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One-dimensional acoustic modeling of the Şimşal considering the external interaction of the open finger holes

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A one-dimensional model in Python was developed to analyze the acoustic behavior of the Kurdish wind instrument, the şimşal. This model was developed using the Transfer-Matrix Method (TMM), which was refined by taking into account the external interactions between the open tone holes. This research focuses on the acoustic resonator part of the şimşal with the lattice of finger holes in different cross-fingering patterns. The results were validated by measurements using an impedance probe, CapteurZ, which was developed by LAUM[1] and CTTM[2]. The results are in very good agreement with the measurement and despite the possible sources of error, which are discussed, the deviations are within an acceptable range.

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1. INTRODUCTION

The şimşal, which is of Kurdish origin, is made of varied materials. The instrument studied in this paper is the şimşal-şivani (şivani in Kurdish means something that is related to a shepherd), which is composed of metal and is mainly played in the Mukriyan region of Kurdistan. The metal version of şimşal is, of course, more resistant to breakage or damage compared to non-metallic versions made of wood or phragmites (Phragmites or common reed is a type of grass used to make local flute-like instruments.) which were mostly used in the past. Both ends of the şimşal are open and there are 6 finger holes on top and another finger hole at the bottom of the instrument (Figure 1). The sound range of the şimşal is limited compared to the Western flute and normally encompasses less than two octaves (4 tetrachords), so there are different şimşals like şimşal in tuning F, F-sharp, G, etc. with different geometries to overcome this limitation and to be playable in different Kurdish music modes.

Figure 1 The top and bottom views of the şimşal.

The process of manufacturing musical instruments in Kurdistan is mostly subjective and empirical, and the cumulative decisions and actions taken during this process constitute a set of practices that has been transferred from generation to generation throughout history. The modification and innovative ideas for improving the instrument are done based on trial-and-error logic, and a considerable number of şimşals end up being discarded during the process. One of the motivations of our work is to propose an optimized manufacturing practice through more standardized criteria which could be applied in large- or local-scale contexts. In this study, a one-dimensional acoustic model is developed and validated for a sample şimşal as part of a research project for verifying the subjective manufacturing standards of local manufacturers in Kurdistan.

Acoustic analyses of wind musical instruments have been widely reported over the past five decades and in most cases, one-dimensional approximations have been considered adequate to understand the most significant aspects of their behavior. Transfer-Matrix Method (TMM) has been used both for Western classical musical instruments like the flute [1], clarinet [2], saxophone [3], and the local or folk musical instruments like the aulos [4], gaita [5], and Chinese transverse flute [6]. The basic TMM model of Keefe [7] did not consider the external interaction of the open holes, which was initially studied by Leppington [8], and in some cases, there can be considerable discrepancies between the calculated results with and without external interactions [9].

2. MODELING PROCESS

Richardson in 1929 [10] proposed a successive impedance procedure which was later modified and supplemented by several researchers over the decades and finally introduced as the transfer-matrix method (TMM). It is a common technique used to calculate the input impedance or reflectance of 1D acoustic systems which can be approximated in terms of concatenated cylindrical and/or conical sections, as well as side branches. Each section is represented by a transfer-matrix that relates frequency domain expressions from input to output in terms of pressure and volume velocity [11]. At each frequency, it is necessary to multiply the matrix of each section to calculate the acoustic properties of the entire system.

Equation. (1) is the schematic equation for each section of the instrument in which "P_{in}" and "P_{out}" are the acoustic pressure at the input and output of the section. "U_{in}" and "U_{out}" are the acoustic volume flow respectively. After calculating the transfer-matrix "T_i", for each section, the input impedance of the instrument can be calculated as in Eq. (2):

$$\begin{bmatrix} P_{in} \\ U_{in} \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} P_{out} \\ U_{out} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} P_{in} \\ U_{in} \end{bmatrix} = \left(\prod_{i=1}^{n} T_i \right) \begin{bmatrix} P_{out} \\ U_{out} \end{bmatrix}, where\ T_i = \begin{bmatrix} a_i & b_i \\ c_i & d_i \end{bmatrix} \tag{2}$$

