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BELL VIBRATIONS AND RADIATED SOUND OF BRASS WIND INSTRUMENTS – IS THERE AN AUDIBLE CORRELATION?

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Abstract

The question whether wall vibrations of wind instruments can affect their radiated sound has not finally been answered yet. It was and still is a very controversial issue. Acousticians hold that it is the resonant air column which is responsible for the radiated sound and wall vibrations neither have enough potential to radiate nor to significantly affect the standing waves inside the instrument. On the other hand, musicians and instrument makers assert a strong claim, that wall thickness, material and production techniques are crucial factors for sound quality and response of wind instruments. Although they got some support from scientists who seemingly were able to reproduce the claimed effect, there is no plausible theoretical explanation for it. Therefore such experiments have been questioned by sceptics as being inaccurate and not repeatable. New experiments have therefore been made in order to address this legitimate plea. A Viennese Horn was constantly excited by an artificial mouth in an anechoic chamber while its bell vibrations have been damped using dry sand. The radiated sound has been recorded while sand was dropped into a solid box housing the instrument to increase the factor of damping continuously. In order to rule out feedback of structural vibrations to the mouthpiece as a possible cause, the coupling was achieved with a short piece of flexible rubber tube. The experiment was repeated several times to obtain enough spectral data for statistical analysis. Strong and statistically significant correlations between spectral characteristics and bell vibrations have been observed.

1 INTRODUCTION

For hundreds of years there is still the question if wall vibrations influence the radiated sound of wind instruments. There are two opposed views on this topic: Musicians and instrument makers suppose that there is a strong influence of wall thickness, material and production techniques on the sound and response of an instrument while acousticians hold that the resonant air column is the main factor and wall vibrations are minor.

The effect of wall material on the radiated sound of flue pipes and other wind instruments was determined by Boner and Newman [4]. In 1940 they summarized the work of many scientists and instrument makers. One of it is the paper by Miller [12], who constructed a double wall flue pipe which can be filled with water during an experiment in 1909.

Boner and Newman themselves did observe some changes in the amplitudes of partials up to about 3 dB, but in their critical conclusions they rather attributed these effects to small geometric differences of the flue pipes under investigation. Lottermoser and Meyer [11] repeated that experiment in 1962. Unlike Boner and Newman they attributed the differences to the wall material without being able to give a convincing proof for their claim.

Zscherpel, Görne and Bastubbe [28] gave a fine review with some focus on organ flue pipes as well. This German technical report is available online (`http:`

`//www.goerneakustik.de/papers/BerichtNV.pdf`) and discusses the experimental and theoretical treatment of Backus and Hundley [3, 1, 2]. They found a dependency of the speed of sound on a pressure induced oscillation of the cross-sectional area. A proportionality between the intensity ratio of sound radiated by the vibrating walls and sound radiated from the open end and the relative shift in frequency could be determined. With reasonable assumptions for typical organ pipes this results in wall effects being about 40 dB below the main sound intensity.

Ten years later Wogram started to investigate wall vibrations of trombones in Bb [25]. He asked players to play the instruments and let them assess subjective quality. He also did objective measurements using artificial lips. Observing spectral differences of up to 3 dB for different wall materials he claimed the sound variations to be almost indistinguishable. Some interesting correlations between subjective assessments and objective measurements he attributed to differences in the response of the instrument.

In 1978 Richard Smith entered a scientific dispute [20]. He expressed his opinion that

> "... it is an impossible task for the scientist to be able to produce sufficient evidence to show that a player may be wrong in his opinion, ..."

His own opinion at that time was that material does not matter with respect to sound timbre or response but wall thickness does. According to his observations on trumpets at that time he found the difference between two brass bells, one 0.5 mm thick, the other 0.3 mm thick, quite noticable. He agrees with Wogram in that

> "... extremly thin-walled bells turn out the worst response characteristics ..."

He determined that vibration amplitude is inversely proportional to the fourth power of wall thickness and he published beautiful holograms of bell Eigenmodes which even made it into Nature about ten years later [22]. His conclusion in 1978 was that

> "... material vibration appears to accentuate the higher frequencies and increase the responsiveness of the upper register. Further work is being undertaken to increase our understanding of this phenomenon."

Meanwhile Lawson published experiments with French horns [10] where equal bells of different alloys, annealed as well as unannealed, have been compared. Although observed spectral differences did not exceed the range of 3 dB he concludes in his following paper [9]:

> "The results of this experiment demonstrates unequivocally that the effect of the bell material vibration on the radiated sound is exceptionally strong."

However, sceptical readers might criticize that no artificial player has been used, so it was easily possible that spectral differences could be caused by small variations in embouchure which even a professional player might not be able to avoid.

