Experimental investigation into the reed structure and articulation modes of the western Chinese instrument Hulusi

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Introduction

As a traditional Chinese national wind instrument, hulusi's unique timbre characteristics largely depend on the vibration behavior of the reed[1]. Reed is the sound core of hulusi, and its material characteristics, geometric shape and vibration mode directly affect the timbre, intonation and performance stability of the instrument[2].

In recent years, many scholars have made remarkable progress in the study of vibration characteristics of reed instruments. Braasch et al. (2023) compared the differences in the structure, sounding waveform, and new development of the reed of Asian and Western free reed instruments and expounded their acoustic principles and classification characteristics[3]. Rucz et al. (2021) studied the three-dimensional vibration mode of organ tongue reeds through laser vibration measurement technology, revealing the complex vibration behavior of different reeds under different pressures[4]. Martin et al. (2019) analyzed the vibration characteristics of the reed of Khaen pipe through experimental measurement and carried out physical modeling with the finite element method[5]. Chatziioannou et al. (2019) proposed a time-domain physical model for clarinet sound synthesis and experimentally verified it with a hand-blown machine based on high-speed photography technology[6]. Yang et al. (2023) measured the vibration characteristics of Chinese sheng reeds using the traditional contact method[7]. However, these studies have not focused on the reed of hulusi, and its sound mechanism is still unknown.

This study aims to comprehensively and systematically measure and analyze the vibration characteristics of hulusi reed through laser vibration measurement technology[8], focusing on revealing the vibration mode, harmonic structure, and nonlinear dynamics characteristics of reed under different playing conditions. The study will explore the relationship between reed materials, geometric parameters, and vibration characteristics and how these characteristics affect the final acoustic output. The correlation model between reed vibration and timbre characteristics is established to provide a theoretical basis for the modeling of Hulusi reed.

Experimental Materials

This paper introduces a measuring method for the alternative blowing of hulusi pipe. The experimental equipment consists of three parts, including the sealing instrument pipe, the air pressure supply part, and the laser measurement part, as shown in Figure 1. In terms of air pressure, since the hulusi performance is basically for blowing, high-pressure gas cylinders and decompression valves are used to provide continuous stable air flow required for blowing. The laser system uses Polytec's PSV 500 scanning laser vibrometer, which has a frequency range of 25 MHz and a vibration speed range of 0.01 Î¼m/s -30 m/s, which can accurately observe the vibration mode of the reed. The central reed of the hulusi wire is inserted into a plexiglass cube roughly equal to the volume of the gourd (15 cm*10 cm*8 cm), the opening on the opposite side of the tube is the intake hole connected with the pressure-reducing valve, and the sensor is connected above it (MIK model MK300). In order to better play different pitches, all holes are closed in pitch order (paper tape), and the sealed glass box and pipe are fixed with screw clips and tripods, respectively.

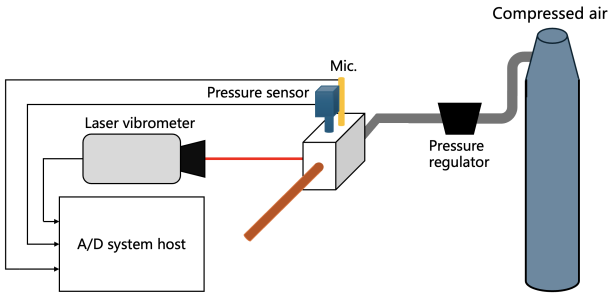

Abbildung 1: Measurement tools and setup.

The pipe in this experiment is the main pipe of the C-tuned hulusi wire. Figure 2 shows a close-up photo of the reed marked with the scale. In the photo, the fixed end of the reed is located at the top (the position of the fixed end can be changed depending on the process), and the free end is located at the bottom. As shown in Figure 3, the free end of the reed has an upward curve near the free end, while the fixed end remains horizontal.

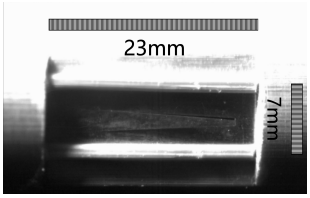

Abbildung 2: Measurement tools and setup.