A. AIR COLUMN

As the main part of the şimşal is a cylindrical waveguide, the transfer-matrix for a cylinder with a length of L considering the thermos-viscos losses may be calculated as in Eq. (3):

$$T_{cyl} = \begin{bmatrix} cosh(\Gamma L) & \bar{Z}_c . sinh(\Gamma L) \\ \dfrac{sinh(\Gamma L)}{\bar{Z}_c} & cosh(\Gamma L) \end{bmatrix} \tag{3}$$

"Γ" is a complex-valued propagation wavenumber and "$\bar{Z}_c$" a normalized complex-valued characteristic impedance to include the boundary layer losses within the transfer-matrix which could be calculated based on Keefe's equations [12].

B. RADIATION AT THE OPEN END

At the open end of the instrument, acoustic waves are partly reflected to maintain self-sustained oscillation and are partly transmitted into the air. The radiation impedance, which is frequency dependent, was developed by Levine and Schwinger [13] for an unflanged pipe and approximated by Caussé [14] as Eq. (4):

$$\begin{aligned} \bar{Z}_r = 0.6113jka - j(ka)^3[0.036 - 0.034\,log(ka) + 0.0187(ka)^2] + \frac{(ka)^2}{4} \\ + (ka)^4[0.0127 + 0.082\,log(ka) - 0.023(ka)^2], \end{aligned} \tag{4}$$

where "a" is the radius of the main bore, and "k" is the wavenumber which is equal to the ratio of the angular frequency "ω" and the speed of sound "c".

C. FINGER HOLE

As mentioned above, a şimşal has seven finger holes on its dorsal surface which play the primary role in modifying the produced frequency. They are considered as discontinuities which affect the self-sustained oscillation inside the bore. To simulate the finger hole transfer-matrix, Keefe [15] proposed a symmetric T-section depending on shunt $\bar{Z}_s$ and series impedances $\bar{Z}_a$ using Eq. (5):

$$T_{hole} = \begin{bmatrix} 1 & \dfrac{\bar{Z}_a}{2} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{1}{\bar{Z}_s} & 1 \end{bmatrix} \begin{bmatrix} 1 & \dfrac{\bar{Z}_a}{2} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 + \dfrac{\bar{Z}_a}{2\bar{Z}_s} & \bar{Z}_a \left(1 + \dfrac{\bar{Z}_a}{4\bar{Z}_s} \right) \\ \dfrac{1}{\bar{Z}_s} & 1 + \dfrac{\bar{Z}_a}{2\bar{Z}_s} \end{bmatrix} \tag{5}$$

The shunt and series impedances for a closed (c) and open (o) tone hole are calculated using Eq. (6) to Eq. (9) proposed by Keefe [16].

$$\bar{Z}_s^{(o)} = jkt_e^{(o)} + \xi_s \tag{6}$$

$$\bar{Z}_a^{(o)} = jkt_a^{(o)} \tag{7}$$

$$\bar{Z}_s^{(c)} = -\frac{j}{kt_e^{(c)}} \tag{8}$$

$$\bar{Z}_a^{(c)} = jkt_a^{(c)}, \tag{9}$$

where "t_e" and "t_a" are the shunt and series length corrections, and "ξ_s" is the open tonehole shunt resistance which is calculated as $0.25(kb)^2$.

There are several references like Nederveen [17], Keefe [7], Dubos [18], etc. that propose efficient relations for calculating the shunt and series length corrections for regular woodwind and brass instruments with tone holes with chimneys. However, the finger holes of the şimşal are different in that they are drilled directly through the surface of the şimşal as depicted in Figure 2, so there is no raised chimney or pad attached to the bore.