Watkinson and Bowsher strengthened the sceptics presenting results of finite element modeling [23] favoring the position that wall vibrations should not have any noticeable effect.

While more papers were published supporting the hypothesis that wall vibrations do affect the radiated sound of brass wind instruments and organ pipes (e.g. Pyle on the effect of lacquer and silver plating on horn tone [16]) Wogram and Smith became more and more sceptical. Wogram now indicates in [26] that it requires a human player in order to modify the timbre according to what he senses with his hands or what he perceives as a near-field sound radiation which does not propagate to the audience. Smith still reports small but clearly measurable differences for harmonics which were close to structural resonances [21] but his test subjects failed to detect that differences. He now concludes that:

> "... bell thickness does have a significant effect on the sound spectra measured at the player's ear position due to some sound radiation from the material itself. However, under controlled conditions players seem unable to distinguish between thick and thin materials."

On the other hand Pyle is still strongly convinced about the effect of different materials and thicknesses on tone quality and responsiveness of French horns [17] but again his experiments suffer from the fact that no artificial player has been used. Human players even with sound level feedback will hardly manage to consistently replicate all subtle details of their embouchure, especially when they can see and feel the instrument they are playing.

In the late nineties Gautier and Tahani did more work on organ pipes. They developed a physical model of a simplified cylindrical wind instrument with vibrating walls [5]. Runnemalm et al. performed quantitative measurements of structural vibration modes of a blown open organ pipe [19] and Kob confirmed once more that vibrations can alter the sound of flue organ pipes [7, 8].

Theoretical investigations could not provide satisfying explanations for vibrational influences, therefore Ziegenhals provided experimental evidence in [27].

Thomas Moore et al. did convincing experiments to test new hypotheses about the genesis of the observed influence [15, 14, 13]. He measured consistent and audible timbre changes on trumpets when their bell is damped using sand bags. To get information about the statistical spread of the influences the experiments were repeated.

Whitehouse [24] studied structural resonances of simplified wind instruments systematically and gave a detailed review up to 2003 in his PhD-theses.

In 2006 Ziegenhals observed that the measured wall vibrations did contain all the frequency components of the radiated sound [27] even with roughly comparable amplitudes.

2 EXPERIMENTS

2.1 Setup

To detect the influence of wall vibrations on the recorded sound, all parameters apart from damping were kept constant carefully.

The Bell was damped using fine dry sand to bury the whole instrument inside a box made of wood. This sand box is shown in Figure 1. To decouple the mouthpiece vibrations from those of the instrument a flexible rubber tube was used to connect the two (Figure 2).

Figure 1: Sand box in unechoic chamber

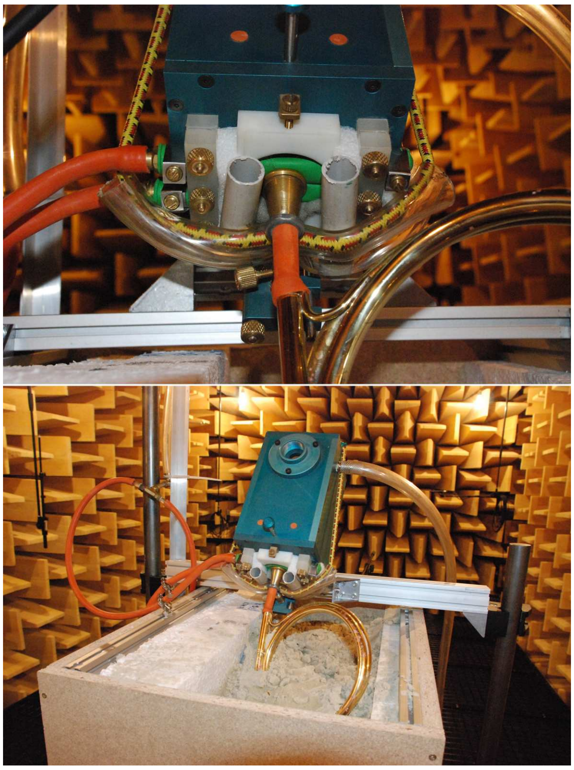

Figure 2: Details: Sand Box and Artificial Mouth

The artificial mouth has been obtained from the Acoustics Group at Edinburgh University where it was built according to [6]. It was mounted on seperate carriers to decouple it from the sand box (Figure 2). The bell looked out through a hole in one sidewall of the box which was just a bit bigger than the rim of the bell. To prevent the sand from flowing out of the box a thin cloth was used.

The box was damped by thick layers of styrofoam inside, first to reduce the amount of sand necessary to fill up the box, second to provide a pretty damped environment even before the sand is filled into the box.

