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# Differences and similarities in the production mechanism of reeds, brass, and voice: the source-filter viewpoint

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## ABSTRACT

The acoustic sound production mechanisms of reed instruments, brass instruments as well as of the human voice (singing and speech) are already well investigated. In this paper these mechanisms will be compared from three viewpoints: (i) sound source (reeds, lips, vocal folds), (ii) filter, i.e., sound transmission and sound radiation via tube or pipe and (iii) interaction mechanisms between source and filter. Interaction can be divided in aerodynamic-acoustical interaction and aerodynamic-mechanical interaction. It is known that the aerodynamic-mechanical interaction decreases from reeds via brass to voice. In this study the influence of this interaction on pitch is investigated for reeds, brass and voice by using a computer model for sound production. Simulations using this model underline the influence of the filter on pitch in reeds and brass while pitch in speech and singing is mainly controlled by source parameters like vocal fold tension.

**Keywords:** Sound production, voice, music instruments, reeds, brass

## 1. INTRODUCTION

While source models for reed and brass instruments are limited, a well-known source model exists for speech and singing. This model is a self-oscillating two-mass model of the vocal folds introduced by Ishizaka & Flanagan (1) and refined by Pelorson et al. (2) and others later. This simulation model constitutes a good compromise between computational efficiency and approximation of the mechanical and dynamical properties of the vocal folds. The mechanic-dynamical part includes two coupled damped spring-mass pairs simulating the lower part (also: inner part: vocalis muscle) and the upper part (also: outer part: mucosa) of the vocal folds. The aerodynamic effects taking place within the region of the glottal narrowing are (i) the Bernoulli pressure drop, (ii) viscous losses due to air flow and wall interactions, (iii) the inertia of the mass of the tracheal-glottal-pharyngeal air column and (iv) turbulent dissipation of kinetic energy occurring in the jet flow at glottal outlet (2). The detailed modeling of these aerodynamic effects is important in order to get the correct external driving forces acting on the surface of the masses of the two-mass model and in order to calculate a correct glottal flow.

The excitation source of a reed instrument, here of a clarinet, can be modelled using a distributed one-dimensional model or a lumped one-mass model approximation of the mechanic-dynamical system representing the lips-reed system of player and instrument. Pressure difference and the resulting airflow occurring between the oral cavity of the player and the mouth piece chamber of the instrument are calculated by taking into account here the Bernoulli pressure and viscous losses (3, 4, 5).

In case of the excitation source of a brass instrument, here of a trumpet, the vibrating lips can be modelled using a one-mass model with one or two degrees of freedom concerning movement direction (6, 7). Two dimensions for lip movement are necessary because the lips move up and down in order to regulate lip aperture (closing and opening) but the front part of the lips as well moves in front-back direction, i.e. inside-outside direction relative to mouthpiece (7).

For the simulation of the aerodynamic and acoustic characteristics of the vocal tract as well as of the bore or tube of a reed or brass instrument, a reflection type line analog or transmission line model can be used (for a vocal tract model, see (8); for a clarinet model, see (9)). In the case of the filter, mainly the radiation losses at the end of the bore or tube (i.e., mouth or bell) as well as the loss due to the backward traveling air flow into the source (glottis or mouthpiece) needs to be calculated. In addition it is useful to include wall vibration losses (shunt losses) in order to allow oral closures in case of speech and singing or in order to allow a correct modeling of losses in case of long and small bores like in the case of brass and reed instruments. An alternative for a pure simulation of the acoustics of the bore or tube, i.e., of the filter, is the calculation of its input impedance (see e.g. 10).

Source-filter interaction – i.e. interaction between sound source (vibrating system which produces the initial air pulses) and the tube (vocal tract tube or instrument bore or tube in which the air pulse is propagated) – can be separated into aerodynamic-mechanical and aerodynamic-acoustical interaction. These interactions are investigated already in detail for speech and singing. Aerodynamic-acoustic interaction influences the glottal flow shape (11, 12). Aerodynamic-mechanical interaction is stronger than aerodynamic- acoustical interaction and leads to changes in vocal fold vibration (13). This can be an alteration of fundamental frequency or a strengthening or weakening of glottal vibration. A strengthening occurs in cases where F0 remains below the frequency of the first (or a higher) resonance of the filter. A weakening occurs if pitch of the source and the frequency of a resonance of the filter are at about the same value (i.e., in the case of a strong resonance coupling of source and filter) or if the vocal tract is closed in case of speech and singing and thus airflow is massively obstructed.

