Megaron, Vol. 17, No. 4, pp. 617–628, December 2022

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/MEGARON.2022.67625

Article

An important parameter in concert hall design: Determination of directivity for instruments

Yalın ÖZGENCİL*, Neşe YÜĞRÜK AKDAĞ

Department of Building Science and Technology, Yıldız Technical University Faculty of Architecture, İstanbul, Türkiye

ARTICLE INFO

Article history
Received: 08 November 2022
Revised: 19 December 2022
Accepted: 19 December 2022

Key words:
Architectural acoustics; instrument directivity; semi-anechoic chamber; sound physics; stage design

ABSTRACT

Instrument sound directivity is of great importance when defining the sound source for research in architectural acoustics. When it comes to the topic of instrument directivity, whereas there are various studies on Western music instruments, only a few studies could be found on the directivity information of Eastern music instruments. For this reason, during architectural acoustic design processes in concert halls, rehearsal rooms, music studios and other Turkish music performance areas, there may be insufficient approaches in terms of defining the sound source. Directivity measurements of the qanun, oud, tanbur and clarinet, which are important instruments of Turkish music, were carried out within the scope of the study. These measurements for all octave band regions were carried out by designing a measurement setup with 20 microphone measurement points in the hemispherical area created in the semi-anechoic room at TÜBİTAK UME. The effect of the tonal spread characteristics of the instruments on the directivity was taken into account and a total of 143 measurements were carried out for all the note regions in the octave ranges of the relevant instruments. The directivity differences among the instruments and the acoustic propagation characteristics of different octave bands for each instrument are interpreted at the end of the study. The obtained values and results will make an important contribution to source modelling in architectural acoustic simulations of concert halls and concert hall stages; and in relation to this, in musician stage arrangements and all the other musical acoustics research.

Cite this article as: Özgencil Y, Yüğrük Akdağ N. An important parameter in concert hall design: determination of directivity for instruments. Megaron 2022;17(4):617–628.

INTRODUCTION

The directivity of performers and musical instruments in music halls such as concert halls, operas, recording studios, etc. is an important topic that needs to be taken into consideration for both performers and listeners when designing such halls. In halls where the directivity of sound sources is not evaluated, there may be a much different acoustic setting than predicted. Therefore, it is necessary to define the directivity information of sound sources as data in the acoustic design of halls and in simulation programs created with the aim of obtaining much more accurate results. An acoustic approach that correctly establishes the relationship between the sound source, volume and receiver will make it easier for the architectural area to be designed to serve its purpose (Sabine, 1964; Benade, 1976).

***Corresponding author**
*E-mail adres: yalinozgencil@gmail.com

Published by Yıldız Technical University Press, İstanbul, Turkey

Therefore, the designs and approaches to be created in the field of musical architectural acoustics cannot be considered separately from instruments with musical sound sources.