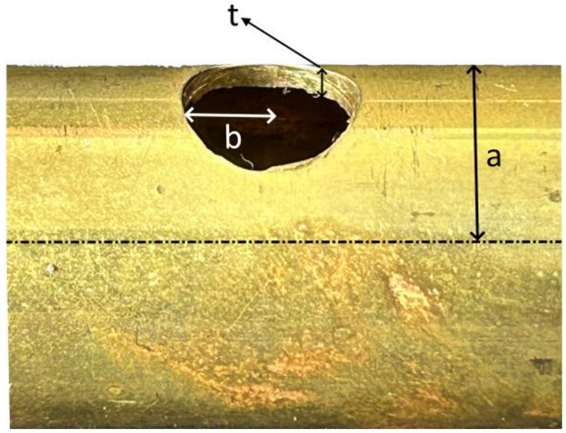


Figure 2 Finger hole drilled directly on a pipe.

Lefebvre [19] used the Finite Element Method for studying the acoustic behavior of a single tonehole drilled directly into a pipe, and the shunt and series length corrections in the current study (Eq. (10) to Eq. (13)) are calculated based on the equations previously derived by him.

$$t_e^{(o)}/b = t/b + \left[1 + f(\delta)g\left(\delta, t/b\right)\right]h(\delta) \text{ , with} \tag{10}$$

$$f(\delta) = -0.044 + 0.269\delta - 1.519\delta^2 + 2.332\delta^3 - 1.897\delta^4 + 0.560\delta^5$$

$$g\left(\delta, t/b\right) = 1 - \tanh\left(0.788\, t/b\right)$$

$$h(\delta) = 1.643 - 0.684\delta + 0.182\delta^2 - 0.394\delta^3 + 0.295\delta^4 - 0.063\delta^5$$

$$t_a^{(o)}/b\delta^4 = -f\left(\delta, t/b\right)g(\delta)\text{, where} \tag{11}$$

$$f\left(\delta, t/b\right) = 1 + (0.261 - 0.022\delta)\left[1 - \tanh\left(2.364\, t/b\right)\right]$$

$$g(\delta) = 0.302 - 0.010\delta - 0.006\delta^2$$

$$t_e^{(c)} = t + \frac{b\delta}{8}(1 + 0.207\delta^3) - \frac{b^2}{8(a+t)}\left(1 + 0.207\left(\frac{b}{a+t}\right)^3\right) \tag{12}$$

$$t_a^{(c)}/b\delta^4 = -f\left(\delta, t/b\right)g(\delta)\text{, where} \tag{13}$$

$$f\left(\delta, t/b\right) = 1 - (0.956 - 0.104\delta)\left[1 - \tanh\left(2.39\, t/b\right)\right]$$

$$g(\delta) = 0.299 - 0.018\delta + 0.006\delta^2,$$

where "t" is the bore thickness, "b" is the finger hole radius, and $\delta = \frac{b}{a}$ is the ratio of the radius of the tonehole to the radius of the main bore.

Moreover, there are no keypads for the toneholes on the şimşal, which are closed directly with the fingers. Thus, a part of the finger passes through the air column, reducing the effective exposed area of each section and, consequently, the shunt equivalent length of the segment in closed condition. This negative effect can be amplified in fingerings with more closed finger holes compared to others with fewer ones. The equivalent length calculation is adjusted by the finger length correction t_f which is approximated by Eq. (14) where "h" is the height of the spherical cap (finger) which enters the tonehole cylindrical section [19]:

$$t_f = \frac{h\left(3 + \left(\frac{h}{b}\right)^2\right)}{6} \tag{14}$$

D. EXTERNAL INTERACTION OF THE OPEN FINGER HOLES

We know that the TMM is based on the one-dimensional acoustic simulation of an air column with finger holes which are considered to be independent from each other. Given the geometry of the şimşal and the size of the finger holes, which are relatively close to each other, these external effects are considered in this work, based on the TMMi ("i" stands for considering the external interaction of the open tone holes) modelling proposed by Lefebvre [20]. Based on his work, the effect of tonehole interactions is generally more important when the toneholes are closer together.

3. ŞIMŞAL SAMPLE AND MEASUREMENT

A sample of şimşal was obtained from a local manufacturer in Kurdistan and its quality was confirmed by a local expert şimşal player. The geometric measures of this instrument are provided in Table 1.