In this paper simulations are executed which support the idea that the aerodynamic-acoustical source-filter interaction is much stronger in case of reeds than in case of singing, while brass instruments are in an intermediate position. In the case of reed instruments the acoustical length of the bore or tube mainly controls pitch. In the case of speech or singing vocal folds parameters like vocal fold tension and pulmonary or subglottal pressure mainly control pitch while the vocal tract here is of nearly no influence. Thus in the case of singing the vocal tube is allowed to be modified in shape and length while pitch is not influenced. This allows the production of different vowel qualities and different sounds with constant glottal excitation. In case of music instruments the situation is different. Here the sound or timbre of a music instrument is mainly fixed by the shape of the instrument itself. The timbre or sound quality (independent of pitch) of the music instrument is one of the main perceptual factors for the identification of the instrument.

In and further experiment of this study it will be shown that brass instruments take an intermediate position concerning pitch control. While F0 is controlled here by lip tension in combination with length of tube or bore, it is known that in specific cases pitch can be controlled by lips alone. A trained trombone player is able to produce a glissando of more than one octave without changing the position of the slide, i.e. an experienced player can produce a glissando covering more than one octave without changing the length of the tube or bore of the instrument. For reed instruments this is not possible. Here pitch is governed mainly by the acoustic length of the bore and lip as well as jaw articulation lead only to small changes in pitch (cf. the complex production mechanism for the clarinet glissando in Gershwin's "Rapsody In Blue", see (14)).

## 2. METHOD: THE SIMULATION MODEL

A reflection-type line analog (8) is used here for time domain simulation of the tube aerodynamics and acoustics, i.e. for simulating the aerodynamics and acoustics within trachea, glottis, pharynx and oral cavity in case of voice, for simulating the aerodynamics and acoustics within oral cavity, tip of mouth piece, mouth piece chamber, bore and bell in case of reeds (here: clarinet) and for simulating the aerodynamics and acoustics within oral cavity, lips, mouthpiece chamber, bore and bell in case of brass (here: trumpet). In case of simulating 20000 time steps per second 22 tube sections (singing) via 68 tube sections (clarinet) up to 162 tube sections (trumpet) with constant length (l = 0.875 cm) and constant cross section area are needed in order to model a tube of 17.5 cm length for vocal tube (voice) via 59.5 cm length for clarinet (reeds) including bell to 140 cm length for trumpet (brass; Fig. 1) including flare and bell. In each case the first three sections represent the end of trachea, laryngeal constriction beginning of pharynx in case of voice, represent the end of oral cavity, tip of reed constriction and begin of mouthpiece chamber in case of reed instruments or represent the end of oral cavity, labial constriction and mouthpiece chamber in case of brass instruments (see light blue sections in Fig. 2). The further sections represent the vocal tract tube or the bore and bell of the reed or brass instrument (Fig. 1).

In case of the vocal tract the cross sectional area was set to a constant value from larynx to mouth (A = 4.9 $cm^2$; diameter d = 2.5 cm) representing vowel, i.e., a schwa sound. In case of the clarinet the bore has a diameter of approximately 2.8 cm, leading to a cross sectional area of A = 6.16 $cm^2$. The bell was modelled by increasing the cross sectional area in a nearly exponential way for the last 13 tube sections (last 11.5 cm of clarinet length) up to a maximum area of A = 38.5 $cm^2$ (d = 7.0 cm). The first cross sections representing the upper part of the mouthpiece chamber of the clarinet were set to A = 1 $cm^2$ (see Fig. 2). In the case of the vocal tract the first formant (first vocal tract tube resonance) appears at F1 = 500 Hz while the first resonance for the clarinet bore appears at about 147 Hz and that of a trumpet at about 63 Hz. While the clarinet is modeled geometrically by a cylindrical bore plus a short and small bell, the bore, flare and bell of a trumpet is more complex. Detailed data for cross sectional diameter values for a trumpet are given by Kipp (15). The diameter of the trumpet bore is very small (of about 1.2 cm) while the diameter increases up to 14 cm at the end of the bell.

Losses are modelled (i) at the first tube section as free radiation of the backward traveling partial flow wave in the trachea (for voice, see (16)) or in the mouth cavity (for reed and brass instruments), (ii) at the second tube section in order to simulate the Bernoulli pressure drop at the strongest constriction within the whole line (2) and (iii) at the last tube section in form of radiation losses due to radiation at the mouth (for voice, see (16)) or at the bell (for reed and brass instruments). Spatially distributed losses are implemented as shunt losses for simulating wall vibrations over the whole length of the bore or vocal tract (ibid.).

