Research and development of a casual wind instrument: Venova(TM)

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A completely new type of casual wind instrument **Venova*** "YVS-100" (Fig. 1) based on a branch-pipe structure was developed by Yamaha and released recently on the market. Although this musical instrument sounds similarly to a single-reed instrument made of a tapered tube, such as the saxophone. It is smaller in size and has a lighter weight compared to the regular saxophone. It also allows performance with finger tone-holes, similarly to the recorder. These characteristics were made possible by a branched-pipe and meandered-pipe structures. In this paper, we introduce the theory, technology, and the different development steps which led to this new product. In particular we explain the research and development processes from the initial acoustic concept, to the realization of a playable and original musical instrument.

1 Introduction

In Yamaha, the first application of branch-pipe musical instruments goes back to the development of a physical modeling synthesizer named Virtual Acoustic Synthesizer VL1 (Fig. 2) that was released in 1993. In the development process, conical pipe resonators were modelled by the series connection of cylindrical pipes with increasing internal diameters.

In order to obtain the acoustic characteristics of an ideal conical pipe, it is necessary to shorten each cylindrical pipe enough to obtain a good discretization of the tapered pipe. This induces an important amount of calculations.

As a consequence, it was difficult to realize a synthesizer which needed real-time synthesis.

An article from Prof. Saneyoshi [1] offered a solution to overcome this limitation. When we interpreted the formula of the paper, it turned out that a conical pipe can be approximated with the branch-pipe structure of two cylindrical pipes.

In digital simulation, a cylindrical pipe can be implemented by the delay elements which simulates forward and backward propagating waves. The branch can be implemented with a simple waveguide junction element.

Consequently, we succeeded in dramatically reducing the computation cost. [2]

In this development, I got idea that if we can apply such equivalence using a physical model synthesizer, it might be possible to realize a real musical instrument. After that, a first prototype was produced (Fig. 3).

Figure 1: Casual wind instrument **Venova** "YVS-100"

Figure 2: Virtual Acoustic Synthesizer VL1

Figure 3: First prototype of branch-pipe saxophone

2 Theory of branch-pipe

2.1 Basic theory

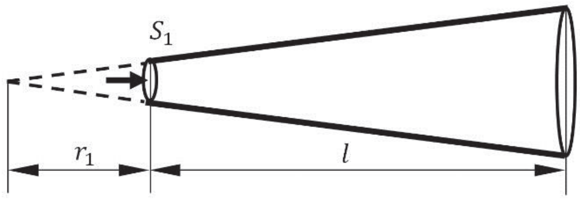

Figure 4: Geometrical parameters of a conical pipe

The acoustic input impedance $\dot{Z}_l$ which is seen from the entrance of the conical pipe shown by an arrow in the case of the conical pipe as in Fig. 4, is calculated as follows according to paper [1].

If we assume that the diameter of the entrance is sufficiently smaller than the wavelength, that the reflection is complete at the pipe end, that the tube wall is sufficiently rigid, and that other losses are ignored, then the acoustic field inside the pipe follows a spherical wave. In this case, the velocity potential inside the pipe $\dot{\phi}$, acoustic pressure $\dot{p}$, and velocity $\dot{v}$ are denoted by the Eq. (1), (2), and (3).

$$\dot{\phi} = \frac{\dot{A}}{r}e^{-jkr} + \frac{\dot{B}}{r}e^{jkr} \tag{1}$$

$$\dot{p} = \frac{j\omega\rho}{r}\left(\dot{A}e^{-jkr} + \dot{B}e^{jkr}\right) \tag{2}$$

$$\dot{v} = \frac{1}{r^2}\left\{\dot{A}(1+jkr)e^{-jkr} + \dot{B}(1-jkr)e^{jkr}\right\} \tag{3}$$

Eq. (4) is obtained by substituting $\dot{p} = 0$ at $r = r_1 + l$ in Eq. (2) as a boundary condition.

$$\dot{B} = -\dot{A}e^{-j2k(r_1+l)} \tag{4}$$

If this is substituted in Eq. (2) and (3) we can obtain $\dot{p}$ and $\dot{v}$ at $r = r_1$.