To ensure that the sound generation was basically not affected by the sand, an accelerometer has been attached to the mouthpiece. A second accelerometer was positioned on the outside of the bell where most modes were expected to have a vibrational anti-node.

The sand box has been placed in an unechoic chamber to avoid the room influence. Two microphones (AKG C414) have been positioned in front of the horn, the nearfield microphone at an axial distance of 1 m perfectly centered within the radiation cone, the farfield microphone in a distance of 4 m, 1.5 m dislocated from the axes.

2.2 Conditions

Eight recording runs have been performed. Six of them (1, 2b, 3, 4, 5, 7) started with an empty box which was slowly filled up with sand during the recording. Two runs (2a and 6) started with a filled box which was slowly emptied during the recording. The sound generation has been turned on much earlier allowing the system to stabilize.

Run 1 was eliminated because of poor stability caused by too wet sand which did not smoothly fill up the box. The reverse runs 2a and 6 have been dropped because it turned out not to be possible to empty the box completely thus undamp the bell properly without moving the horn and destabilizing the sound generation.

The test instrument was a thin walled Viennese Uhlmann Horn playing a slightly flat A4 (438 Hz) at 105 dBA. The water pressure in the lips was set at about 65 cm H_2O. The air pressure was derived from a vacuum cleaner being held constant at about 70 mPa. It was positioned outside the anechoic chamber to ensure that there is no additional noise. Sensitiveness and patience are requred to get a stable sound.

For statistical analysis the language and environment R [18] has been used. To compare the variables (RMS, Harmonics etc.) with damped and undamped bell, 1080 signal windows each consisting of 16384 audio samples have been processed. Data has been collected during five independent runs (2b, 3, 4, 5, 7) using 108 undamped (initial condition) and 108 damped (final condition) spectral samples from each run. To find out differences of harmonics with damped and free bell t-tests were used.

3 CONCLUSIONS

There were big differences in timbre caused by bell damping. Sound samples recorded before and after damping could easily be distinguished by listeners. This is also documented by the harmonic centroids of the far-field sound. The differences of their mean values are statistically significant ($p<0.001$). The spectral centroids show the same characteristics ($p<0.001$), which is illustrated in figure 3.

The fundamental frequency (FF) increases with damping poor but statistically significant. The null hypothesis, that there is no pitch difference with respect to damping, was rejected at a significance level of 0.001. That was unexpected and has to be investigated in future experiments. Small instabilities of embochure may be the reason. The standard deviation of the fundamental frequency with a damped bell (1.75 Hz) is much higher (2.75 times) than with a free bell (0.63 Hz). Due to the fact that the median of the fundamental frequency with a damped bell is lower then undamped some outliers seem to influence the results, particularly the mean value.

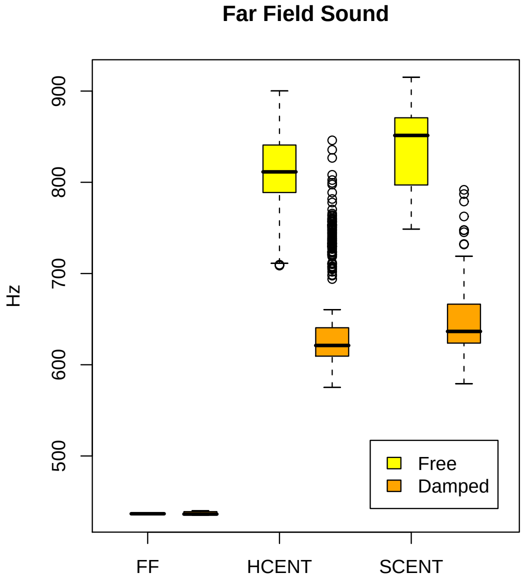

Figure 3: Fundamental Frequency (FF), Harmonic Centroid (HCENT) and Spectral Centroid (SCENT) with respect to damping

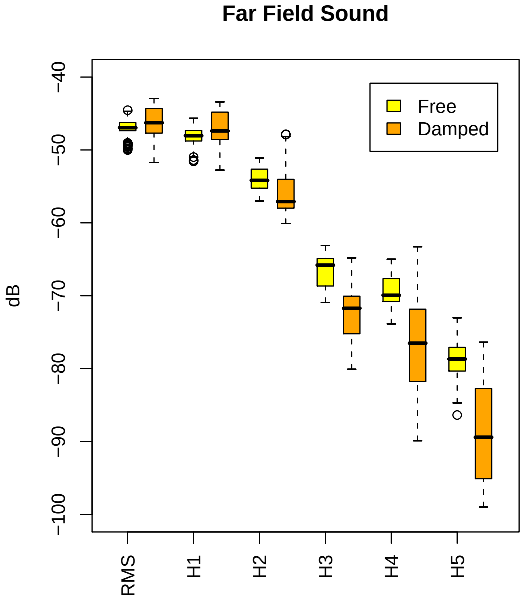

Figure 4: RMS and Harmonics 1 to 5 with respect to damping

RMS and all Harmonics (H1-H20) show statistically significant differences of their mean values ($p<0.001$) with respect to bell damping. Figure 4 shows that RMS and the first harmonic (H1) of the far field increase with damping the bell. However, the higher harmonics (H2+) decrease – the higher the more (figures 4, 5 and 6).

