Vibro acoustic modeling of wall vibrations of a trumpet bell

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A considerable acoustic effect of structural bell vibrations has been consistently observed in a series of experiments on whole brass wind instruments (e.g. [1] or [2]) as well as on trumpet bells without bends and braces (ISMA 2014, same authors). Those straight bells have been especially manufactured with the aim to allow physical modeling using simplified axi-symmetric 2D models and to avoid many of the complications of real world musical instruments. Good agreement was achieved between such structural simulations and corresponding experiments, besides the fact that the usual manufacturing process did not allow to keep wall thickness constant around the perimeter, a fact which cannot be taken into account by axi-symmetric modeling. Good agreement was also achieved between input impedance simulations and experiments done with and without damping sandbags. Theoretically wall vibrations have been modeled as distributed air density fluctuations due to the vibrating boundary. Transmission function measurements, however, consistently deviated from theory, triggering an exhaustive search for possible explanations. Investigating several possible reasons for that divergence increased the understanding of underlying mechanisms and eventually led to a hypothesis explaining the observed results. New preliminary measurements do confirm the postulated effect and their results are in good agreement with theory now. The bottom line is that wall vibrations of trumpet bells can affect input impedance and transfer function in a frequency range containing two to four natural notes in a region around the bell's structural resonance by up to several dB.

1 Introduction

Studying the effects of wall vibrations on the radiated sound of brass wind instruments is a research project that extends over several years now. Starting with independent observations, made by two different research teams in Winter Park, FL, and Vienna, Austria, that the sound spectrum of a note continuously played on a trumpet or on a French horn by means of an artificial mouth changes considerably when mechanical bell vibrations are damped by sand.

The team in Florida used a trumpet radiating through a well fit circular hole into a semi-anechoic chamber containing the observer microphone. Sandbags were used to dampen the bell vibrations during the experiment.

The Viennese team used a box with massive walls which could be filled with dry sand during the experiment. The box had a circular hole on one side with a diameter matching that of the bell of a French horn which was mounted inside the box. The whole box with the instrument played by an artificial mouth was situated inside an anechoic chamber when the radiated sound was recorded.

Differences between the sound spectra of played notes when bell vibrations were damped by sand and when the bell was allowed to vibrate freely, were attributed to the effect of wall vibrations and published in [3].

Later these experimental setups were used to determine the effect of wall vibrations on acoustical input impedance as well as on the sound pressure transfer function. For this purpose the artificial mouth was replaced by an impedance measurement head and respectively by a horn driver with a microphone recording the sound pressure in the mouthpiece. Results have been published in [2].

In order to understand the cause of the differences the structural mechanics of straight bells have been modeled in several ways [4] and a predominant axial resonance around 800Hz was found and later on confirmed by experiments [5].

Coupling this structural model to an acoustic simulator in order to include the bidirectional interaction between the two domains yielded predictions for the effect of wall vibrations on input impedance and transfer function of the enclosed air column [6]. While the agreement between theory and experiment was quite good for the acoustical input impedance (see Figure 1), there was a qualitative and quantitative mismatch concerning transfer function.

In order to find an explanation for this obvious discrepancy, different mechanisms not included in the model so far have been studied and eventually a possible explanation for the differences has been found and will be presented below. Preliminary measurements seem to confirm the given explanation and to validate the proposed structural and acoustical model (see Figure 2).

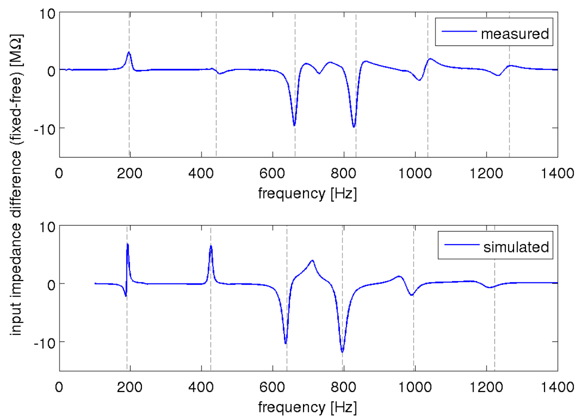

Figure 1: Measured and simulated input impedance difference curve (damped-free) of straight trumpet bell made from 0.55mm brass connected to a standard mouthpiece (dashed lines are air resonances).