Table 1 Geometric measures of the şimşal sample.

Design Parameter	Measured value (mm)
Instrument Length	496
Instrument internal diameter	15.8
Bore thickness	1.1
Finger holes diameter	8
Distance between inlet and the 1st finger hole	243.5
Distance between inlet and the 2nd finger hole	273
Distance between inlet and the 3rd finger hole	303
Distance between inlet and the 4th finger hole	332
Distance between inlet and the 5th finger hole	361
Distance between inlet and the 6th finger hole	387
Distance between inlet and the 7th finger hole	418

The tone holes diameter is supposed to be 8 mm, but some imperfections are present on the sample. A close-up view of these imperfections in the toneholes on the sample şimşal is shown in Figure 3.

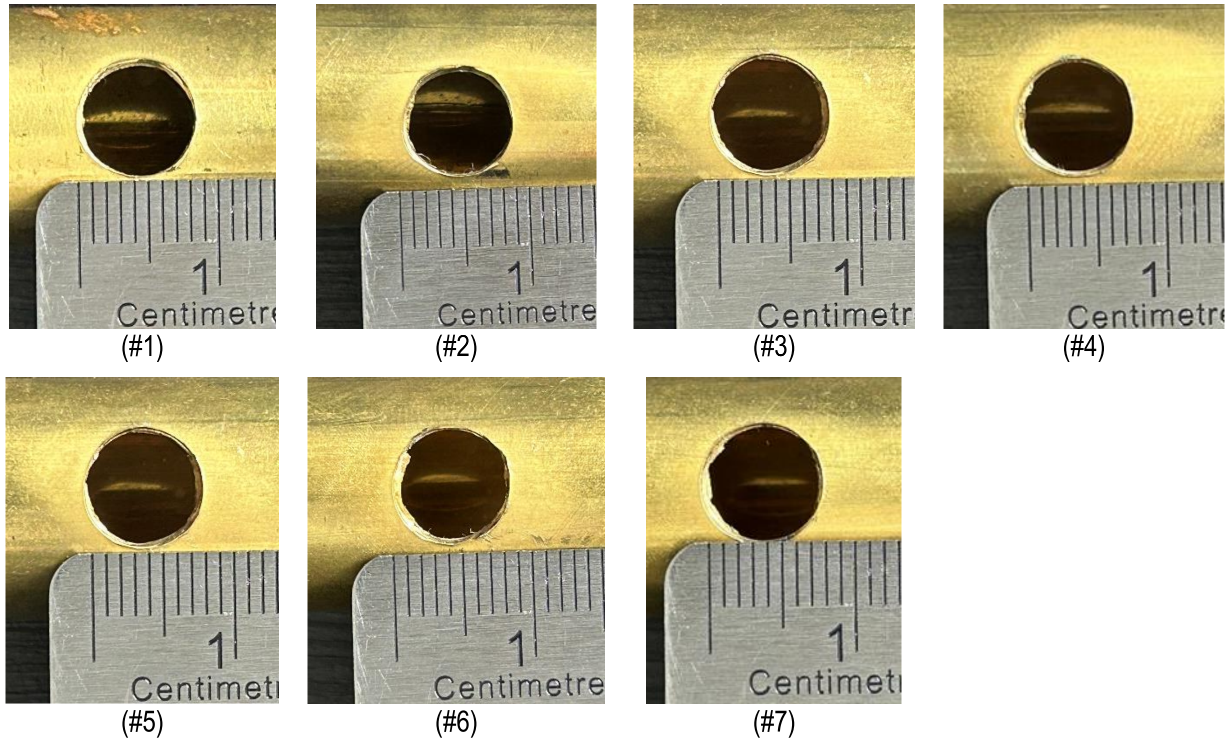


Figure 3 Tonehole drilling quality on the sample şimşal (numbering starts from the closest hole to the inlet).