Concerning the vocal folds which are simulated by the two-mass model mass 1 ($m_1$) represents the lower muscular part of the vocal folds (main mass) while the smaller and lightweight mass $m_2$ represents the vocal fold tissue (mucosa) occurring at the outlet region (upper region) of the glottal narrowing. The complete dynamically coupled spring mass system is displayed as red structure in Fig. 2. Two masses are needed to model the oscillatory behavior of the vocal folds correctly, because it is an important characteristic of glottal vibration that the upper part of the vocal folds ($m_2$) opens and closes later than the lower main part of the vocal folds ($m_1$). This allows the correct modeling of aerodynamic to mechanic energy transfer: During the closure period of the upper part of the glottis the subglottal pressure acts on the main mass and causes glottal abduction in this lower region of the vocal folds. Later, the upper part of vocal folds opens, and Bernoulli under-pressure occurs as a result of the now occurring upstreaming strong air flow. This under-pressure – beside the restoring forces resulting from the mechanical part of the two mass oscillators – helps to re-adduct the vocal folds and leads to glottal closure as part of each glottal vibration cycle. Thus the two mass model is needed in order to generate a stable two phase energy transfer (positive pressure on the lower part of the vocal folds for vocal fold abduction in the opening phase of glottal cycle and later negative pressure on upper and lower part of the vocal folds for vocal fold adduction during closing phase of the glottal cycle) for stabilizing glottal vibration independent from acoustically generated over- or under-pressure occurring in pharynx right above the glottis which results from the occurring standing waves in the vocal tube.

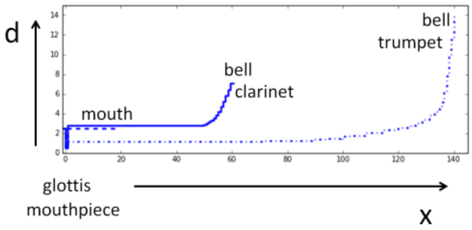


**Figure 1** – Geometrical models used for our numerical simulations for vocal tract (a "technical" schwa-vowel is articulated, dashed line), for a Bb-clarinet (all tone and register holes are closed, solid line) and for a Bb-trumpet (no valve is pressed, dash-dotted line); x-axis: length x of instrument in cm; y-axis: diameter d of bore or tube in cm.

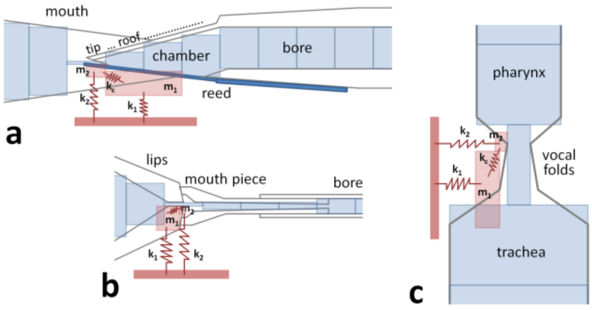


**Figure 2** – Two mass approximation of the mechanical part of the sound source (red and light red structures: springs and masses) and tube section model of the filter (light blue boxes represent sections of cavities) for clarinet (a), trumpet (b) and voice (c). The smallest tube section represents the reed tip narrowing for clarinet, the lip narrowing for trumpet and the glottis narrowing for voice.

For reeds as well as for brass, a one mass model would be sufficient as sound source (see Introduction). We approximate that one mass approach by increasing the coupling stiffness $k_c$ between $m_1$ and $m_2$ in our two mass model by a factor 1000, which leads to a relatively tight mechanic coupling between both masses. In case of clarinet $m_2$ represents the upper part of the reed (tip of the reed) in the region of the buffle and tip of the mouthpiece while the main mass $m_1$ represents the main vibrating part of the reed in the region of the mouth piece window (upper thin part of the reed; upper half length of the reed). This mass $m_1$ is mainly driven by the pressure occurring in the chamber region of the mouthpiece below the buffle (roof region) while the small mass $m_2$ is driven by the pressure occurring in the buffle and tip region of the mouthpiece.

In case of the lips as sound source of a brass instrument the main mass $m_1$ represents the main part of the lips and the small mass $m_2$ represents the front part of the lips within the mouthpiece. But because of the stiff coupling between both mass pairs the oscillation of both mass pairs is nearly identical. The driving force for the spring mass system is the oral pressure for lip opening and thus the situation for energy transfer from the aerodynamic to the mechanical system is comparable to the situation already described above for the vocal folds. But it should kept in mind that the acoustically generated over- or under-pressure occurring in the mouthpiece tube right in front of the lips which results from the occurring standing waves in the bore or tube now is higher compared with that occurring in the pharynx during phonation and thus may influence lip vibration (see below, experiment 6).