There are many studies in the literature that musical instruments are reviewed from different perspectives. (Meyer, 1993; Causse, Derogis & Waresful, 1995; Fletcher & Rossing, 1997; Rossing, Moore & Wheeler, 2002). However, the research on instrument directivity is quite little. It is obvious that the directivity of the symphony orchestra has been taken into consideration in the studies dating back to the 1970s and performed by Meyer (1978). Although these studies provide insights about instrument directivity, they do not provide detailed information about the measurement methods. In the later years, it could be seen that Fletcher and Rossing (1997) conducted extensive research on the acoustics of musical instruments. However, these studies do not provide a detailed methodology and results about instrument directivity (Rossing, Moore & Wheeleri, 2002). Although sound propagation of musical instruments has received more attention recently, most of the published research has still concentrated on the physical properties of instruments, and instrument performances have been carried out with mechanical setups (Patynen & Lokki, 2010). Although this approach is correct, it ignores the human factor (Wang & Vigeant, 2004). Later on, research taking into account the musician factor started to be carried out, and instead of using a mechanical device, instruments have been performed by musicians. Studies of directivity measurements with the help of microphones positioned horizontally in the middle plane have contributed to the literature (Otondo & Rindel, 2004). Examples of vocal or wind orchestral instruments are seen in this two-dimensional approach, and these studies include a directivity research approach based on different tones. However, it is observed that most studies focus on average values during performances and fall short in focusing on relevant frequency regions that are important during performances (Causse, Derogis & Waresful, 1995). Although it can be observed that different frequency regions of instruments show different directivity patterns in these studies since measurements are performed only on a horizontal plane, the approaches within the scope of research may be insufficient (e.g., resource descriptions in concert hall simulations). In later research, different studies were conducted that evolved to three-dimensional measurements in the form of a sphere with increasing microphone numbers and placement points that varied between 22 and 64 (Patynen & Lokki, 2010). Cook and Truman (1998) used 12 microphones in an icosahedron experiment setup for the directional impulse response of string instruments. Conducting research on symphony orchestra instruments, Patynen (2010) designed a study in which he examined different octave bands by creating a spherical measuring instrument with 22 microphones. This study is an elaborate resource for understanding how directivity changes for different instruments and how the same instrument acts for different octave bands. The values obtained as a result of directivity research taking musician factors into consideration can be simulated within a concert hall or similar buildings. In research in this field, the variability of the directivity of instruments in room acoustic simulations and auditory simulations can significantly affect the "perceived sound" associated with the acoustic quality in the room (Dalenback, Kleiner & Svensson, 1993; Vigeant, Wang & Rindel, 2007). Studies have shown the effect of incorporating the directivity of the sound source into computer models both in terms of the objective values in the acoustic parameters and the subjective values of the auralizations (L. M. Wang, M. C. Vigeant). Musical instruments owe part of their acoustic characters to differences in tone varying in different directions. (Pollow, Behler & Masiero, 2009). This confirms the effect of source type and performance type on acoustics (Weinreich, 1997). In addition, recent studies have shown that the movements of the musicians during the performance affects the spread of the sound in the medium (Ackermann, Böhm, Brinkman & Weinzierl, 2018). Last research has also shown this allows computerised testing of the resource and space relationship at the design stage for purpose-oriented architectural structures. It is clear that these studies give more reliable results in sources defined by accurate instrument acoustic properties and directivity information. It is seen that the studies carried out in the literature so far have been mainly focused on Western music instruments (Martin, 1942; Berg & Stork, 2005). On the directivity of the instruments of Eastern music, there is no detailed study in which the musician factor is also taken into account. Studies in the literature mostly consist of mechanically designed measuring devices and investigate instrument vibration modes and propagation motion in the instrument body (Erkut, Tolonen, Karjalainen & Valimaki, 1999; Degirmenli, 2017).

This study aims to find out the directivity characteristics of qanun, oud, tanbur and clarinet which are Turkish music instruments with different characteristics. Measurements were performed in an accredited laboratory and results were evaluated in accordance with the relevant standard. First of all, a semi-anechoic chamber, microphones, calibration and methods related to measurements are designed. Within the scope of the study, directivity measurements were performed for Turkish music instruments of qanun, oud, tanbur and clarinet, and the results were evaluated. These measurements were made in the semi-anechoic chamber in line with the relevant measurement standard. The measuring device designed as a hemisphere has 20 measuring points consisting of the same types of microphones. Measurements for all instruments were carried out using the same microphones. The musicians who performed were professional.

METHODOLOGY

The steps listed below were followed in the study.

- Selection of Turkish music instruments whose directivity would be found out,
- Directivity measurements in an accredited laboratory environment,
- Demonstration of measurement results in tables and graphs,
- Comparative evaluation of the results.