The input acoustic impedance of the şimşal sample was measured with different fingering patterns using CapteurZ [21], which is based on a measurement method using two microphones (See Figure 4). The measurement was conducted at the Spatial Audio Lab of the Centre for Interdisciplinary Research in Music, Media, and Technology (CIRMMT), which is a hemi-anechoic room.

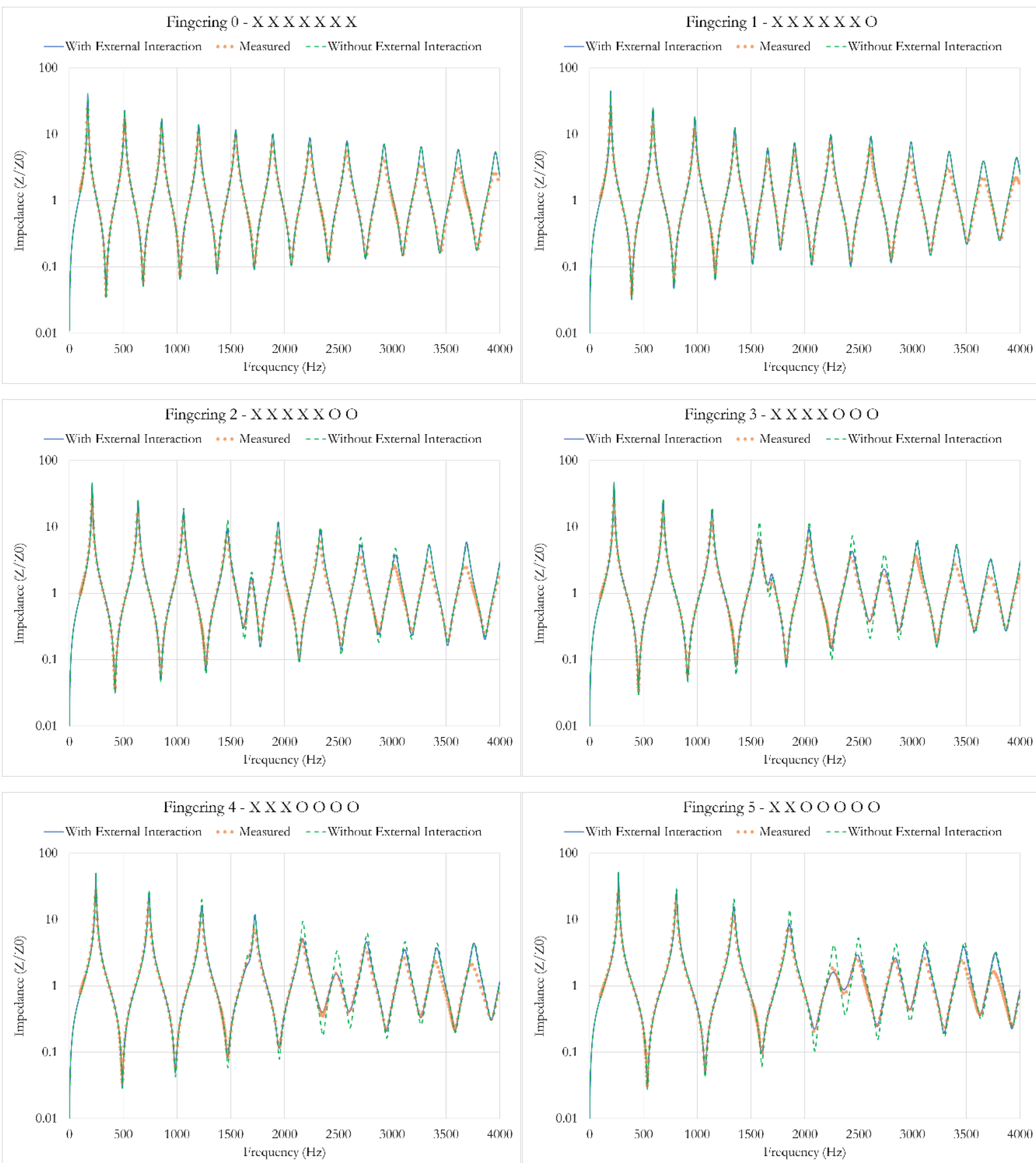
Figure 4 Impedance measurement of şimşal with CapteurZ.