The spring mass parameters of the two mass model representing the vocal folds in case of singing, representing the lips in case of brass instruments (here: trumpet) and representing the reed plus lips in case of the reed instruments (here: clarinet) are listed in Table 1. The masses of both mass pairs are set a factor 10 lower for the reeds and set a factor 2 lower for the lips in brass mouthpieces in comparison to vocal folds. The stiffness value of the springs of both oscillators is set a factor 10 higher in case of the reed and a factor 2 in case of the lips in the brass mouthpiece in comparison to the vocal folds. This leads to a resonance frequency of 109 Hz in case of vocal folds to 218 Hz in case of the lips in the brass mouthpiece and to 1092 Hz in case of the reed if only the resonance of the main mass $m_1$ is taken in consideration, i.e., using the formula for an undamped single spring mass system:

$$f = 1/(2*\pi) * \sqrt{(k/m)} \qquad (1)$$

In case of reeds and brass the damping parameters of both oscillators are reduced by a factor 100 in comparison to vocal folds. For the reeds the stiffness parameters are increased by a factor 100 for the impact case, i.e. for the case of a correct modelling of the hard collision of reed with the mouthpiece table in comparison to the soft collision of the left with the right side of the vocal folds in case of the voice source or the soft collision of the upper with the lower lips in case of the brass source.

**Table 1** – Parameters of the spring mass system for all three cases (voice, reed instrument, brass instrument).

| | | mass [g] | stiffness [N/m] | resonance frequency [Hz] | oscillation frequency [Hz] (note) |
|---|---|---|---|---|---|
| **voice<br>(vocal folds)<br>register: bass** | **oscillator 1** | 0.170 | 80 | 109 | 109<br>(A2) |
| | **oscillator 2** | 0.030 | 8 | - | |
| | **coupling** | - | 55 | - | |
| **trumpet<br>(lips)** | **oscillator 1** | 0.085 | 160 | 218 | |
| | **oscillator 2** | 0.015 | 16 | - | |
| | **coupling** | | 55000 | - | |
| **clarinet<br>(reed+lips)** | **oscillator 1** | 0.017 | 800 | 1092 | 127<br>(B2) |
| | **oscillator 2** | 0.003 | 80 | - | |
| | **coupling** | - | 55000 | - | |

In the case of the vocal folds for singing as well as in the case of the lips for brass instruments a q-factor called vocal fold or lip tension is introduced in order to allow the parameters of the coupled spring mass system (increasing stiffness and decreasing mass, see equation 2 and 3; the index tab represents the values, listed in table 1) to change. This is needed in order to tune the vocal folds or lips with respect to a specific pitch. The introduction of the q-parameter in case of the vocal folds is described in detail in Ishizaka & Flanagan (1972) for vocal folds.

$$m = m_{tab} * (1/q) \tag{2}$$

$$k = k_{tab} * q \tag{3}$$

In this study the q-parameter is adapted for lips as well as a first approximation in order to be able to control pitch in case of brass instruments. The q-parameter was set to $q = 1$ for the reeds without any variation.

Simulations are carried out for different pulmonary pressure values (see below), different mass and stiffness values for vocal folds, lips or reed as well as for different bore or tube length in case of vocal tract, reed and brass instruments as introduced here. Six simulation experiments are executed using the parameter settings introduced above.

## 3. SIMULATION RESULTS

### 3.1 Experiment 1: *basic settings of model parameters for singing (low male voice: bass register), brass (trumpet) and reeds (clarinet)*

In this first experiment a preliminary adjustment of the parameters of the self-oscillating source model and of the reflection type line analog for the singing voice, for a Bb-trumpet (brass) and for a Bb-clarinet (reeds) is realized. The parameter settings for the self-oscillating source model, i.e. of the two-mass model, as well as for the filter, i.e. for the tube section model or reflection type line analog, are already discussed in the Method section of this paper.

In addition, the pulmonary pressure (PP) which is inserted in the trachea for singing or in the oral cavity of the player for reeds and brass, i.e. in the first tube section of the model, is set to PP = 1000 Pa for singing, to PP = 1500 Pa for brass and to PP = 2500 Pa for reeds. In case of voice and brass the q-parameter is set to $q = 0.75$ (low pitch). The q-parameter is always set to $q = 1$ for the reed.

Typical oscillation patterns of both mass pairs, of the time course of the forces acting on each mass as well as of the time course of the aerodynamic parameters glottal flow and sub- and supraglottal pressure are displayed in Figure 3. From these patterns typical differences in in aerodynamic-mechanical interaction can be unfolded which lead to the resulting differences in vocal fold oscillations. These differences are discussed in the results section.

### 3.2 Experiment 2: *constant pitch in singing despite varying tube length (low male voice)*

In this experiment the tube length is varied from 14 cm (like it occurs during production of vowel /i/ or /a/) to 24.5 cm (like it may occur in vowel /u/ for some speakers) in steps of 2*0.875 cm. The vocal folds were adjusted as defined in experiment 1 (male singer with PP = 1000 Pa and $q = 0.75$). It can be seen from Fig. 4 that the fundamental frequency F0, i.e., the pitch of the singing voice remains stable (F0 = 120 Hz), while the frequency F1, i.e., the frequency of the first resonance or first formant of the vocal tract tube decreases with increasing tube length. The interpretation is given in the discussion section.

