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Spectral composition of the attack portion of a recorder tone: How the player can affect the tone color

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ABSTRACT

We have used Navier-Stokes-based simulations to study the spectral content of tones produced by a soprano recorder. Our focus is on the attack portion of a recorder tone and how it can be influenced and controlled by the player. We show that both the blowing speed and the time taken to initiate blowing can be used to control the amplitudes and time variations of the upper partials during the attack. Our simulations are consistent with previous experimental results reported in the literature for flue instruments and with a new analysis of tones produced by a soprano recorder. The results illustrate how a player can control the expressiveness of a recorder tone.

Keywords: Musical instruments, recorder, Navier-Stokes

1. INTRODUCTION

Physical modeling has yielded important insights into tone production by a wide variety of musical instruments. Wind instruments have been especially challenging for such studies, since the fundamental equations of fluid mechanics, the Navier-Stokes (NS) equations, are a complicated set of nonlinear equations that require a computational approach when applied to a realistic instrument. Even so, available computer resources now make it possible to study a variety instruments using the NS equations. During the course of such simulations we have observed interesting that interesting spectral content is predicted during the attack phase of tones produced by flue instruments. This behavior was first noted some time ago in NS simulations in (1); in this paper we report further studies which give some qualitative insights into the behavior and also show that similar spectra features are found in simple tones produced by a recorder played by a beginner (i.e., one of the authors). It is also worth noting that unknown to the authors at the time of reference (1), the same basic behavior has been reported in a number of previous studies of flue instrument tones.

2. Modeling Details

We use an explicit finite-difference-time-domain algorithm to numerically solve the compressible 3D Navier-Stokes equations for a soprano recorder. Simulation details are described elsewhere (1). The numerical model had dimensions similar to the Yamaha YRS23 soprano recorder, with a chamfer on the lower edge of the windway (Fig. 1) and an inner diameter that tapered as one moves from the labium to the open end. The simulations positioned the instrument inside a closed "box" (which could be visualized as a very small room) with walls that reflect and damp sound produced by the instrument. The calculations yielded the air density and velocity inside and outside the recorder. Variations in the density are proportional to the variations of the pressure, and the results below shown below show the sound pressure at a location above the labium. The sound pressure beyond and off the axis of the open end exhibited similar behavior. In previous work we have verified [1] that the absolute magnitude of the sound pressure *inside* the instrument was approximately 130 dB, which is comparable to that found in real instruments. The calculated value of the sound pressure outside the recorder and about 10 cm distant and off axis from the open end was smaller by typically two orders of magnitude.

All of the results in this paper were obtained with the tone holes in Fig. 1 all closed so that the

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instrument produced its lowest note. For the soprano recorder this is C5, which has a fundamental frequency of approximately 525 Hz. These tones also contained components (higher partials) at frequencies that are approximately integer multiples of the fundamental frequency.

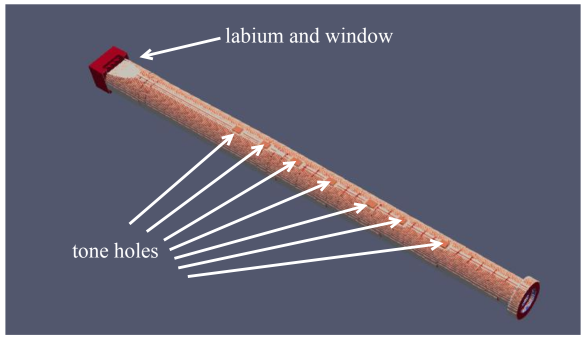

Figure 1. Model of the recorder studied in the simulations. The distance from the exit of the channel the labium was 4.0 mm, and from the end of the channel to the end of the resonator was 28 cm. The model contained tone holes that could be open or covered as if by a player. For all the results in this paper the tone holes were all closed.

3. Simulated Tones

Figure 2a shows the sound pressure outside the instrument for the note C5 when the recorder plays at a relatively low volume. Specifically blowing was initiated at t = 0 with the blowing speed ramped up uniformly to its final value of 10 m/s (in the windway) at t = 5 ms. This choice of ramp up time is at the low end of times reported in experiments in the literature but seems consistent with what can be achieved by human players. This blowing speed is then maintained until 250 ms at which time the blowing speed is ramped to zero and the tone dies away. From Fig. 2b it is seen that a steady state oscillation with a frequency of about 525 Hz (corresponding to the pitch of C5) is reached by about t = 60 ms and maintained thereafter. The time it takes to reach steady state is much greater than the ramp up time due to the time it takes for the sound to reach steady state inside the recorder tube and in the somewhat reverberant enclosure than surrounds the instrument.