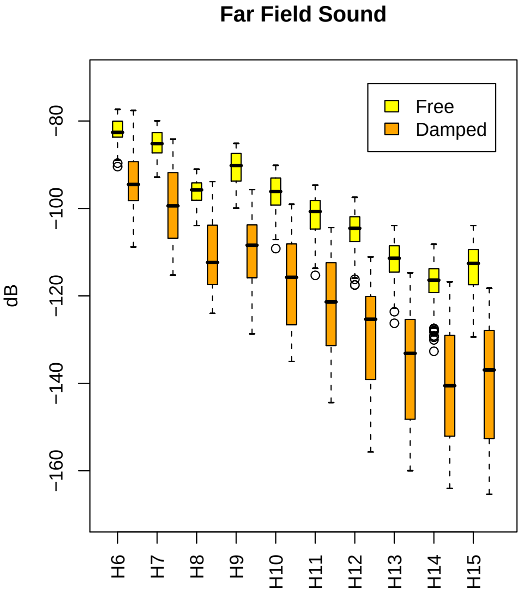

Figure 5: Harmonics 6 to 15 with respect to damping

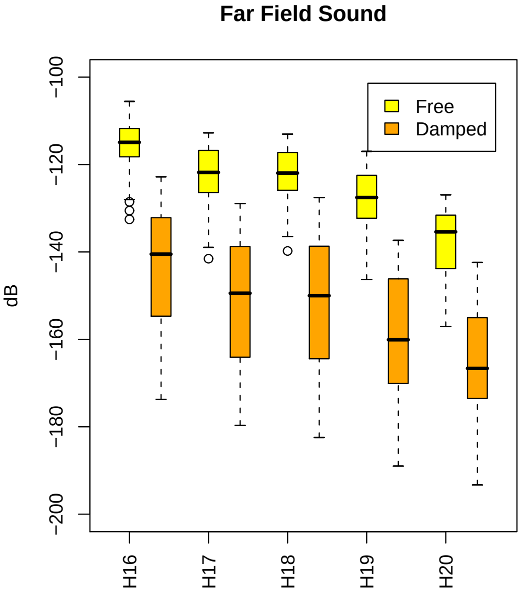

Figure 6: Harmonics 16 to 20 with respect to damping

The vibration amplitude of the bell should be directly related to the measured accelerometer signal. However, not all harmonic sound components do correlate with corresponding acceleration components. Obviously there were modes undetectable at the position of the sensor. Higher far field harmonics show positive correlations with bell harmonics and bell RMS. To give some examples the coeffiecients of correlation of far field harmonics 8, 13 and 18 with bell RMS and bell harmonics were shown in table 1.

	H8.FarMic	H13.FarMic	H18.FarMic
RMS.Bell	0.80	0.80	0.77
H1.Bell	0.78	0.78	0.75
H2.Bell	0.73	0.79	0.82
H3.Bell	0.79	0.80	0.81
H4.Bell	0.66	0.59	0.52
H5.Bell	0.70	0.73	0.67
H6.Bell	0.79	0.81	0.79
H7.Bell	0.66	0.60	0.65
H8.Bell	0.60	0.48	0.48
H9.Bell	0.72	0.79	0.75
H10.Bell	0.72	0.83	0.78
H11.Bell	0.85	0.90	0.89
H12.Bell	0.63	0.82	0.81
H13.Bell	0.53	0.68	0.63
H14.Bell	0.78	0.91	0.91
H15.Bell	0.69	0.82	0.81
H16.Bell	0.70	0.77	0.75
H17.Bell	0.81	0.82	0.90
H18.Bell	0.77	0.84	0.90
H19.Bell	0.73	0.76	0.83
H20.Bell	0.73	0.79	0.83

Table 1: Coefficients of Correlation of Far Field Harmonics 8, 13 and 18 with Bell RMS and Bell Harmonics

All observed facts favor the hypothesis that the influence is caused by a change in radiation impedance caused by oscillating boundary conditions in the flaring part of the bell. The hypothesis that sound generation is modulated by a mechanical feedback of structural resonances back to the oscillating lips can be ruled out because of decoupling. The acceleration of the mouthpiece was almost independent of the damping.

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