4. ACCEPTANCE CRITERION

The Wier [22] criterion is considered in this research as the "acceptable range" to evaluate the calculated results. It was proposed as the smallest difference in frequency of successive tones that could be detected by a listener, which is approximately 8 cents for frequencies around 400 Hz and decreases linearly to 2 cents for 1000Hz. Cent is the unit of measure for the ratio between two frequencies. There are 100 cents per semitone and 12 semitones per octave in an equal-tempered tuning system, so a cent is equal to $1200\log_2(f_2/f_1)$.

5. RESULTS

The calculated acoustic input impedance using TMMi was validated against the measured impedance for each fingering of the instrument in Figure 5 below. It is evident that as the number of open finger holes increases, the effect of the external interaction between the open tone holes is more important.



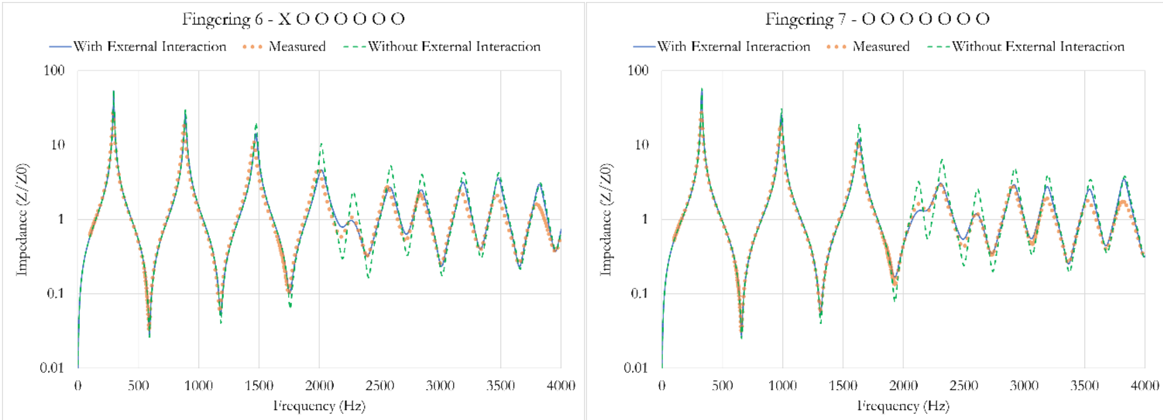


Figure 5 Comparison of measured acoustic input impedance and calculated input impedance (with and without external interaction) for all fingerings of the şimşal. X and O indicate closed and open finger holes, respectively.

The difference between the calculated result and the measured one for each fingering is presented in Table 2. As can be seen in this table, the calculated results for different fingerings for the first impedance non-zero minimum, assumed to correspond to the fundamental playing frequency of the instrument, are within an acceptable range of the measured ones.

Table 2 Comparison of calculated and measured first impedance minimum for different fingerings of şimşal.

Fingering	**Measured (Hz)**	**Calculated (Hz)**	**Difference (Cent)**
0	342.4	341.3	5.57
1	392.2	392	0.88
2	424.2	424.4	0.82
3	454.6	454.6	-
4	491.8	492.2	1.41
5	536.6	536.8	0.65
6	591.4	592.2	2.34
7	658.8	659.3	1.31

In order to get an idea of the harmonic content, the frequency ratios of the subsequent minima of the measured results (shown in Table 3) are compared with the calculated ones and are presented in Table 4.

Table 3 Harmonic ratios of the measured results of şimşal.