Figure 3 shows spectra analysis of the waveform in Fig. 2. These different spectra were calculated using Fast Fourier transforms of data segments extending over about 20 ms centered at times given in the caption. The blue spectrum, calculated at 80 ms, shows the steady state behavior. This spectrum is dominated by the first partial at frequency f1 = 525 Hz, with only a very small peaks at the second partial (f2 approximately 1050 Hz) and the third partial (f3 approx. 1600 Hz). The position of the second partial is extremely weak so we have assumed its frequency is twice f1. Interestingly, the position of the third partial at the earliest time appears to be a bit higher than found at longer times; a similar shifting of the partial frequencies will be seen at other blowing pressures below.

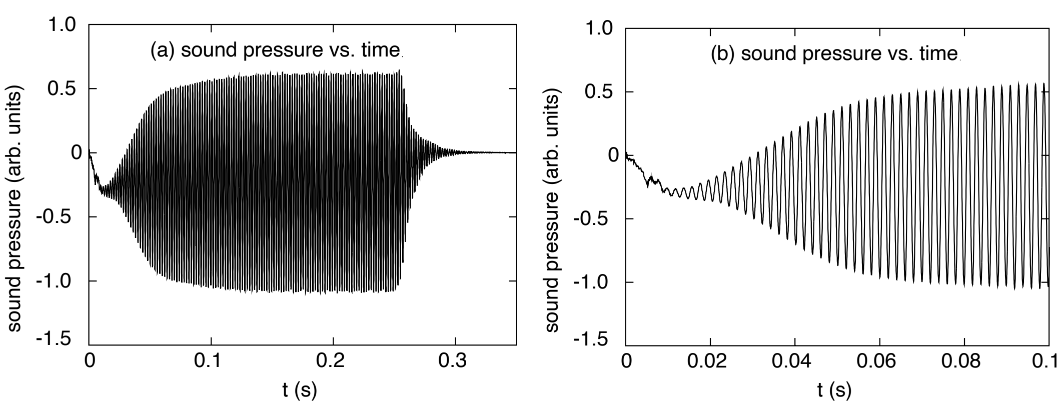

Figure 2. Simulated sound pressure versus time for the note C5 played by a soprano recorder at a blowing speed of 10 m/s and a ramp up time of 5 ms. (a) Full note. (b) Early portion of the tone.

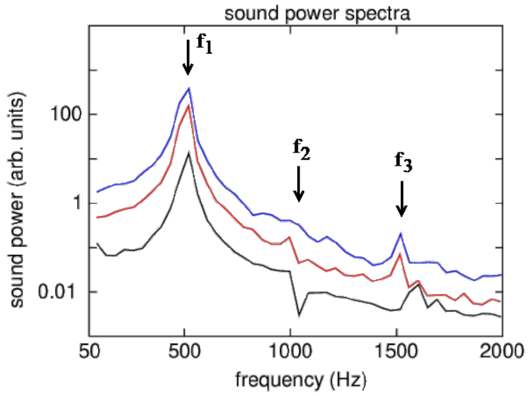

Figure 3. Spectra for the sound pressure waveform in Fig. 2 showing the approximate positions of the first, second, and third partials of the tone at different times.Black: Fourier spectrum calculated using data centered at t=20 ms using data extending approximately 10 ms before and after that time in Fig. 2b. Red: Spectrum at t=40 ms. Blue: Spectrum at t=80 ms. Note that the vertical scale is logarithmic.

Another way to view how the spectral composition of the tone in Fig. 2 varies during the course of the tone is to plot the peak powers of the different partials as functions of time; see Fig. 4. The first partial dominates during the entire course of the tone, with the power at the second and third partials being typically three orders of magnitude smaller at all times. In other words, the amplitudes of the partials are typically smaller by a factor of at least 30. This tone, produced at a low blowing pressure, is thus very close to being a pure tone.