Selection of Turkish Music Instruments

The differences between Turkish music and Western music are quite a few. Basically, both music styles have 8 notes. However; in Western music, these 8 notes are divided into 12 equal parts, while in Turkish music they are divided into 24 unequal parts. Whereas 1 note is divided into 2 equal parts in Western music, 1 whole note is divided into 9 separate parts called "comma" in Turkish music (Açın, 1998). The genres and modes of the two styles vary because of all these differences. For this reason, there are also differences in the instruments used to perform these music styles. Both music style approaches have their own instruments. Within the scope of the project, 4 different instruments were selected, which are respectively qanun, clarinet, tanbur and clarinet. To select these instruments, Turkish music performance examples were examined and experts with conservatory education on the subject were consulted. The acoustic characteristics and octave ranges of these four instruments are different from each other, and this difference provides diversity when comparing the sources (Figure 1).

Directivity Measures

The directionality measurements of musical instruments were carried out in a semi-anechoic room at TÜBİTAK UME (The Scientific and Technological Research Council of Turkey National Metrology Institute) in accordance with the relevant standard (ISO Standard 3745:2003, 2003). The semi-anechoic room is 7.6 m in length, 9.8 m in width and 10.3 m in height. For directivity measurements, a hemispherical area with a radius of 2.7 m was created, meeting the relevant standard. The person playing the musical instrument was placed in the center of the hemisphere with the instrument. Measurements were performed by placing microphones at 20 points on the hemispherical surface. Microphones were positioned at angles of 22.5 degrees, 45 degrees, 67.5 degrees and 90 degrees from the center in the vertical direction and 60 degrees from the center in the horizontal plane, respectively (Figure 2).

The G.R.A.S. 40AF type capacitive microphones and Brüel & Kjaer type 3560 D Pulse multichannel analyser system were used for directivity measurements. Sound pressure level measurements were carried out at 1/3 octave band centre frequencies in the frequency range of 31.5–16000 Hz. Carried out as 2 sets by using 20 microphones, the measurements were repeated twice. In sets of 10 microphones, measurements at each microphone position were made simultaneously. The measurement system was

Figure 1. Selected instruments (Oud, Tanbur, Clarinet, Qanun, respectively).

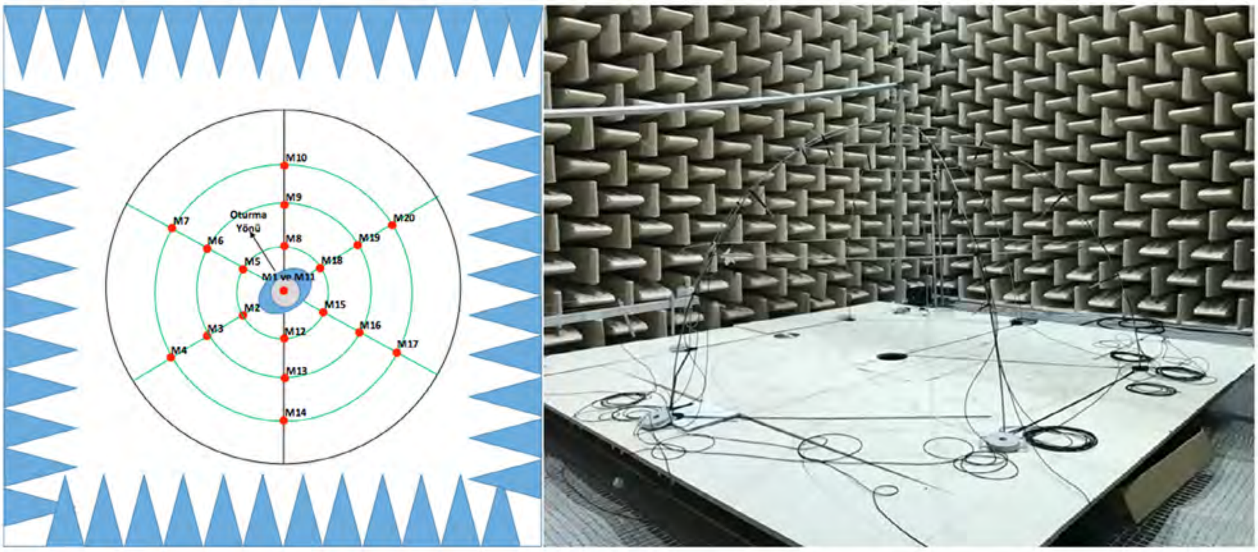

Figure 2. Microphone array of full non-anechoic room recordings.

checked with a Brüel & Kjaer type 4231 Acoustic Calibrator before and after the measurements. The system used in the measurements meets the requirements of the IEC 61672 standard, type 1 and the sound calibrator meets the requirements of the IEC 60942 standard, class 1. Figure 3 shows the equipment used in the measurements.