All measurements were installed in the Department of Systematic Musicology laboratory at the University of Hamburg, Germany. The experiment used SchrÃ¶der Gas's 200-bar high-pressure air cylinder connected to Vulkan's 0-15 bar variable pressure valve to provide constant airflow pressure. A pre-polarized microphone (PCB model 378A04) records sound and is placed directly above the sealed box (5 cm* 4 cm). The reed vibration is measured using a Polytec psv500 laser vibrometer with the beam focused near the free end of the reed (2-3 mm). The MIK PX300 sensor monitors the pressure of the sealed box.

Measurements Results

Steady state analysis

This measurement is performed at a pressure of 900Pa when all the pitches of the measuring tube can emit a stable tone.

Figure 3 shows the steady state spectrum of the fenugreek reed in the sealed box under 900pa pressure. Above is the bass spectrum, and below is the middle and high spectrum. It can be seen that the amplitude of the even partial tone is smaller than that of the odd partial tone because the two holes at the end of the measuring tube are close to each other. The resident pressure waves of even harmonics generated are in opposite phases at the two holes, interfering with each other and reducing the radiation of even partial frequency.

Interestingly, the bass in the figure above presents a more prosperous harmonic component, the sound contains more high-frequency components, and the timbre is fuller and brighter, which accords with the conclusions of our previous experiments. In addition, the reed may have a nonlinear effect (bending, twisting, etc.) during bass playing, which will excite more harmonics.

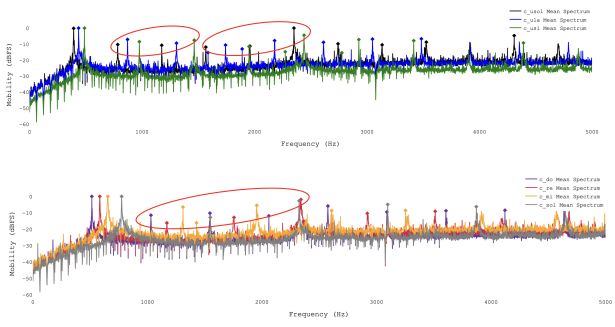

Abbildung 3: Steady-state spectra of the experimental pipes at a pressure of 900 Pa.

Figure 4 shows the STFT spectrum diagram and spectrum centroid of the reed vibration. It can be seen that the STFT spectrogram (above Figure 4) shows a relatively consistent spectrum envelope throughout the 5.5-second analysis window, and there is a decrease in energy around 3 seconds, especially in the mid-frequency range (2000-3000 Hz), which indicates that the reed response has changed. The spectral centroid of all pitches (below Figure 4) remains remarkably stable at about 2500 Hz, indicating that the overall spectral energy distribution remains in a consistent central position despite the difference in fundamental frequencies.

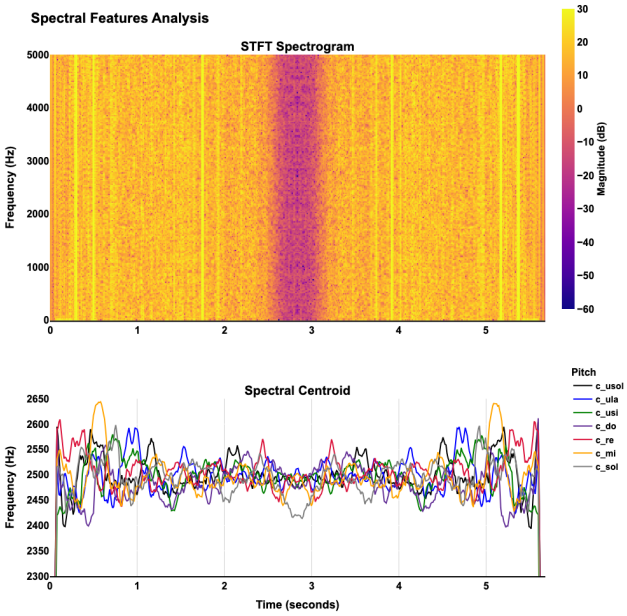

Abbildung 4: The centroid of the spectrum of different pitches in steady state. The upper figure is the STFT spectrum diagram, and the lower figure is the time domain diagram of the spectrum centroid.