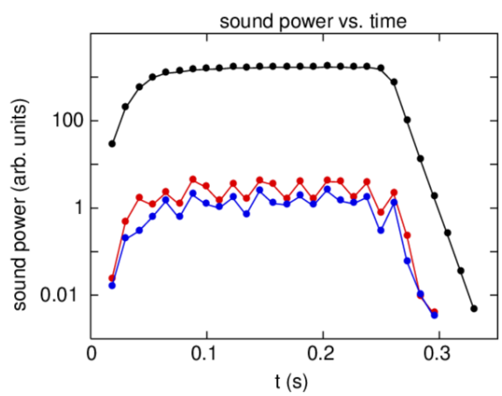

Figure 4. Power at the peaks of the first, second, and third partials in Fig. 3 as a function of time during the full course of the tone. Black: First partial. Red: Second partial. Blue: Third partial.

The spectral properties of the simulated tones change as the recorder is blown harder. Figure 5 shows results for the early part of a tone produced with a steady state blowing speed of 12 m/s. The *only* difference between this tone and the one in Fig. 2 is that the steady state blowing speed was increased from 10 to 12 m/s. There is now a region between about 30 and 60 ms in which there seems to be a new spectral component (in addition to the first partial near 525 Hz). Figure 3 shows spectra analysis of the waveform in Fig. 2. These different spectra were calculated using Fast Fourier transforms of data segments extending over about 20 ms centered at times given in the caption. The orange spectrum, calculated at 100 ms, shows the steady state behavior. This spectrum is dominated by the first partial at frequency f1 = 525 Hz, with only a very small peaks at the second partial (f2 approximately 1050 Hz) and the third partial (f3 approx. 1600 Hz). At early times, especially at 30, 40 and 60 ms, the third partial is quite significant. Also apparent at early times are substantial components around 800 and 1300 Hz; these frequencies do not appear to be related to the base (f1) component of the tone and we refer to them as inharmonic partials. We will consider their origin below.

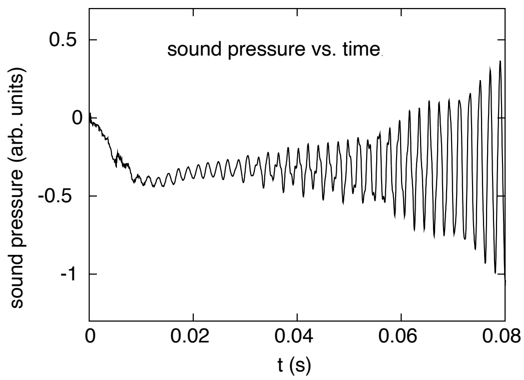

Figure 5. Simulated sound pressure versus time during the initial (attack) portion of the tone for the note C5 played by a soprano recorder with a blowing speed of 12 m/s and a ramp up time of 5 ms.

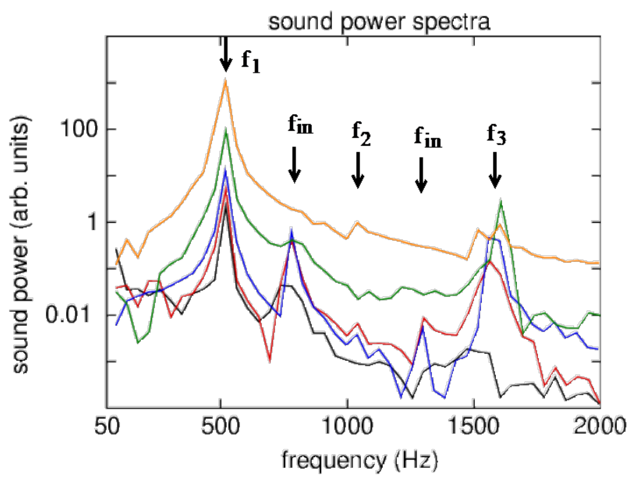

Figure 6. Spectra for the sound pressure waveform in Fig. 5 showing the approximate positions of the first, second, and third partials of the tone at different times. Also indicated are spectral components referred to as inharmonic partials in the text. Black: Fourier spectrum calculated using data centered at t=20 ms using data extending approximately 10 ms before and after that time in Fig. 5b. Red: Spectrum at t=30 ms. Blue: Spectrum at t=40 ms. Green: Spectrum at t=60 ms; Orange: Spectrum at 100 ms.

Figure 7 shows how the power at the different partials vary with time for the tone produced by blowing at 12 m/s. While the first partial again dominates throughout the tone, at early times (before about 30 ms) the third and inharmonic partials are about an order of magnitude weaker than the first partial, corresponding to an amplitude smaller by about a factor of 3-5. This is consistent with what is seen by eye in the waveform in Fig. 5.