		Harmonic Ratio								
		2nd/f0	**3rd/2nd**	**4th/3rd**	**5th/4th**	**6th/5th**	**7th/6th**	**8th/7th**	**9th/8th**	**10th/9th**
Fingering	**0**	2.00	3.01	4.02	5.03	6.04	7.04	8.05	9.06	10.08
	1	2.00	2.98	3.88	4.53	5.27	6.19	7.16	8.09	8.96
	2	2.00	2.99	3.83	4.19	5.03	5.95	6.79	7.50	8.30
	3	2.00	3.00	3.67	4.03	4.95	5.72	6.33	7.10	7.87
	4	2.01	2.99	3.97	4.79	5.29	5.99	6.64	7.28	7.97
	5	2.00	2.98	3.90	4.41	4.98	5.54	6.14	6.76	7.32
	6	1.99	2.95	3.69	4.05	4.59	5.09	5.63	6.18	6.68
	7	1.99	2.93	3.33	3.79	4.15	4.65	5.11	5.58	6.06

Table 4 Difference between calculated and measured higher harmonic ratio for different şimşal fingerings.

		Difference in Harmonic Ratio								
		2nd/f0	3rd/2nd	4th/3rd	5th/4th	6th/5th	7th/6th	8th/7th	9th/8th	10th/9th
Fingering	**0**	0.2%	0.1%	-0.1%	-0.1%	0.0%	0.0%	0.0%	0.0%	-0.1%
	1	0.0%	-0.1%	-0.1%	0.0%	0.2%	0.0%	0.0%	0.1%	-0.1%
	2	-0.2%	0.0%	-0.3%	0.2%	0.2%	0.1%	-0.2%	0.1%	-0.1%
	3	-0.2%	0.0%	-0.4%	0.4%	0.0%	0.2%	-0.1%	-0.1%	0.0%
	4	-0.3%	0.0%	0.0%	-0.1%	0.2%	0.0%	-0.1%	0.1%	0.0%
	5	-0.1%	0.0%	0.0%	-0.1%	0.2%	-0.1%	0.0%	0.1%	-0.1%
	6	0.3%	0.1%	-0.2%	-0.4%	0.2%	-0.2%	0.0%	0.0%	-0.1%
	7	0.0%	-0.1%	-0.8%	0.7%	0.1%	-0.2%	0.2%	0.0%	-0.1%

6. CONCLUSION

The calculated acoustic response of the air column of the şimşal with different fingering patterns was modeled using the TMMi method, which accounts for external interactions between open holes. The calculated frequencies of the first impedance minima correspond with the measured ones, with a difference of about ±5 cents for each fingering which is an acceptable difference. In addition, the calculated frequency ratios of the subsequent minima are in very good agreement with the measurement. The highest difference is about 0.8% and is observed for the third and fourth frequency ratios in the 7th fingering pattern in the range of 1700 Hz - 2100 Hz where the cut-off is observed.

There are some sources of error which need to be addressed. First, there were some challenges related to the shape of the finger holes of the şimşal sample. This is important because in TMM, the toneholes are assumed to be perfectly circular, whereas the holes on our sample were not drilled perfectly. Secondly, the calculations require that the temperature be known, but what was specified to the impedance measuring equipment may have been slightly different from the actual ambient temperature and/or the temperature inside the instrument, as the room temperature sensor was permanently located at a distance from the experimental apparatus. This is not ideal because the possible temperature difference between the sensor location and the air inside the instrument affects the calculation results.

Despite the discussed discrepancies and possible sources of error, the developed model is shown to be capable of predicting the acoustic behavior of the Kurdish şimşal. It is thus possible to use this model to verify the subjective manufacturing standards used by local manufacturers in producing the instrument. Indeed, the model would be even more accurate if the sound generation mechanism, the interaction of the produced air jet by the player and the resonator, could be integrated into the present model.

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REFERENCES

1] P. Dickens, *Flute acoustics: measurement, modelling and design (PhD Thesis),* Sydney: University of New South Wales, 2007.

2] G. Scavone et J. O. Smith, «A Stable Acoustic Impedance Model of the Clarinet using Digital Waveguides.,» *In Proceedings of the 2006 International Conference on Digital Audio Effects (DAFx-06),* pp. 89-94, 2006.

3] A. Lefebvre et G. Scavone, «On the bore shape of conical instruments,» *Proceedings of the Acoustics Week in Canada,* vol. 39, pp. 128-129, 2011.