$$\dot{p}|_{r=r_1} = \frac{j\omega\rho}{r_1}\dot{A}\left(e^{-jkr_1} - e^{-jkr_1-j2kl}\right) \tag{5}$$

$$\dot{v}|_{r=r_1} = \frac{\dot{A}}{{r_1}^2}\left\{(1+jkr_1)e^{-jkr_1} - (1-jkr_1)e^{-jk(r_1+2l)}\right\} \tag{6}$$

Therefore, the acoustic input impedance $\dot{Z}_l$ becomes as follows:

$$\dot{Z}_l = \left.\frac{\dot{p}}{\dot{v}}\right|_{r=r_1} / S_1 = \frac{j\rho c}{S_1}\frac{kr_1 \sin kl}{\sin kl + kr_1 \cos kl}. \tag{7}$$

The acoustic input admittance $\dot{Y}_l$ becomes as follows:

$$\dot{Y}_l = \frac{S_1}{j\rho c k r_1} + \frac{S_1}{j\rho c \tan kl}. \tag{8}$$

Equations (1)-(8) come from Prof. Saneyoshi's considerations.

I added the following considerations:

The second term in Eq. (8) is the acoustic input admittance of the cylindrical pipe itself with the same cross section S_1 as the input cross section of the conical pipe and same length l as the conical pipe length. The first term can be considered as the input admittance of a cylindrical pipe of cross-sectional area S_1 length l when kr_1 is small, that is under big taper factor and low frequency conditions, since in this case $kr_1 \approx \tan kr_1$.

$$\dot{Y}_l \approx \frac{S_1}{j\rho c \tan kr_1} + \frac{S_1}{j\rho c \tan kl} \tag{9}$$

Therefore, it can be interpreted as the ability of a conical pipe to be approximated by the system shown in Fig. 5, the parallel connection (i.e. the branch-pipe structure) of a cylindrical pipe of cross-sectional area S_1 and length l, and a cylindrical pipe of cross-sectional area S_1 and length r_1, under such conditions.

The hole of the cross-sectional area S_1 is opened at the location indicated by the arrow in Fig. 5.

This is the basic theory of a branch-pipe that was interpreted by Yamaha from the paper [1].

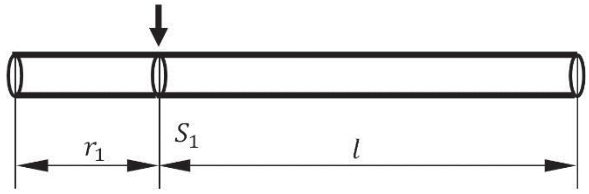

Figure 5: Basic theory of branched pipe structure

2.2 Extended theory

In the conical pipe of an actual musical instrument, a taper factor is small. It is difficult to realize the characteristic of a conical pipe with sufficient accuracy in high frequency with this basic theory since small taper factor means large value of r_1.

In order to improve the degree of approximation of a conical pipe, the denominator and numerator of the first term are multiplied by a positive number H smaller than 1.

$$\dot{Y}_l = \frac{HS_1}{j\rho c k H r_1} + \frac{S_1}{j\rho c \tan kl} \tag{10}$$

By this modification, even if a large value of r_1 is needed because of small taper factor, the value of H can be approximated as $kHr_1 \approx \tan kHr_1$ if H is small enough.

$$\dot{Y}_l \approx \frac{HS_1}{j\rho c \tan kHr_1} + \frac{S_1}{j\rho c \tan kl} \tag{11}$$

Therefore, it becomes possible to approximate the acoustic characteristics of a conical pipe up to high frequencies by using a thinner and shorter branch pipe which cross-sectional area is HS_1 and length is Hr_1 as shown in Fig. 6.

The hole of the cross-sectional area S_1 is opened at the part shown by the arrow in Fig. 6.