### *3.3* Experiment 3: *variation of pitch in singing (low male voice: bass register) due to varying vocal fold tension and varying pulmonary pressure*

In this experiment vocal fold tension q is modified in combination with pulmonary pressure PP in order to demonstrate the range of pitch variation for a low male voice (bass register). In the first part of the experiment the phonation threshold pressure $PP_{threshold}$ is estimated for a wide range of vocal fold tension ($q = 0.5$ to $q = 2.5$). PP is decreased continuously until vocal fold vibration ends. The pressure at that end point is labeled as PP (see blue dotted line in Fig. 5).

In the second part of the experiment, pitch (fundamental frequency F0) as generated by the self-oscillating glottis model is measured for each q value (vocal fold tension) in combination with a co-varying pulmonary pressure PP which is set 300 Pa above the phonation threshold value (see blue dashed line in Fig. 5) in order to guarantee a stable vocal fold oscillation, i.e., a stable phonation even if vocal fold tension changes. Our model is capable to produce a pitch range of about two octaves (F0 = 80 Hz [Eb2] to F0 = 320 Hz [Eb4] (normal bass register is from F2 (87 Hz) to D4 (293 Hz); normal tenor register is from C3 (131 Hz) to G4 (392 Hz)).

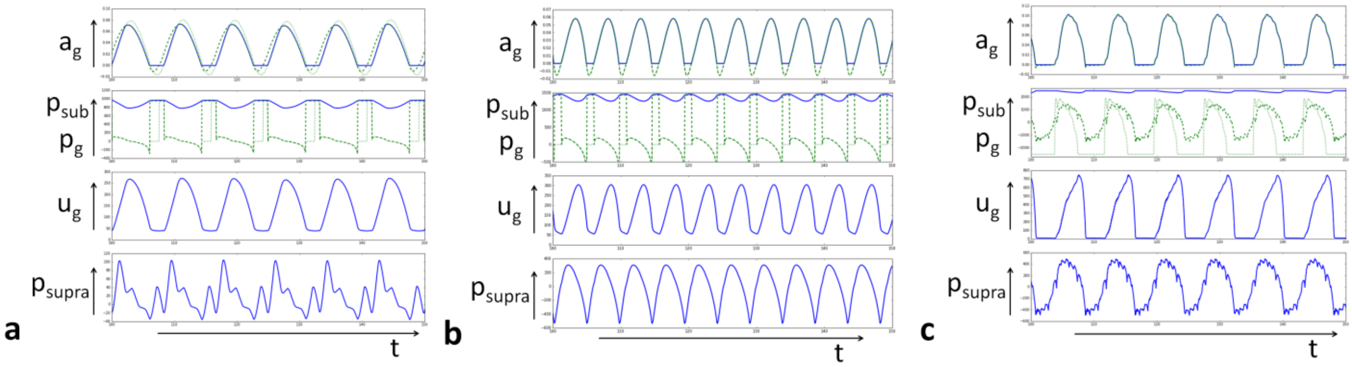
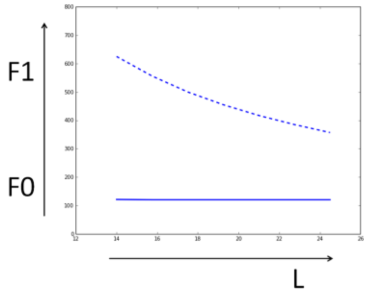


**Figure 3** – Oscillation patterns of self-oscillating source model $a_g$ (solid line, blue), $a_{g1}$ (dash-dotted line, green) and $a_{g2}$ (dotted line, green), subglottal pressure $p_{sub}$ (solid line, blue), pressure $p_g$ acting on the inner sides of both mass pairs $p_{g1}$ (dash-dotted line, green) and $p_{g2}$ (dotted line, green), glottal flow $u_g$ (solid line, blue) and pressure at glottal outlet $p_{supra}$ (solid line, blue) for singing voice (a), for trumpet (b) and for clarinet (c).



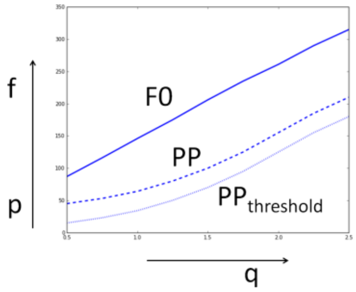


**Figure 4** – Variation of pitch (fundamental frequency F0, solid line, blue) as function of vocal tube length L for a male singer. Beside pitch the frequency F1, i.e., the frequency of the first resonance of the vocal tube is displayed as well (dashed line, blue).