2 Structural excitation

From many possible structural oscillation modes one has been found to be most relevant for affecting the sound field inside and outside the vibrating instrument. This mode can be described as oscillation of the physical length of the bell. Rim plane and mouthpiece end of the horn vibrate in opposite direction along the length axis with a nodal region somewhere in between. The location of the nodal region depends on the distribution of momentum along the axis and can be forced to some place by applying external forces using clamps and braces.

The good thing with this mode is that a 2-dimensional axi-symmetric simulation will be able to predict everything which is required to know - at least for straight bells and respectively the straight part of a bell. The bad thing is that mouthpiece amplitude, bell plane amplitude, the location of the central node, and - due to the latter - the resonance frequency of the whole system, depend on the masses attached to certain parts of the instrument (rim wire, mouthpiece and even the player's head) and on the forces due to holding (the player's hands) or clamping the bell.

This axial vibration mode can be excited at the bell side by the sound pressure present in the open mouth of the bell. This sound pressure is relatively small compared to that in the mouthpiece but the area where it interacts with the structure is relatively large, it is mainly a disk with the diameter of the bell.

It can also be excited in the mouthpiece cup where the sound pressure is 100 to 1000 times bigger than in the bell region. But this factor is partially compensated by an effective cup area which is about 60 times smaller than the bell. It should be noted here that at the mouthpiece rim there is also the oscillating force of the player's vibrating lips which can exceed the forces related to the sound pressure by an order of magnitude. As this excitation mechanism is not included in the Figures 1 and 2, those acoustical characteristics will only indicate a very pessimistic lowest threshold and will certainly be surpassed by far in actual playing.

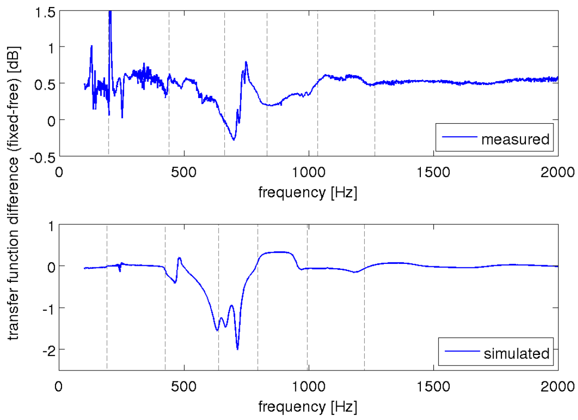

Figure 2: Measured and simulated transfer function (damped-free) of straight trumpet bell made from 0.55mm brass connected to a standard mouthpiece (dashed lines are air resonances).

3 Vibroacoustic interaction

The main effect of the vibrating bell on the enclosed air column derives from the modulation of the cross-sectional area along the axis of the instrument. Assuming longitudinal velocity of the wall there is only a small bore modulation in cylindrical parts of the bell. This marginal diameter change is due to the Poisson's ratio of the material which reduces the tube's diameter when it is stretched in length.

A more significant effect is created in steeply flaring parts of the bore. Taking the coordinate system of the air column as our frame of reference, then we will observe a flaring piece of boundary moving in longitudinal direction which will either widen or constrict our local air space. A positive flare moving to the right or a negative flare moving to the left will decrease the available volume of the local air column slice, while a negative flare moving to the right or a positive flare moving to the left will increase that volume.