We next consider a simulated tone produced by blowing at the even larger blowing speed of 15 m/s. Again, all the other conditions and parameters are the same as for the two tones considered earlier. The resulting waveform at the first part of this new tone is shown in Fig. 8. While the behavior at long times is again nicely periodic with the expected frequency (525 Hz) a range of times during which other spectral components are important is again seen. In addition, the time required to reach steady state is significantly longer than found at a blowing speed of 12 m/s, which was itself longer than found at 10 m/s. The length and spectral nature of the attack portion of the tone thus vary systematically as the blowing speed is increased.

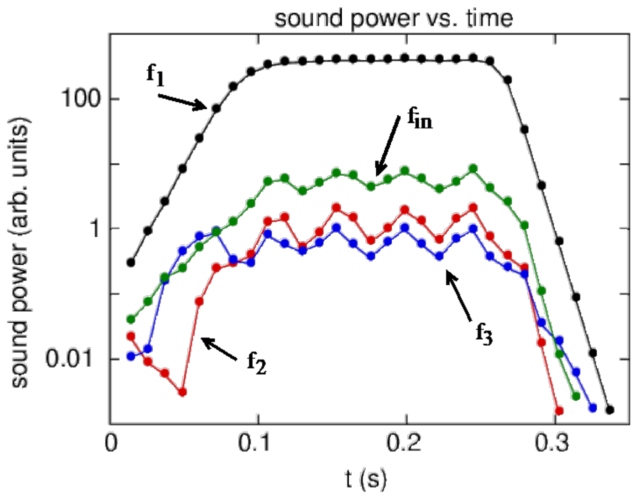

Figure 7. Power at the peaks of the first, second, and third partials (labeled as f1, f2, and f3), and the inharmonic partial near 800 Hz (fin) in Fig. 6 as functions of time.

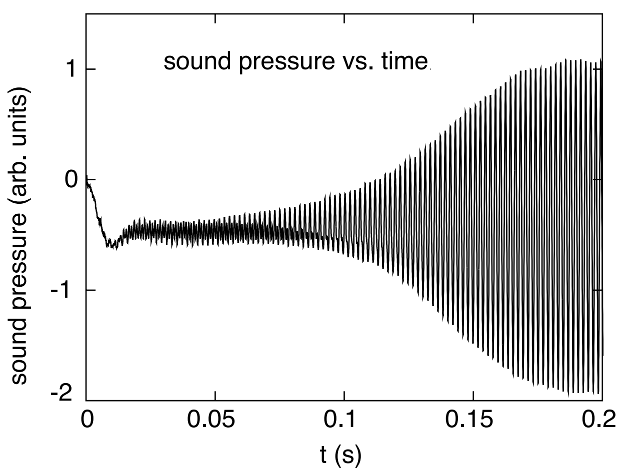

Figure 8. Simulated sound pressure versus time during the initial (attack) portion of the tone for the note C5 played by a soprano recorder with a blowing speed of 15 m/s and a ramp up time of 5 ms.

Spectra at several times during the course of this tone are shown in Fig. 9. The first partial is seen to increase with time, while the second partial initially increases and then decreases as the steady state is reached. The third partial behaves in an opposite manner, being small initially and then increasing at long times. In addition, the second partial seems to be somewhat smaller than 2xf1 at early times and then shifts to a slightly higher frequency at longer times. The uncertainties for the third partial are greater, but it too seems to shift some as time progresses.

The behavior of the different partials is shown in Fig. 10 and we see that the second partial now dominates until abut 80 ms before becoming smaller than the third partial after about 160 ms. The spectral composition of the tone is thus complex and varies substantially during the course of this tone, which a listener would presumably still recognize as C5.