4] S. Polychronopoulos, D. Marini, K. Bakogiannis, G. T. Kouroupetroglou, S. Psaroudakes et A. Georgaki, «Physical modeling of the ancient Greek wind musical instrument Aulos: a double-reed exciter linked to an acoustic resonator,» *IEEE Access,* vol. 9, pp. 98150 - 98160, 2021.

5] C. A. G. Bonilla et C. Gómez, *Sound Synthesis of a Colombian Gaita by Means of Physical Modeling (MSc Theisi).,* Montreal: McGill University, 2020.

6] X. Luan, S. Wang, Z. Li et G. Scavone, «Acoustical Analysis of the Chinese Transverse Flute (dizi) Using the Transfer Matrix Method,» *Proceedings of Meetings on Acoustics,* vol. 49, 2022.

7] D. Keefe, «Theory of the single woodwind tone hole.,» *The Journal of Acoustical Society of America,* vol. 72, p. 676–687, 1982.

8] F. Leppington, «On the theory of woodwind finger holes,» *Journal of Sound and Vibration,* vol. 83, pp. 521-532, 1982.

9] E. Petersen, P. Guillemain, J. Kergomard et T. Colinot, «The effect of the cutoff frequency on the sound production of a clarinet-like instrument,» *Journal of the Acoustical Society of America,* vol. 145, p. 3784–3794, 2019.

10] E. G. Richardson, The Acoustics of Orchestral Instruments and of the Organ, London: E. Arnold & Company, 1929.

11] G. Scavone, «A tutorial on the transfer matrix method for acoustic modeling,» *The Journal of the Acoustical Society of America,* vol. 149, 2021.

12] D. H. Keefe, «Acoustical wave propagation in cylindrical ducts: Transmission line parameter approximations for isothermal and nonisothermal boundary conditions,» *Journal of the Acoustical Society of America,* vol. 75, pp. 58-62, 1984.

13] H. Levine et J. Schwinger, «On the radiation of sound from an unflanged circular pipe,» *Physical Review,* vol. 73, pp. 383-406, 1947.

14] R. Caussé, J. Kergomard et X. Lurton, «Input impedance of brass musical instruments – Comparaison between experimental and numerical models,» *The Journal of the Acoustical Society of America,* vol. 75, p. 241–254, 1984.

15] D. H. Keefe, *Woodwind Tone Hole Acoustics and the Spectrum Transformation Function (PhD Thesis),* Ohio: Harvard University, 1981.

16] D. H. Keefe, «Woodwind air column models.,» *Journal of the Acoustical Society of America,* vol. 88, pp. 35-51, 1990.

17] C. Nederveen, K. M. Jansen et R. R. van Hassel, «Corrections for woodwind tone-hole calculations,» *Acta Acustica United With Acustica,* vol. 84, pp. 957-966, 1998.

18] V. Dubos, J. Kergomard, A. Khettabi, J. P. Dalmont, D. H. Keefe et C. Nederveen, «Theory of sound propagation in a duct with a branched tube using modal decomposition,» *Acta Acustica (Stuttgart),* vol. 85, pp. 153-169, 1999.

19] A. Lefebvre, *Computational Acoustic Methods for the Design of Woodwind Instruments (PhD Thesis),* Montréal: McGill University, 2010.

20] A. Lefebvre, G. P. Scavone et J. Kergomard, «External tonehole interactions in woodwind instruments.,» *Acta Acustica united with Acustica,* vol. 99, pp. 975-985, 2013.

21] J.-C. Le Roux, M. Pachebat et J.-P. Dalmont, «Un capteur de nouvelle génération pour la mesure d'impédance acoustique en contexte industriel,» *Acoustique et Techniques : trimestriel d'information des professionnels de l'acoustique,* vol. 68, p. 6, 2012.

22] C. C. Wier, W. Jesteadt et D. M. Green, «Frequency discrimination as a function of frequency and sensation level,» *Journal of Acoustics Society of America,* vol. 61, pp. 178-184, 1977.