Reed mode analysis

Laser vibration analysis of reed reveals the evolution of vibration modes from fundamental frequency to high frequency under different pitches.

Figure 5 shows the vibration mode diagram of the reed (pitch is u_sol). It presents a typical first-order up-and-down vibration mode near the fundamental frequency (about 392-488 Hz). The vibration is mainly concentrated at the free end of the reed; the red area indicates the maximum displacement and the blue area indicates the minimum displacement or node position. As the frequency increases to double frequency (about 784-976 Hz), the reed develops a distinct second-order mode, characterized by a node-line in the direction of the reed length, dividing the reed into two regions of antiphase vibration.

The mode presents two longitudinal nodal lines near the triple frequency (about 1175-1464 Hz). In the frequency range (2- 3 kHz), the reed presents a complex high-order mode, which not only shows multiple node lines in the longitudinal direction but also shows non-uniform vibration in the transverse direction, indicating that the reed has a complex vibration mode of flexural and torsional at the same time. Especially above 3000 Hz, the vibration modes become highly complex, and the node region presents an irregular distribution, indicating the mutual coupling and influence of multiple vibration modes.

FIG. 6 shows that the reed (pitch mi) exhibits a first-order mode in the fundamental frequency region (about 655 Hz) similar to that of the reed in FIG. 5. However, the maximum displacement region of its free end is relatively small. Near the frequency doubling (about 1311 Hz), the

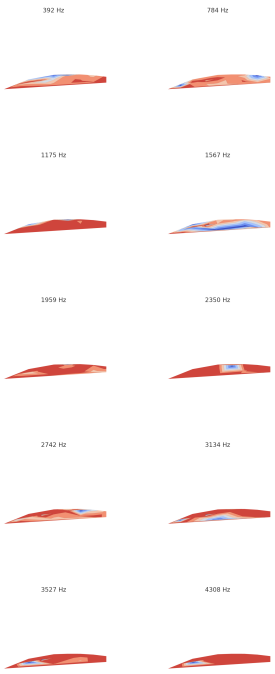

Abbildung 5: The vibration mode diagram of the reed under the pitch U_sol, red is the maximum vibration displacement, blue is the minimum vibration displacement. The number above each small chart is the corresponding peak frequency.

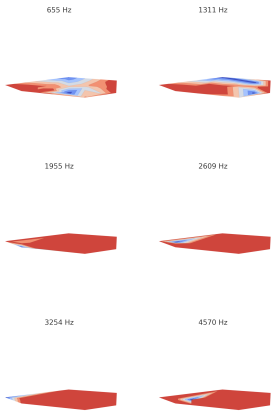

Abbildung 6: The vibration mode diagram of the reed under the pitch Mi.

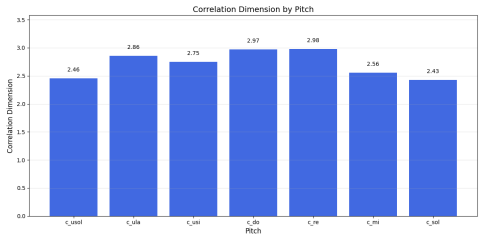

Abbildung 7: Fractal correlation dimension of different pitches.

treble reed also develops a second-order mode. However, compared with the bass, the node-line position is closer to the fixed end, and a more apparent blue region appears on the side edge of the reed, indicating the enhancement of the transverse vibration component.

In the range of 2- 3 kHz, the vibration mode of the treble reed presents significantly different characteristics from that of the bass reed: the node distribution is more concentrated, and the red (maximum displacement) area is mainly concentrated in the free end and side edge of the reed. Especially above 3000 Hz, the treble reed shows a more stable vibration mode, with most reed areas showing uniform red and only blue nodes appearing in local areas, which is in sharp contrast to the complex irregular vibration of the bass reed at the same frequency.