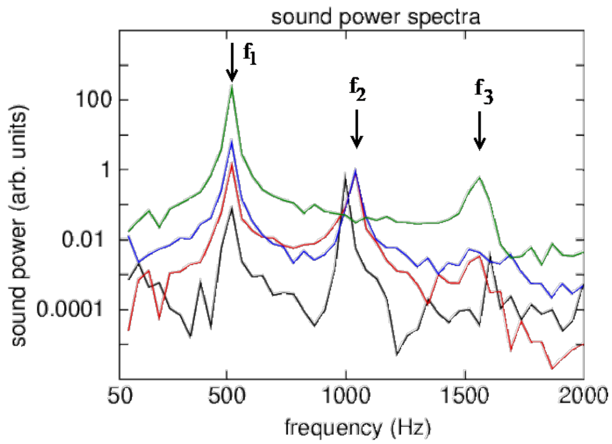

Figure 9. Spectra for the sound pressure waveform in Fig. 5 showing the approximate positions of the first, second, and third partials of the tone with blowing speed 15 m/s at different times. Black: Fourier spectrum calculated using data centered at t=30 ms using data extending approximately 10 ms before and after that time in Fig. 5b. Red: Spectrum at t=80 ms. Blue: Spectrum at t=100 ms. Green: Spectrum at t=200 ms.

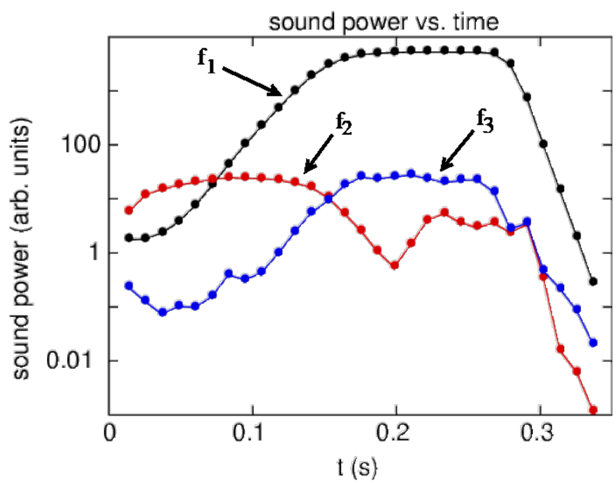

Figure 10. Power at the peaks of the first, second, and third partials in Fig. 9 as a function of time during the full course of the tone. Black: First partial. Red: Second partial. Blue: Third partial.

The results in Figs. 2-10 show that our simulations predict a systematic variation of the tone color as the recorder is blown harder, with an essentially pure tone at low blowing speeds to a tone in which the attack is dominated by the second partial. We should note that these tones are all in the blowing range in which C5 is produced; the regime change transition to C6 occurs at a higher blowing speed near 18 m/s. That transition and a fuller discussion of these tones will be discussed in a future paper.

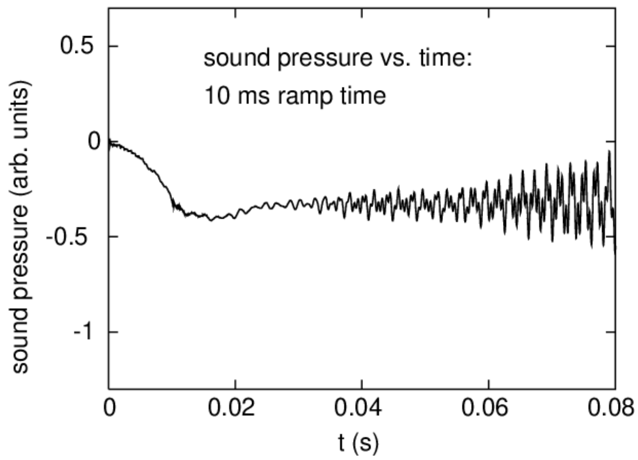

Figure 10. Simulated sound pressure versus time during the initial (attack) portion of the tone for the note C5 with a blowing speed of 12 m/s and a ramp up time of 10 ms.

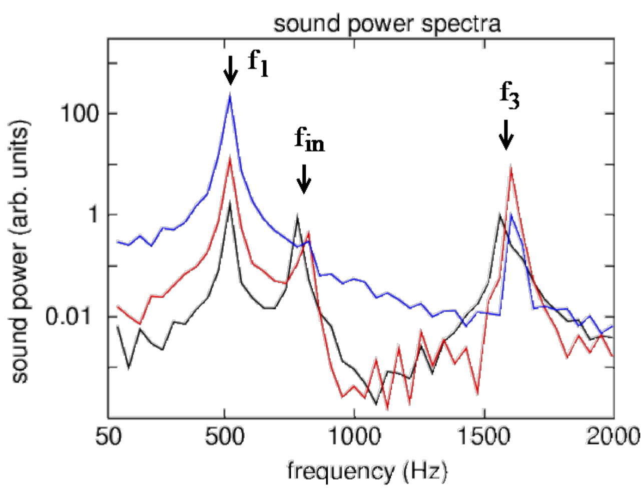

Figure 12. Spectra for the sound pressure waveform in Fig. 11 showing the approximate positions of the first (f1), third (f3), and inharmonic (fin) partials of the tone with blowing speed 12 m/s and ramp up time 10 ms, at different times during the tone (Fig. 11). Black: Fourier spectrum calculated using data centered at t=50 ms using data extending approximately 10 ms before and after that time in Fig. 11. Red: Spectrum at t=70 ms. Blue: Spectrum at t=100 ms.