The volume modulation due to the oscillating boundary will cause a local air density modulation. All these local air density fluctuations represent sound pressure sources distributed along the bore. These distributed sources emit little sound pressure wavelets which propagate along the bell. After having propagated to the mouthpiece plane they have to be superimposed to get their overall effect on input impedance and transfer function. The formulation of this effect has been carried out in [2], assuming isothermal conditions. Adiabatic conditions are more appropriate to reality and have generally been assumed for generating all theoretic curves of this paper.

Another effect which should be considered in an air column model is related to the air flow which is lost into the vibrating wall. If the radial velocity of the enclosing boundary is known, this is straightforward. At least in trumpets analyzed up to now this influence is typically smaller than that of the volume modulation described above.

3.1 Extra bell flow

If the reference coordinate system is connected to the air column then there is no extra bell flow. It is the boundary which moves and there is no relative velocity between the enclosed air column and the surrounding air space.

Instead of an oscillating air column boundary a simplifying assumption can be made, that the only effect of an axial bell velocity would be some extra volume flow into the bell. If this extra flow given by the velocity and area of the rim of the bell were the dominant mechanism then this simplification would be justified.

The extra flow can be taken into account by changing the radiation impedance of the bell. This change in radiation impedance is shown in Figure 3. It directly effects the transfer function but it has little impact on the bell's input impedance. It can be seen that this effect only explains some part of what we observe.

It can also be seen that this bell flow affects even and odd air resonances in an opposite way because the main structural excitation mechanism is the mouthpiece pressure, yet the associated bell pressure is alternatingly in and out of phase. A standing wave with a velocity antinode at its open end toggles its phase there when a further antinode comes along. As bell velocity toggles its phase at the structural resonance around 700Hz there is the same kind of influence on both adjacent air resonances left and right of that frequency.

3.2 Whole body motion

Below structural resonance whole body motion can occur when no part of the instrument is rigidly clamped to the table and no heavy mass is attached to the instrument. This kind of motion can be stimulated by the air pressure in the mouthpiece or in the bell or by oscillating mechanical forces like those applied by the vibrating lips of the player. In order to estimate the order of magnitude of the latter we can assume a vibrating mass M for a volume $V = 1\ cm^3$ per lip with a mass density $\rho \approx 1000\ kg/m^3$ of water, a displacement amplitude $D = 5\ mm$ and a frequency $f = 100\ Hz$. With these assumptions we obtain a force amplitude $F = 4f^2\pi^2\rho VD$ of 4 N.

Figure 4 illustrates the effect of wall vibrations including

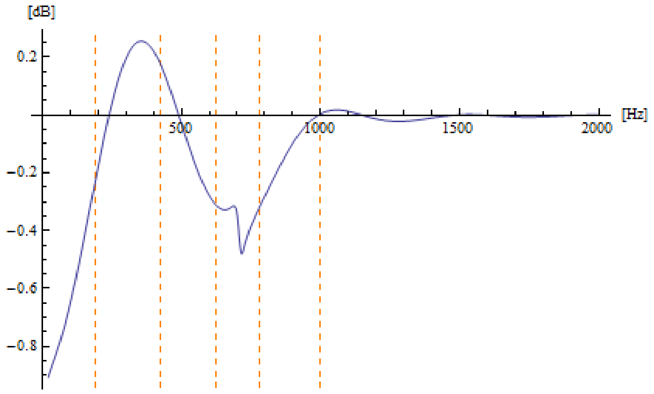

Figure 3: Difference in Radiation Impedance of trumpet bell when extra bell flow due to axial bell vibrations is taken into account (dashed lines are air resonances).

whole body motion on the theoretical pressure transfer function without and with structural excitation of 0.1 N and 1 N. It can be seen that structural excitation can multiply the effect of wall vibrations especially in the low register.

However, lowering the frequency by one octave will reduce the lip excitation force to a quarter if oscillating lip volume and vibration amplitude do not increase accordingly. It can be observed in high speed recordings of brass player's vibrating lips that amplitude and participating share of total lip volume increase strongly at lower frequencies until some kind of saturation is reached which mainly depends on the mouthpiece diameter.