All musicians were positioned in the centre of the hemisphere and performed in the same position (Figure 4). At this stage, all note regions between the lowest sound and the highest sound according to the octave range of the instruments were analysed for tonal directivity. Thus, a detailed frequency analysis according to octave band ranges could be carried out. For example, for the clarinet instrument, the 3rd octave B note (246.94 Hz) was taken as the centre for the 250 Hz octave band region, but the tonal spreads of the 3rd octave B flat (233.08 Hz) and 4th octave C note (261.63 Hz) were also taken into consideration for the average values. Sample measurement value results are shown in Table 1. As in the example, results for all octave bands were obtained for all notes.

As seen in Table 1, when making a tonal measurement, the data for sound pressure levels in all octave bands were obtained and the propagation information within the hemisphere was obtained numerically. In order to focus on frequency regions tonally, according to the sample table, the 250 Hz region was taken into consideration to proceed. To reach the directivity distribution data of the 250 Hz region, one lower and one upper-frequency note was also taken into consideration and their data were analysed. Table 2 shows the data of 3 notes in the relevant frequency region tonally. This table was created by examining all octave band values for the related notes and taking 250 Hz values into account in the related note measurement.

Examining the Table, we can see the 3rd octave B flat (233.08 Hz), 3rd octave C note (246.94 Hz) and 4th octave C note (261.63 Hz) measurement data for the clarinet instrument for all microphone points. After this phase, the directivity data of the clarinet in the hemisphere in the 250 Hz region is obtained by averaging these values.

Within the scope of this study, these procedures were carried out for all instruments and octave bands. In brief, reduced values were created by taking the average of the tonal region measurements for the relevant octave bands into account. Aspiring to obtain the measurement results of all octave bands, the tables are averaged out according to the relevant frequency regions as in the example narrative. Table 3 shows the average measurement results for all octave bands of the clarinet.

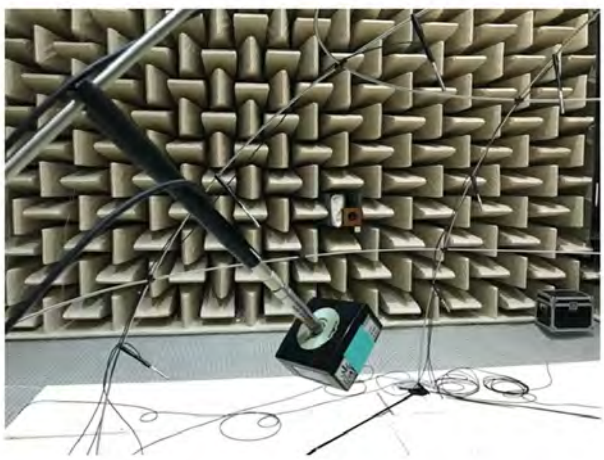

Figure 3. TÜBİTAK's full non-anechoic room recording equipment.