**Figure 5** – Variation of pitch F0 as function of vocal fold tension q and pulmonary pressure PP for a low male singer (bass register). The co-varying pulmonary pressure PP is based on phonation threshold pressure $PP_{threshold}$.

### *3.4* Experiment 4: *pitch variation in reeds resulting from varying bore length (clarinet)*

In this experiment the bore or tube length L of the clarinet is modified (shortened) in order to mimic the opening of tone holes in order to play different tones. It can be seen that the pitch is changing together with the frequency of the first resonance of the bore and thus is changing with bore length L. The frequency F1 of the first resonance is simply calculated for quarter-length standing waves in a tube. $c_{sound}$ is propagation velocity of sound waves (about 350 m/sec):

$$F = c_{sound} / (4*L) \qquad (4)$$

This calculated resonance frequency (dashed line in Fig. 6) is higher than that of the pitch F0 resulting from the self-oscillating source model (frequency of source oscillator, solid line in Fig. 6) if tube length becomes short. That results from the fact that the influence of the bell becomes more prominent for shorter tubes. This effect is not included in equation 4 but occurs in our simulation model of the clarinet.

### *3.5* Experiment 5: *constant pitch for a reed resulting from constant bore length despite changing mass or stiffness of the reed*

In the first part of this experiment (experiment 5a) the bore or tube length is held constant (L = 59.5 cm) representing the condition that all tone and register holes are closed. But one main parameter of the source oscillator, i.e., the stiffness of the reed (stiffness of both oscillators) is varied. The stiffness of spring-mass pair 1 is changing from $k_1$ = 400 N/m to $k_1$ = 800 N/m in steps of 50 N/m and in parallel the stiffness of the second spring mass pair is changed from $k_2$ = 40 N/m to $k_2$ = 80 N/m in steps pf 5 N/m. The masses of both oscillators are held constant ($m_1$ = 0.017g, $m_2$ = 0.003 g). Results of the simulation are displayed in Fig. 7. No change of pitch F0 occurs (frequency of the source oscillator, i.e., of the two-mass model) despite a change in the oscillator dynamics reflected by the frequency of the reed resonance $F_{reed}$ which varies from 750 Hz up to 1100 Hz ($F_{reed}$ is calculated using eq. 1).

In the second part of this experiment (experiment 5b) the bore or tube length is held constant (L = 59.5 cm) as well but now the other main parameter of the source oscillator, i.e., the mass of the reed, i.e., the masses of both oscillators are varied ($m_1$ = 0.0085g in 3 steps to $m_1$ = 0.017g and in further 4 steps to $m_1$ = 0.034g; $m_2$ is varied with same amount of steps from $m_2 = 0.0015_g$ via m2 = 0.003 to $m_2$ = 0.006g ). Results are displayed in Fig. 8. Like in the first part of the experiment, no change of pitch $F_0$ occurs (frequency of the source oscillator, i.e., of the two-mass model) despite a strong variation of oscillator masses reflected by the frequency of the reed resonance $F_{reed}$ which now varies from 1550 Hz down to 700 Hz.

### *3.6* Experiment 6: *glissando experiment for trumpet: varying pitch in brass resulting from varying lip tension in case of constant bore length*

While the lip parameters are already adjusted for normal vibration of lips in case of the lowest note of a Bb-trumpet (table 1, fig. 3b) in this experiment a glissando is simulated by increasing the lip stiffness (q = 0.5 to q = 3.5) and at the same time increasing pulmonary pressure and thus oral pressure from PP = 1000 Pa to PP = 3500 Pa). The length of the bore is not changed in order to mimic a trumpet glissando without pressing any valve. Fig. 9 illustrates that our virtual trumpet player can perform this glissando by covering a pitch interval from F0 = 120 Hz to F0 = 470 Hz. But the increase in frequency is not as linear as is in case of the singing (see for example Fig.5). It can be speculated that the occurring irregularities result from an interaction of higher resonances of the bore of the trumpet (res2, res3, res4) with the source oscillator, i.e., with the lips of the trumpet player. It can be assumed that the resonances of the bore try to “catch” and “hold” a tone. Thus the fundamental frequency is no longer controlled by the lips alone, i.e., by varying lip tension (changing mass and stiffness of the lip mechanical resonator), but in addition the resonances of the bore become important and try to “catch” and “hold” the fundamental frequency F0 generated by the source oscillator (self-oscillating two-mass model). That seems to be comparable to the mechanism how beginners search for their first notes on the trumpet, i.e., how they try to adjust lip tension in the right way for producing a note referring to the bore length and thus to the fingering of the player.