Because of the nonlinear behavior of the middle and high-frequency vibration of the reed, it is very appropriate to use the fractal correlation dimension to detect the vibration sound. FIG. 7 shows the fractal dimensions of different pitches. The reed vibration of all pitches presents high nonlinear complexity, and the correlation dimension is greater than 2, which indicates that the reed vibration has specific chaotic characteristics under all pitches. Middle registers (Do and Re) show the highest correlation dimensions (2.97 and 2.98, respectively), while low registers (U_sol) and high registers (Sol) show relatively low correlation dimensions (2.46 and 2.43, respectively), forming an inverted U shaped distribution.

Discussion

Correlation between spectral characteristics and vibration modes

A clear correspondence can be found when comparing the vibration mode diagram with the previous spectrum analysis (Figure 3). When the bass is played, the spectrum of the reed (U_sol, U_la, U_si) shows a strong peak at the fundamental frequency, corresponding to the definite first-order mode observed in the modal diagram. On the other hand, the frequency spectrum of the reed (Do, Re, Mi, Sol) is more evenly distributed over multiple harmonics, which is consistent with the complex vibration characteristics shown in the modal diagram, even at the fundamental frequency.

Dynamic relationship between vibration modes and correlation dimension

When the reed plays bass (U_sol, U_la, U_si), the first-order modes mainly dominate the fundamental frequency vibration. However, the correlation dimension still reaches 2.46-2.86, indicating that even the seemingly simple bass vibration contains considerable nonlinear components. It can be observed from the modal diagram that the reed in the bass state also exhibits complex higher-order modes in the high-frequency part, and these higher-order modes contribute to the overall vibration complexity.

In the middle register (Do, Re), the correlation dimension reaches the highest value (about 3.0), indicating that the vibration in this region reaches the highest degree of complexity. The modal diagram shows that the vibrati-

on modes of the reed in the middle tone range show more complex node distribution and vibration patterns in each frequency segment, especially in the 1-3 kHz range, showing a strong coupling of longitudinal and transverse vibration. This highly complex vibration state may be because the reed-tube system in the middle range is in an optimal coupling state so that multiple vibration modes can be effectively excited and maintained simultaneously.

When the reed blows high notes (Mi, Sol), the correlation dimension decreases slightly (2.56 and 2.43), indicating that the complexity of the vibration is reduced. This may be because higher lip pressure and air velocity impose more substantial constraints on the reed when playing high notes, limiting certain degrees of vibration freedom. The modal diagram also shows that the vibration energy of the reed in the high register is more concentrated in a specific region in the high-frequency part rather than being widely distributed as in the middle register.

Next, we need to optimize the design of the experiment to measure the transient state of the hulusi attack state, which will provide the basis for the physical modeling of the musical instrument.

Literatur

[1] Cottingham, J.: The Asian free-reed mouth organs. The Journal of the Acoustical Society of America (2002), 112(5).

[2] Yang, C.: A review of the research on musical instruments of ethnic minorities in Yunnan. Journal of Xinghai Conservatory of Music (2017), (04).

[3] Braasch, J. & Cottingham, J.: Free Reeds: An Intertwined Tale of Asian and Western Musical Instruments. Acoustics Today (2023), Volume 19, Issue 4.

[4] Rucz, P. & Miklos, A. & Angster, J.: Experimental investigation of dynamic lingual organ pipes with blown open tongue. The Journal of the Acoustical Society of America, (2021), 150, 3664.

[5] Martin, W. & Nash, K. & Cottingham, J.: Finite element simulation and experiment in khaen acoustics. Proc.Mtgs.Acoust. (2019), 39, 035003.

[6] Chatziioannou, V. & Schmutzhard, S. & Pamies-Vila, M. & Hofmann, A.: Investigating Clarinet Articulation Using a Physical Model and an Artificial Blowing Machine. ACTA ACUSTICA UNITED WITH ACUSTICA. (2019), 105, 682-694.

[7] Yang, C.: Research on the resonators of wind instruments of ethnic minorities in southwest China. Chinese Music. (2023), 03, 006.

[8] Bakarezos, E. & Orphanos, Y.: Laser-based interferometric techniques for the study of musical instruments. Computational Phonogram Archiving. Springer Verlag. (2019) 251-268.