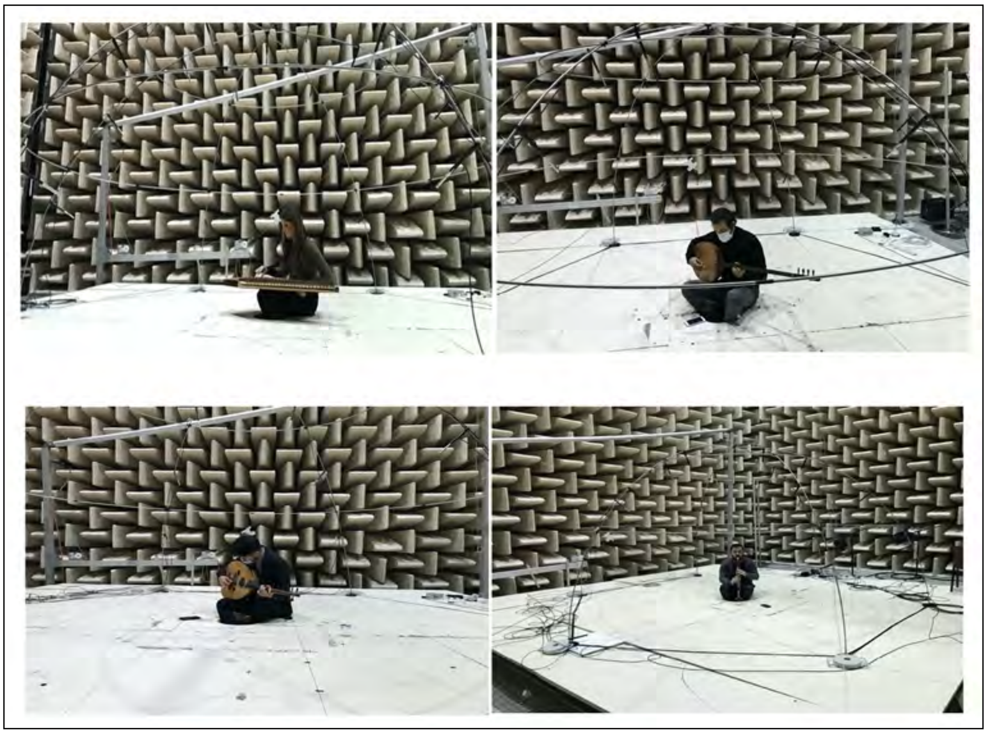

Figure 4. Directivity measurements of instruments.

Table 1. Effect of energy consumption on the LCC

Frequency (Hz)	Sound Pressure Level, dB Ref. 20 µPa									
Microphone Points	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**
31.5	18.9	20.7	21.8	22.8	20.8	21.0	21.5	24.1	25.6	15.5
63	14.0	15.6	15.1	14.7	14.5	15.4	16.1	22.4	23.7	15.1
125	11.6	13.4	13.3	13.2	12.0	12.3	10.9	19.9	20.4	10.6
250	71.8	69.6	71.3	75.7	68.0	71.4	76.3	69.7	68.3	75.5
500	50.1	49.1	42.5	39.9	42.4	52.1	41.6	49.7	46.1	38.6
1000	53.6	59.7	51.1	62.5	63.0	58.0	61.0	59.9	60.8	61.9
2000	61.0	59.2	56.2	54.9	60.0	55.6	54.4	57.5	60.7	59.3
4000	52.0	49.6	52.7	44.2	54.7	57.3	53.2	58.4	55.5	46.5
8000	30.3	30.8	30.3	34.5	34.1	37.4	35.6	35.1	32.4	35.0
16000	25.0	25.5	26.9	31.5	26.5	30.4	30.0	30.2	29.9	31.3
A	73.7	71.6	71.7	79.1	74.4	78.6	80.0	77.0	73.4	75.3
L	75.4	73.2	74.2	80.1	74.9	79.1	81.0	77.4	74.1	77.8
Frequency (Hz)	**Sound Pressure Level, dB Ref. 20 µPa**									
Microphone Points	**M11**	**M12**	**M13**	**M14**	**M15**	**M16**	**M17**	**M18**	**M19**	**M20**
31.5	17.1	18.8	19.0	19.4	19.8	20.0	21.6	32.4	43.2	15.4
63	18.1	19.2	19.9	20.3	18.4	18.2	18.8	30.1	37.9	15.8
125	12.4	13.7	12.2	14.9	13.3	11.4	12.7	26.6	36.2	13.3
250	73.1	71.3	67.7	70.7	69.7	65.8	72.0	70.2	68.2	74.7
500	51.9	52.1	50.4	42.2	51.3	49.2	38.7	51.1	52.3	43.5
1000	55.7	55.8	57.6	63.0	55.2	59.0	59.1	59.6	62.6	63.2
2000	60.2	53.9	53.6	55.5	52.7	48.1	50.1	55.1	57.7	57.8
4000	43.7	39.6	39.6	28.4	38.9	36.7	30.2	43.6	44.2	34.5
8000	25.9	24.9	20.3	14.0	24.6	17.7	8.9	21.3	22.8	21.9
16000	19.2	17.6	15.5	10.3	16.7	12.2	7.0	17.4	19.1	16.9
A	72.3	70.0	69.2	69.4	70.6	65.0	67.3	69.2	71.2	73.2
L	75.5	73.6	71.5	72.7	73.4	68.0	72.9	72.7	73.2	76.5