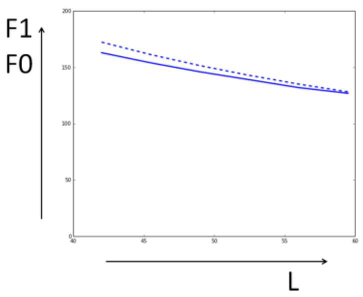


**Figure 6** – Variation of pitch (F0) as function of bore or tube length L for a clarinet. Beside pitch F0, resulting from the self-oscillating source model (solid blue line), the calculated lowest resonance frequency of the bore F1 is displayed (dashed blue line).

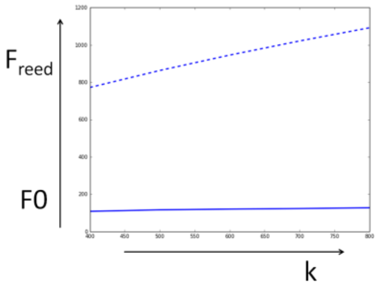


**Figure 7** – Variation of pitch (F0) for clarinet as function reed stiffness if of bore or tube length is constant. Beside pitch the eigenfrequency of the source system $F_{reed}$ is displayed as well (dashed line).

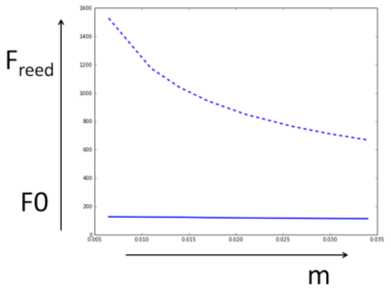


**Figure 8** – Variation of pitch (F0) for clarinet as function reed mass if of bore or tube length is constant. Beside pitch the eigenfrequency of the source oscillator $F_{reed}$ is displayed as well (dashed line).

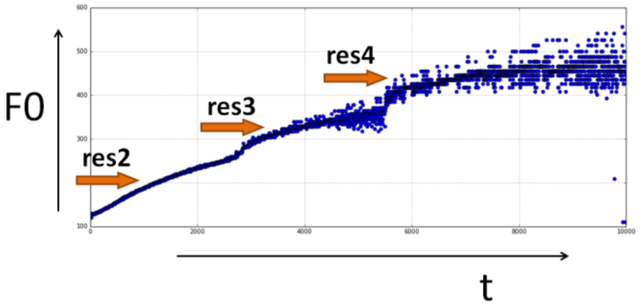


**Figure 9** – Display of simulation parameters for a trumpet glissando

## 4. DISCUSSION

The basic differences and similarities of the acoustics and aerodynamics of a clarinet as example for a reed instrument of a trumpet as example for a brass instrument and of a low male singing voice were illustrated in this paper by using a computer simulation model. A reflection type line analog representing the filter coupled with a self-oscillating damped spring-mass model representing the sound source is used for modelling all three cases (voice, reeds, brass).

Experiment 1 clearly indicates aerodynamic-*acoustical* interactions like the ripple within air flow of the source $u_g$ in case of the clarinet (see (12) for voice). Strong aerodynamic-*mechanical* interaction is found for clarinet as well as for trumpet. While in case of voice the pitch is mainly controlled by the vocal folds itself (i.e., by vocal fold tension, see experiment 3) and while here vocal tract shape and vocal tract length has nearly no influence on pitch (see experiment 2) the situation is different for reeds and brass. Our simulations indicate that the pitch of the clarinet is mainly determined by the first resonance of the bore or tube and thus strongly depending on bore length (experiment 4) while the dynamic parameters mass or stiffness of the oscillating source can be varied in a relatively wide range without influencing the pitch (experiment 5).

The brass instruments are in an intermediate position between voice and reeds. Simulating a trumpet glissando by increasing lip tension and oral pressure indicates an increase in pitch comparable to increasing vocal fold tension and pulmonary pressure for a low male voice (experiment 2). But in the case of the trumpet this increase in pitch is not as linear as it occurs for the voice. In case of the trumpet the increase in pitch is comparable to a step function despite the fact that the lip tension and oral pressure increase continuously (experiment 6). A possible explanation is that pitch seems to "being hold" in frequency regions representing the 2nd and higher resonances of the bore. This aerodynamic-mechanical interaction seems to be lower for brass in comparison to reeds – where pitch always is in line with the first resonance of the bore – but higher than aerodynamic-mechanical interaction for voice if the pitch of voice is below the first tube resonances, i.e. below the frequency of the first formant.