It should be noted that structural excitation not only stimulates whole body motion but also amplifies the effect of existing structural resonances and it can even create new deflection shapes at different resonance frequencies. In real instruments with bends and braces it will be very difficult to predict the effect of a mechanical mouthpiece stimulus on the amplitude of bell vibrations. Although the mechanical transfer function from mouthpiece to bell can be measured, it is very sensitive to boundary conditions and can change chaotically when extra masses, damping and elastic forces are applied by holding the instrument and pressing lips and teeth against the mouthpiece rim.

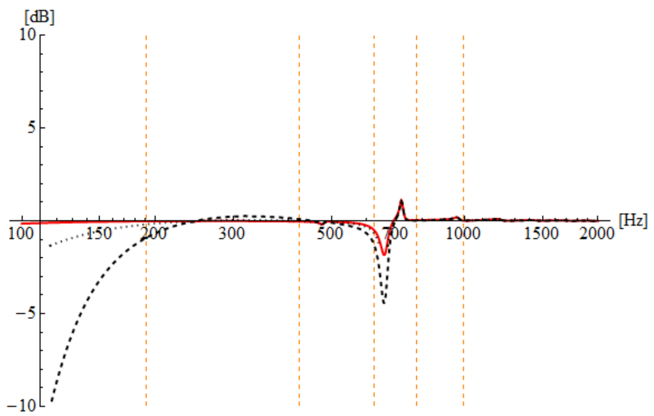

Figure 4: Theoretical difference in transfer function of trumpet bell with mouthpiece due to wall vibrations when oscillating force (0.0N solid, 0.2N dotted, 1.0N dashed) acts on mouthpiece (dashed vertical lines are air resonances).

3.3 Boundary layer loss

Assuming axial vibrations as the dominant vibroacoustic mechanism, viscous boundary layer losses might have to be reconsidered. With non-slip conditions at the enclosing wall there must be a gradient of the longitudinal particle velocity inside the boundary layer which is responsible for viscous losses. For static walls this gradient is the plane wave velocity divided by the boundary layer thickness.

If the longitudinal (axial) wall velocity is not zero then the difference between plane wave velocity and axial wall velocity will cause the losses. Therefore local boundary layer losses can become zero when the axial component of the wall velocity is equal to the air velocity and it can be significantly increased if these velocity components have opposite phase.

After having studied several cases with acoustic excitation of structural vibrations, it can be safely stated that axial wall velocities are typically by two orders of magnitude smaller than acoustical particle velocities in the air column. This means that wall vibrations do not have any significant influence on the viscous boundary layer loss in these cases. Maybe, if some strong additional structural excitation is present, the situation has to be reanalyzed.

3.4 Effect of baffle

As all experiments done so far were using a kind of baffle it is worth investigating the effect of this baffle on measured input impedance and transfer function. Theory provides models for the radiation impedance of a vibrating circular piston into the three-dimensional space or half-space.

The half-space case is usually referred to as baffled case because it can be realized as a very large wall, the baffle, with a circular hole in it, in which a perfectly fitting piston vibrates in a direction perpendicular to the wall. An analytic expression for the radiation impedance in such a case was given by Zorumski [7]. It is important that the baffle inhibits any acoustical short circuit between the half space in front of the piston and the half space behind.

The unbaffled or unflanged case was treated by Levine and Schwinger [8]. This model also assumes that no acoustic short circuit is possible between the regions above and below the piston. This is only possible if the piston vibrates in a tightly fitted cylinder with infinitely thin walls and infinite length. This notion is usually associated with acoustic plane waves leaving a long cylindrical duct with very thin but rigid walls.

Applying these two different radiation models to the trumpet bell under study, its input impedance and sound pressure transfer function can be calculated theoretically. The difference between the two cases in radiation impedance, transfer function and input impedance has been plotted in Figure 5. The 3 dB difference in radiation impedance at low frequencies obviously has to do with the fact that the acoustic energy propagates into a space twice as big in the unbaffled case.