Table 2. Measurement results of the relevant tonal regions of the clarinet instrument

Frequency (Hz)	Sound Pressure Level, dB Ref. 20 µPa									
Microphone Points	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**
250	69.9	68.1	70.1	74.1	67.5	71.1	74.8	69.5	67.3	74.6
250	71.8	69.6	75.7	75.7	68.0	71.4	76.3	69.7	68.3	75.5
250	73.5	72.4	77.9	77.9	72.1	71.8	78.5	72.4	71.1	78.3
Frequency (Hz)	**Sound Pressure Level, dB Ref. 20 µPa**									
Microphone Points	**M11**	**M12**	**M13**	**M14**	**M15**	**M16**	**M17**	**M18**	**M19**	**M20**
250	72.2	68.8	68.2	71.3	68.8	67.6	73.1	71.4	68.4	74.0
250	73.1	71.3	67.7	70.7	69.7	65.8	72.0	70.2	68.2	75.7
250	71.3	70.4	67.5	72.1	71.3	71.3	72.1	69.0	70.3	74.4

Table 3. Average directivity sound pressure level measurement results for all octave bands of the clarinet instrument

Frequency (Hz)	Sound Pressure Level, dB Ref. 20 µPa									
Microphone Points	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**
125	72.1	72.4	72.1	71.6	73.4	73.6	73.5	73.6	73.1	73.3
250	71.4	69.6	71.3	75.7	68.0	71.4	76.3	69.7	68.3	75.5
500	79.0	75.5	63.6	74.5	75.6	78.5	80.4	77.8	76.6	78.0
1000	74.2	85.1	77.5	88.3	90.4	86.1	93.3	88.3	86.6	90.9
2000	85.4	83.6	82.5	78.9	82.4	82.8	77.6	82.7	85.7	85.7
4000	73.7	66.6	71.3	61.8	78.2	80.5	69.1	78.8	78.6	75.3
8000	60.5	56.4	55.6	58.9	62.3	61.2	59.5	61.5	56.9	60.4
Frequency (Hz)	**Sound Pressure Level, dB Ref. 20 µPa**									
Microphone Points	**M11**	**M12**	**M13**	**M14**	**M15**	**M16**	**M17**	**M18**	**M19**	**M20**
125	71.6	71.1	70.2	69.1	70.8	69.8	69.2	70.1	71.1	68.6
250	73.1	71.3	67.7	70.7	69.7	65.8	72.0	70.2	68.2	74.7
500	79.2	77.0	68.4	75.5	76.8	71.1	73.5	62.9	75.4	77.0
1000	61.5	77.7	83.7	88.5	73.1	77.3	80.7	82.8	83.5	86.3
2000	83.4	73.6	61.6	75.9	65.3	65.5	71.4	73.3	81.8	78.2
4000	69.0	61.7	65.6	60.1	61.2	61.8	54.5	66.7	62.4	63.2
8000	53.1	43.8	43.1	41.7	42.1	34.8	30.2	46.2	42.7	46.2

