2007**). "Clarinet acoustics: Introducing a compendium of impedance and sound spectra," Acoust. Austr. **53**, 17–24.

Ganzengel, B., Guimezanes, T., Dalmont, J. P., Doc, J. B., Fagart, S., and Léveillé, Y. (**2007**). "Experimental investigation of the influence of the mechanical characteristics of the lip on the vibrations of the single reed," in *International Symposium on Music Acoustics*, Barcelona, Spain.

Gilbert, J., Kergomard, J., and Ngoya, E. (**1989**). "Calculation of the steady-state oscillations of a clarinet using the harmonic balance technique," J. Acoust. Soc. Am. **86**, 35–41.

Gingras, M. (**2004**). *Clarinet Secrets: 52 Performance Strategies for the Advanced Clarinetist* (Scarecrow, Lanham, MD), p. 30.

Grey, J. M., and Gordon, J. W. (**1978**). "Perceptual effects of spectral modifications on musical timbres," J. Acoust. Soc. Am. **63**, 1493–1500.

Idogawa, T., Kobata, T., Komuro, K., and Iwaki, M. (**1993**). "Nonlinear vibrations in the air column of a clarinet artificially blown," J. Acoust. Soc. Am. **93**, 540–551.

Mayer, A. (**2003**). "RIAM (reed instrument artificial mouth): A computer controlled excitation device for reed instruments," in *Proceedings of the Stockholm Music Acoustics Conference*, Vol. 1, pp. 279–282.

Music Acoustics (**2008**). Information on the robot clarinet available at http://www.phys.unsw.edu.au/jw/clarinetrobot.html (Last viewed 6/21/2013).

Nederveen, C. J. (**1998**). *Acoustical Aspects of Woodwind Instruments* (Northern Illinois University Press, DeKalb, IL), p. 35.

Pay, A. (**1995**). "The mechanics of playing the clarinet," in *The Cambridge Companion to the Clarinet*, edited by C. Lawson (Cambridge University Press, London), pp. 117–118.

Rehfeldt, P. (**1977**). *New Directions for Clarinet* (University of California Press, Berkeley, CA), pp. 2, 58.

Schubert, E., and Wolfe, J. (**2006**). "Does timbral brightness scale with frequency and spectral centroid?" Acustica **92**, 820–825.

Thurston, F. (**1977**). *Clarinet Technique* (Oxford University Press, London), p. 4.

Wilson, T. A., and Beavers, G. S. (**1973**). "Operating modes of the clarinet," J. Acoust. Soc. Am. **56**, 653–658.

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