These differences in degree of aerodynamic-mechanical interaction can be understood if we compare the transfer of energy from the aerodynamic system to the mechanic source system. The occurring forces on both masses of the coupled spring-mass pairs in the oscillator system representing the source are displayed in Fig. 3 (experiment 1). It can be seen that the pressure-induced forces acting on the reed is different from those acting on the vocal folds in case of singing or on the players lips in case of brass instruments. In the case of the vocal folds subglottal pressure is acting on both masses during the closed phase which forces the vocal folds to open. Within the open phase of the glottis – beside the (not shown) restoring forces of the spring-mass system – an under-pressure acts on the masses within the closing phase of the vocal folds. Thus a phase-correct transfer of energy occurs during the closed and open phase of the glottis and the same holds for the closed and open phase of the lips in case of the brass instrument. The only difference is that in case of brass no phase lag occurs between both mass pairs which leads to a shorter closed phase and the occurring forces on the open phase are strongly related to the *pressure in the mouthpiece* resulting from the *standing waves established in the bore*. This pressure right above the oscillator – i.e., pressure in the pharyngeal cavity in case of singing, pressure in the mouthpiece in case of brass instruments – is much lower in the case of singing. During singing, the main effect is the small negative pressure occurring within the closing phase of the glottal open phase which results from Bernoulli under-pressure, while the stronger negative lip closing pressure in the case of the brass instrument stems from a phase-correct occurring standing wave established in the instrument bore. During the closed phase the subglottal pressure for singing as well as the oral pressure for the lips-mouthpiece system of the bass instrument is positive in order to allow the vocal folds (respectively the lips) to open again.

In the case of the reed the force acting on the tip of the reed during closure of the reed-mouthpiece system is the oral cavity pressure which acts on the *outer side of the reed* in order to hold the closure. This pressure – in contrast to the subglottal pressure in case of singing which acts on the inner side of the vocal folds and in contrast to the oral pressure in case of the brass player's lips which act on the inner side of the lips – is negative. Thus the related resulting force tries to hold the closure of the reed-mouthpiece system. Consequently in case of reeds the opening and closing mainly results from the pressure acting on the *inner side of the reed* and this pressure as function of time results from the *standing waves occurring in the bore*. Thus these standing waves within the bore dominate the changes of pressure within the chamber of the mouthpiece and let the reed move outside in the case of positive pressure or sucks in the reed in the case of negative pressure. Thus the fundamental frequency of reed oscillation is driven by the frequency of the standing wave (first resonance frequency of the bore or tube) and not by the dynamical parameters of the two-mass oscillator itself as it is the case for singing. The resonance frequency of the damped mass-spring oscillator representing the reeds alone is much higher (about 1000 Hz, see table1; 1400 Hz to 3000 Hz following (17, 4)).

It should be kept in mind that in the case of singing specific vocal tract shapes lead to a better sustain and thus professional singers change vocal tract shape with pitch even for producing the same vowel quality. This is an indicator that aerodynamic-mechanical interaction is important for singing as well, but only, if pitch is near and possibly higher than the first vocal tract resonance frequency (which is tried to be avoided, see (18)).

One more important difference between reeds and brass is that the bore or tube of reeds (here clarinet with about 60 cm) is short in comparison to brass instruments (here trumpet with about 140 cm). But because of the flare and huge bell of brass instruments the resonances of brass instruments do not form a strict harmonic row and the first resonance frequency F1 is far below pitch F0. Thus brass players adjust pitch with respect to the second and the higher resonance frequencies (F2, F3, …) while the pattern of resonance frequencies due to the instrument bore is much more regular in case of reeds and here the pitch is strictly oriented with respect to the first resonance frequency F0 as well as to higher resonance frequencies of the bore in case of playing higher registers. Thus pitch for brass is *above* first resonance or bore, pitch of reeds in its lowest register *exactly equals* that of the first resonance of the bore and pitch of voice preferably is *below* the first resonance of vocal tract.

## 5. CONCLUSIONS

A first main result of this study is that different control mechanisms of pitch in source-filter systems like voice, brass or reeds can be modelled by a time domain simulation of tube acoustics coupled with a two-mass damped mass-spring oscillator as source model. The interaction between the tube system and the source oscillator is simulated by calculating the time varying pressure inside the tube sections acting on the mass pairs of the source oscillator. Using this simulation system, different degrees of source-filter interaction can be simulated as they occur for the speaking and singing voice, for brass instruments and for reed instruments. Voice pitch is mainly determined by vocal fold tension. On the other hand we were able to demonstrate that pitch for a reed instrument (here for a clarinet) is mainly controlled by the length of the bore, i.e., by the fingering of the player. Brass instruments take and immediate position. Here the lip tension of the player always needs to be adjusted correctly with respect to bore length in order to produce clear sounds.

Some of these results are already known and published but this study clearly indicates how these basic findings can be easily simulated in a simple geometrical and time domain simulation system representing voice as well as music instruments like reeds and brass. Thus the software used here and the parameter optimizations discussed in this study can be taken as a basis for developing a valuable demonstration tool in music acoustics.

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