RESULTS AND DISCUSSION

Average Sound Pressure Levels According to Frequency of Directivity Measurements of Instruments

Considering the octave ranges of the instruments, a total of 143 measurements (43 for the qanun, 40 for the clarinet, 25 for the tanbur and 38 for the oud) were performed from 20 different points. For the qanun, the lowest note is "C" in the first octave, while the highest note is "G sharp" in the fourth octave; for the clarinet, the lowest note is "B" in the second octave and the highest note is "Re" in the sixth octave; for the tanbur, the lowest note is "A" in the second octave and the highest note is "A" in the fourth octave; for the oud, the lowest note is "C sharp" in the second octave and the highest note is "D" in the fifth octave. The average sound pressure level values of 20 different points obtained from the averages for the sample octave band (246.94 Hz) are shown in Table 4 and the schematic representations of the directivity of all results obtained according to octave bands are shown in Figures 5–9, respectively.

When the measurement results are evaluated;

- The qanun generally demonstrates an inhomogeneous directivity characteristic, as seen in the measurement results. For the 2000 and 4000 Hz octave bands, the instrument reaches the highest sound pressure levels, and the directivity is more prominent at these frequencies.
- For the clarinet, the highest sound pressure values are observed in the 1000 Hz and 2000 Hz octave bands. It shows a more homogeneous and unclear propagation of

Table 4. Average directivity sound pressure level measurement results for all octave bands of the instruments