4. EXPERIMENTAL OBSERVATIONS

Tones produced by flue instruments – organ pipes, recorders, and flutes – have been studied for many years by many researchers. The phenomena of interest to us in this paper have been observed previously (see for example Refs. [2-7], which consider both organ pipes and recorders), but to the best of our knowledge have not been analyzed in quite the ways or in the kind of detail for a particular instrument as required for comparison with the modeling work presented earlier in this paper. We therefore next present an analysis of a single tone produced by a real soprano recorder and analyze that tone in the same way as we have analyzed the simulated tones discussed earlier. The recorder is a Yamaha model YRS25 (a student quality instrument composed of plastic), and we consider the lowest note produced by this instrument with all tone holes closed, C5, the same tone as considered in our simulations.

Figure 11 show the waveform for a typical C5 tone produced by the YRS25 blown by one of the authors; (a) shows the entire tone while (b) shows the initial, attack portion in more detail. An attempt was made to ramp the blowing speed smoothly to a final value that was then maintained until the end of the tone. The periodicity achieved around 0.08 ms continued until the tone finished.

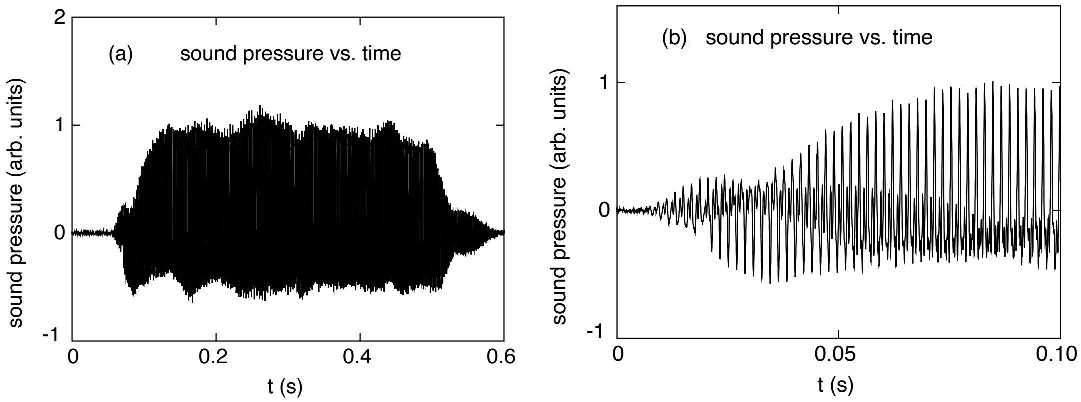

Figure 11. Sound pressure versus time waveform for the note C5 produced by a soprano recorder as played by one of the authors. (a) Full note. (b) Attack portion of the tone. Note that t=0 in (b) has been shifted to be nearer to the start of the tone.

An interesting feature seen in Fig. 12 is the way the frequencies of the second and third partials vary small but significant amounts during the course of the tone. We believe that these frequency shifts are real, and note that they resemble similar shifts seen in the simulations.

Figure 13 shows how the power in each partial varies with time. It is notable that the second partial is as large or nearly as large as the first partial until about 80 ms, while the first partial dominates by about an order of magnitude or more at longer times. This again is similar to the behavior of the simulated tones at the larger blowing speeds.