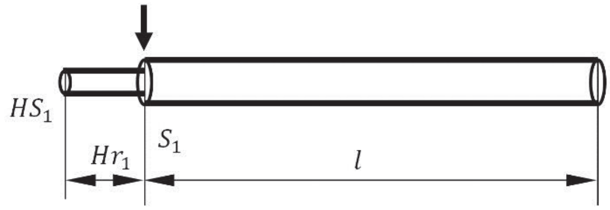

Figure 6: Branch-pipe structure by extended theory

Figure 7 shows the amplitude of acoustic input impedance $|\dot{Z}_i|$ calculated by basic theory for a cone of $S_1 = 113.1[mm^2], r_1 = 180.0[mm],\ l = 442.0[mm]$, and approximation result by the extended theory with $H = 4/9$.

According to Eq. (11), when H is reduced to the limit, it seems that the approximation tends towards an optimal fit with extremely short and narrow branch-pipe. Actually, there is a suitable internal diameter since a branch-pipe does not function as an open pipe in extremely small diameter conditions.

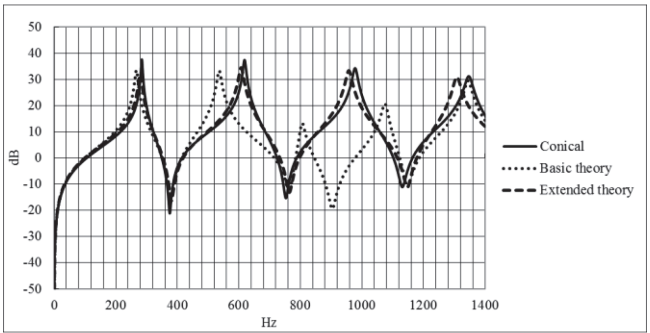

Figure 7: $|\dot{Z}_i|$ comparison of basic theory and extended theory of conical pipe approximation

3 Acoustic design

The specifications of **Venova** "YVS-100" (henceforth **Venova**) require using a mouthpiece and reed equivalent to a soprano saxophone, chromatic fingering using the same fingered tone-hole as a recorder, and a playing range of about two octaves of the soprano (from C4 to C6).

In order to meet the required specifications, the following adjustment steps were repeated:

- Calculation of acoustic input impedance
- Trial production of a straight model
- Measurement of the acoustic input impedance
- Playing evaluation

3.1 Simulation

Calculation of the acoustic input impedance is based on the transfer matrix method [3], using a computer program developed in Yamaha.

This program makes it possible to take into account the branch-pipe (a branch-pipe part and a tone-hole part) by a branch option. It is possible to calculate the acoustic input impedance of a pipe having a branched structure.

In order to improve accuracy, the branch-pipe and tone-hole height is compensated by the following formulas [4]. Branch-pipe and tone-hole length t_w are compensated to t_e by Eq. (12) or Eq. (13) for close-end or open-end conditions respectively.

These correction parameters are taken into account in our computer simulation program.

Here a is radius of the main-pipe and b is radius of the branch pipe or tone-hole.

$$t_e = t_w + [b(b/a)/8][1 + 0.172(b/a)^2] \quad (12)$$

$$t_e = t_w + b[1.40 - 0.58(b/a)^2] \quad (13)$$

In the actual simulation, the whole pipe is decomposed into basic geometrical component parameters, and we carry out the simulation at each fingering.

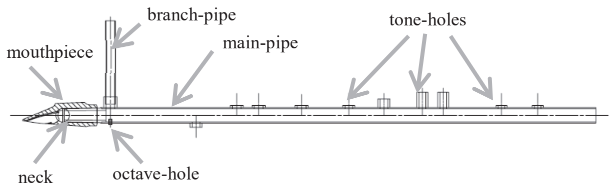

Figure 8: Basic acoustic structure of **Venova**

In the process of optimization using our impedance calculation program, each basic geometrical parameters were adjusted by paying attention to the following fundamental requirements:

- The frequency ratio of first and second acoustic input impedance resonances is about two.
- Make sure that the amplitude levels of first and second resonances do not become too low.

3.2 Trial of straight model

After carrying out this optimization process, a straight model which can actually be played was manufactured and playing evaluations were carried out.

The capillary method [3] was used for measurement of acoustic input impedance.

Regarding impedance calculation, an acceptable level of correlation with measurements, required for the design, was obtained.

3.3 Adjustment of pitch

In actual playing conditions, the oscillating frequency and the resonance frequency of the acoustic input impedance of pipe are not exactly identical.