It should be noted that the radiation impedance difference directly modifies the transfer function difference while it does not affect the input impedance difference in a comparable way. The effect of the radiation conditions on the input impedance is rather small and close to zero in the low frequency region. This seems to be the main reason why it is much easier to achieve a good match between

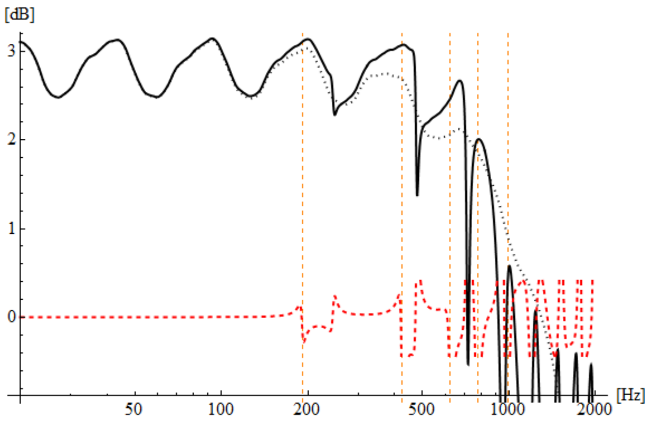

Figure 5: Difference in Radiation Impedance (dotted), Transfer Function (solid) and Input Impedance (dashed) of trumpet bell with Zorumski (baffled) and Levine (unbaffled) radiation model (dashed lines are air resonances).

experiment and theory when input impedance differences are compared.

Transfer function measurements consistently exhibited a constant shift by up to 3dB in the low frequency region which was attributed to wall vibration effects. But as there is no theoretical explanation for such a shift the experimental setup was reconsidered. Eventually a small gap of 1 to 2 mm was noted that surrounded the rim in order to let it vibrate freely in one case. When the bell was damped with sandbags or by filling up the sandbox this gap was tightly closed.

This condition - a finite baffle separated by a narrow gap from the rim - was modeled using Finite Element Methods (FEM) and it turned out, that this gap does render the baffle almost ineffective. That means what was considered the damped case was simultaneously a baffled case while in the undamped case the effect of the baffle was lost to a great extent.

Preliminary experiments where the gap was filled with silicone paste were able to confirm the baffle issue. In recent transfer function measurements shown in Figure 2 the constant shift by up to 3 dB down to low frequencies was no longer present, leaving a remaining difference due to wall vibration which is now close to what we expect from theory.

4 Conclusion

Recently a significant step forward has been made towards a correct understanding of the effects of wall vibrations on the acoustic properties of brass wind instruments. While a certain wide band shift of the transfer function, observed in many experiments with different instruments and at different locations, was attributed to wall vibrations in the past, it has now been recognized as an influence of the baffle which was not tightly sealed in the undamped case. A 1-2 mm gap had been left free intentionally in order not to obstruct any vibrations of the rim.

The remaining acoustic effect of wall vibrations predicted by physical modeling and observed in related experiments is still considerable and in the absolute worst case of thick wall material, perfect symmetry, no mechanical stimulus and no coincidence between structural and air column resonances in a range of a dB and even more. In practice there will be some mechanical stimulus, broken symmetries and thinner walls at least in the most critical part of the bell.

Although such realistic cases are still to be studied, it is very likely that the claim of musicians and brass wind instrument makers, that wall thickness and wall materials do matter, is justified. Not to mention the fact that a vibrating mouthpiece might disturb or support the highly non-linear feedback loop of the sound generating lip oscillator. The lips critically depend on external forces keeping them synchronized and, as it was already shown in a slightly different context, mechanical forces can easily be stronger than even forces due to the very high sound pressure inside the mouthpiece.

The ease of making the lips vibrate is usually referred to as response or responsiveness. Investigating the effect of wall vibrations on the response of brass wind instruments will be the next step. It requires an experimentally proven vibroacoustic model, which is now very close to finalization, and some knowledge on how it applies or relates to whole instruments.

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