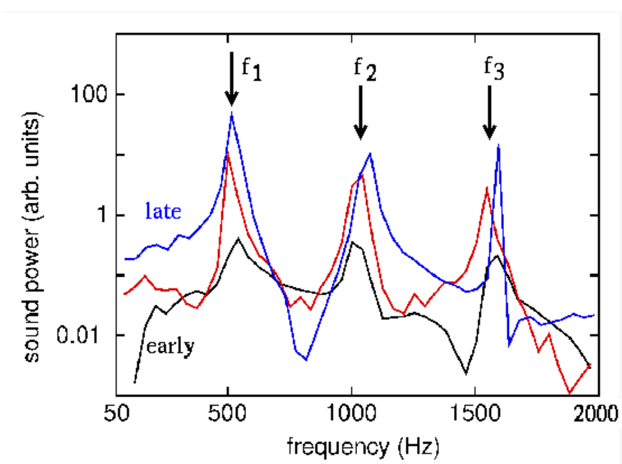

Figure 12. Spectra showing the first, second, and third partials of the tone during different portions of the attack. Black: Fourier spectrum calculated using data centered at t=10 ms in Fig. 1b. Red: Spectrum calculated at t=30 ms. Blue: Spectrum calculated at t=100 ms. The approximate positions of the first (f1), second (f2), and third (f3) partials are indicated.

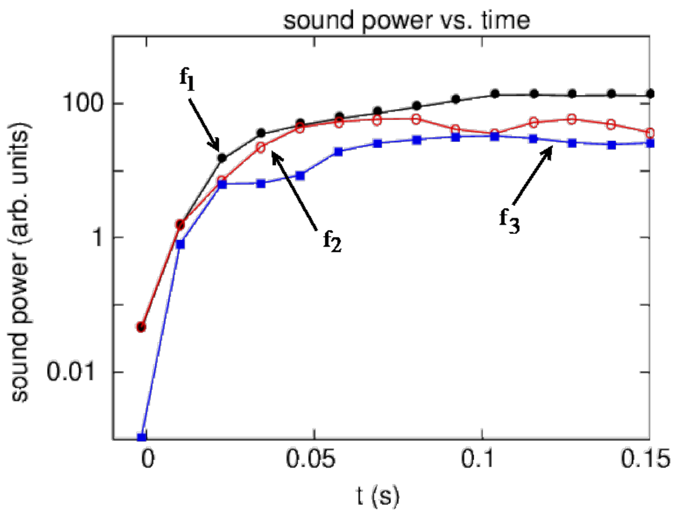

Figure 13. Power of the first, second, and third partials of the tone as functions of time during the full course of the tone. Black: First partial. Red: Second partial. Blue: Third partial.

It is seen that the second partial is essentially equal in power to the first partial for the first 50 ms of the tone with the first partial then dominating at longer times. It is well known (see for example [8-10]) that a human listener is able to perceive pitch and timbre during portions of a tone as short as 20 ms, so the change in timbre evidenced in Fig. 13 is certainly perceptible.

One other feature of Fig. 12 is also worth noting. The frequencies of the different partials appear to also vary some with time. This is most noticeable with the second partial which moves to higher frequency at long times, while the frequency of the third partial seems to fall and then increase during the course of the tone.

5. CONCLUSIONS

In a broad sense, the simulation results are quite similar to that found in the real tone considered in Figs. 11-13. During the attack the higher partials are as large or larger than the first partial, thus contributing very significantly to the timbre. It is well known (see for example [8-10]) that a human listener is able to perceive pitch and timbre during portions of a tone as short as 20 ms, so the changes in timbre we have observed are certainly perceptible. For the real tone it is the second partial that competes for early dominance while for the simulated tone it is the third partial. This difference is certainly significant, but here we have considered simulation results for only one note at one blowing speed and with one ramp up time. Other simulations, which will be reported in the future, show that the behavior during the attack phase depends on those parameters. Our simulations have also found that the behavior can depend on the specific instrument geometry, so while the simulation model in Fig. 1 is intended to resemble the Yamaha soprano recorder, the effect of remaining differences between the geometry of the actual instrument and the model still need to be explored and understood.

Our results also clearly show the effect of the player. The recorder is often the first instrument taught to a young student, presumably because it is easy for a beginner to produce a nice tone, in contrast to many other instruments, such as the violin. However, as with other instruments, it is important for the player to have *some* ability to affect the timbre. For the case of the recorder, simulations like those presented in this paper show that the blowing speed and the ramp up time can both profoundly affect the timbre, especially during the attack portion of the tone.

As a general result, our results suggest that Navier-Stokes-based simulations can be used study rather detailed aspects of flue instruments, and address subtle but important questions concerning the tones produced by real instruments. We plan to report more extensive results of this kind in the future.

ACKNOWLEDGEMENTS

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