Adjustment of the pitch was performed with the following procedures.

- Change of basic geometrical parameters
- Extract resonance frequency difference of simulated and measured acoustic input impedance
- Measure playing pitch difference before and after changes of basic geometrical parameters
- Predict basic geometrical parameters in order to improve real playing pitch

3.3.1 Adjustment of octave

The fingering of **Venova** is designed to be almost the same as in the first register of the recorder.

Furthermore, it is designed so that the fingering is almost the same in both second and first registers.

The following adjustments are performed in order to realize them:

- Adjustment of basic geometrical parameters of a branch-pipe part roughly
- Adjustment of each tone-hole height with respect to individual pitch of each fingering

In the case of the recorder, octave relations are adjusted by setting up individually not only the position of each tone-hole but also the diameter of each tone-hole.

In the case of **Venova**, it was adjusted by setting up the height of a tone-hole individually while the diameter was kept constant.

3.3.2 Adjustment of cross fingering

In **Venova**, there is a possibility of cross fingering like in a recorder.

In order to obtain the right pitch by cross fingering, it is necessary to raise the acoustic input impedance amplitude of one open tone-hole located in between closed tone-holes by making the diameter smaller or the length longer (for **Venova**, the length only was adjusted).

However, it is easy to reduce the second input impedance resonance level and decrease the third resonance frequency in this case.

Consequently, this may interfere with playability during actual performance.

In **Venova**, the note that uses cross fingering was adjusted, taking into consideration the balance between pitch and playability.

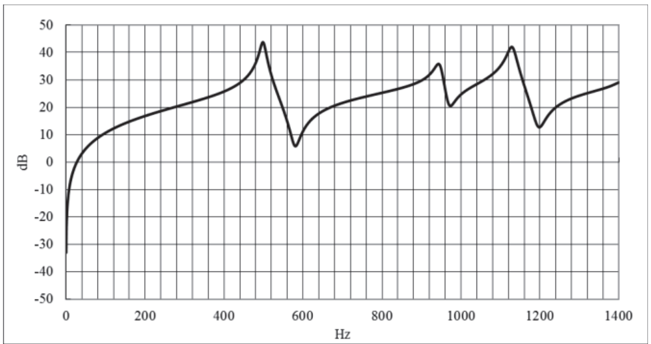

Figure 9: $|\dot{Z}_\iota|$ of cross fingering Bb4

3.4 Adjustment of meandered-pipe

Venova has meandered-pipe so that player's fingers reach tone-holes and keys easily and so that the instrument become compact enough.

Meandering is based on the straight model after pitch adjustment is completed.

If meandering is applied by just bending its axis, resonance frequencies of the acoustic input impedance will change.

This seems to be due to a change in effective acoustic length of the pipe due to bended sections (in many cases, bent pipe induce an acoustic shortening effect compared to original straight pipe) [5].

Adjustment of the pitch was performed with the following procedures:

- Set the straight model whose pitch adjustment has been completed to reference
- Design and production model (just bend its axis)
- Measure the resonance frequency of the acoustic input impedance of the meandering model
- The difference from the resonance frequency of acoustic input impedance of the straight model is replaced with the pipe length, adjustment to meandering shape

4 Conclusion

The extension of branch-pipe basic theory showed that a conical tube could be approximated with sufficient accuracy.

Venova was developed as a new wind instrument based on a design by the "branch-pipe structure" and meandering shape, involving cylindrical pipes, and allowing a single reed instrument blowing feeling, as well as a two-octave range.

By "branch-pipe structure" the acoustic characteristics of conical wind instruments are realized with cylindrical pipes, which makes it possible to produce saxophone-like sounds from a compact-body music instrument.

By making the tube meandered, **Venova** consists of a simple structure with smaller tone-holes spacing, easier to close with fingers. It requires less keys, and allows the same fingering pattern as in the recorder.

With this product, I am hoping that new ways of enjoying wind instruments will spread in various scenes such as outdoor scenes and casual sessions.

Acknowledgments

I am particularly thankful to Prof. Saneyoshi for his research that triggered the development of **Venova**.

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