Frequency (Hz)		**Sound Pressure Level, dB Ref. 20 µPa**									
Microphone Points		**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**
Qanun	125	36.9	38.8	42.6	46.0	36.5	40.5	46.0	33.7	38.6	44.2
	250	61.0	58.5	53.7	58.8	59.3	54.2	57.0	59.4	53.6	57.3
	500	62.2	59.7	57.8	54.2	55.5	53.5	49.8	58.5	60.3	55.2
	1000	61.6	58.5	58.0	48.3	57.7	56.1	47.4	54.5	53.2	52.7
	2000	64.5	62.4	62.8	56.8	58.2	59.6	60.1	63.0	59.8	52.4
	4000	61.6	62.3	60.4	57.2	61.0	59.4	58.8	58.7	55.9	49.2
	8000	45.2	42.0	42.9	35.4	45.1	41.4	33.2	42.2	39.9	33.6
Clarinet	125	72.1	72.4	72.1	71.6	73.4	73.6	73.5	73.6	73.1	73.3
	250	71.8	69.6	71.3	75.7	68.0	71.4	76.3	69.7	68.3	75.5
	500	79.0	75.5	63.6	74.5	75.6	78.5	80.4	77.8	76.6	78.0
	1000	74.2	85.1	77.5	88.3	90.4	86.1	93.3	88.3	86.6	90.9
	2000	85.4	83.6	82.5	78.9	82.4	82.8	77.6	82.7	85.7	85.7
	4000	73.7	66.6	71.3	61.8	78.2	80.5	69.1	78.8	78.6	75.3
	8000	60.5	56.4	55.6	58.9	62.3	61.2	59.5	61.5	56.9	60.4
Tanbur	125	31.7	28.8	26.3	26.2	32.0	33.4	33.5	32.1	31.2	27.3
	250	48.8	49.6	42.5	50.8	49.1	43.4	52.3	48.9	44.5	48.9
	500	59.6	57.1	54.5	47.0	57.7	49.0	50.7	60.9	56.5	49.9
	1000	55.9	57.0	58.5	54.1	56.4	61.6	53.8	57.7	60.0	56.2
	2000	30.4	26.6	28.8	28.8	31.9	31.7	28.3	34.9	27.5	31.5
	4000	27.1	25.7	24.8	26.0	27.1	27.0	26.6	25.2	24.6	17.1
	8000	24.2	25.2	28.6	27.7	28.1	29.5	28.1	27.1	27.6	27.6
Oud	125	57.3	57.9	59.1	58.9	59.1	60.6	60.9	59.5	60.9	61.5
	250	55.5	56.2	61.2	62.8	59.7	64.8	66.3	61.7	64.2	68.3
	500	60.6	58.7	50.3	48.0	61.1	54.6	59.2	62.5	57.8	61.3
	1000	51.5	49.8	38.8	33.8	53.3	52.2	45.3	53.3	48.1	50.6
	2000	32.2	27.7	34.2	30.1	31.2	28.8	34.7	31.1	35.7	36.4
	4000	27.8	26.5	28.4	23.3	28.0	25.0	20.6	24.9	23.3	28.8
	8000	26.0	26.9	27.6	29.3	26.9	23.7	27.3	27.4	23.7	25.8
Microphone Points		**M11**	**M12**	**M13**	**M14**	**M15**	**M16**	**M17**	**M18**	**M19**	**M20**
Qanun	125	26.6	30.6	37.5	40.0	28.8	34.7	40.5	28.6	28.5	39.8
	250	58.0	55.3	48.0	52.0	55.6	49.6	52.6	56.2	51.4	56.5
	500	57.6	57.7	55.5	49.3	58.0	52.9	45.1	56.7	47.8	39.9
	1000	58.7	56.7	53.2	47.7	54.2	50.3	46.8	52.0	53.0	43.3
	2000	64.7	59.9	58.1	59.7	59.0	53.8	59.4	60.9	51.5	52.8
	4000	59.1	56.8	50.9	50.5	48.8	51.6	48.8	54.2	55.0	48.9
	8000	44.2	38.6	37.0	36.6	42.1	40.4	34.6	42.3	44.1	42.3
Clarinet	125	72.1	72.4	72.1	71.6	73.4	73.6	73.5	73.6	73.1	73.3
	250	71.8	69.6	71.3	75.7	68.0	71.4	76.3	69.7	68.3	75.5
	500	79.0	75.5	63.6	74.5	75.6	78.5	80.4	77.8	76.6	78.0
	1000	74.2	85.1	77.5	88.3	90.4	86.1	93.3	88.3	86.6	90.9
	2000	85.4	83.6	82.5	78.9	82.4	82.8	77.6	82.7	85.7	85.7
	4000	73.7	66.6	71.3	61.8	78.2	80.5	69.1	78.8	78.6	75.3
	8000	60.5	56.4	55.6	58.9	62.3	61.2	59.5	61.5	56.9	60.4
Tanbur	125	31.9	31.6	34.1	37.1	36.7	41.2	43.8	35.3	37.6	39.2
	250	52.1	53.0	46.2	49.7	45.2	39.5	41.2	48.2	45.6	45.4
	500	61.8	60.7	57.2	52.3	61.0	55.0	51.7	62.9	59.2	44.7
	1000	58.0	55.1	56.0	44.6	53.0	56.6	56.0	55.7	55.8	52.2
	2000	38.5	31.7	26.4	28.7	34.6	38.7	32.5	36.3	44.6	32.5
	4000	14.2	14.5	13.2	18.1	17.2	16.7	19.5	16.1	19.7	15.8
	8000	14.2	13.1	11.9	12.3	10.3	9.7	10.7	14.1	14.2	15.8
Oud	125	54.3	54.2	54.8	55.7	55.1	56.6	57.5	57.7	56.2	57.9
	250	53.7	55.4	57.9	61.4	56.9	58.8	64.3	62.6	58.1	67.2
	500	56.9	52.4	50.3	42.6	52.3	43.7	39.9	53.2	56.0	50.5
	1000	44.9	38.3	30.6	40.5	41.4	44.1	43.8	45.8	47.4	46.4
	2000	24.1	25.6	21.8	22.1	24.6	20.9	22.2	23.0	27.3	28.1
	4000	24.2	19.7	17.0	18.6	19.1	17.9	22.7	22.4	23.8	21.5
	8000	21.3	20.1	19.6	21.6	14.9	18.4	19.4	25.8	21.5	22.4

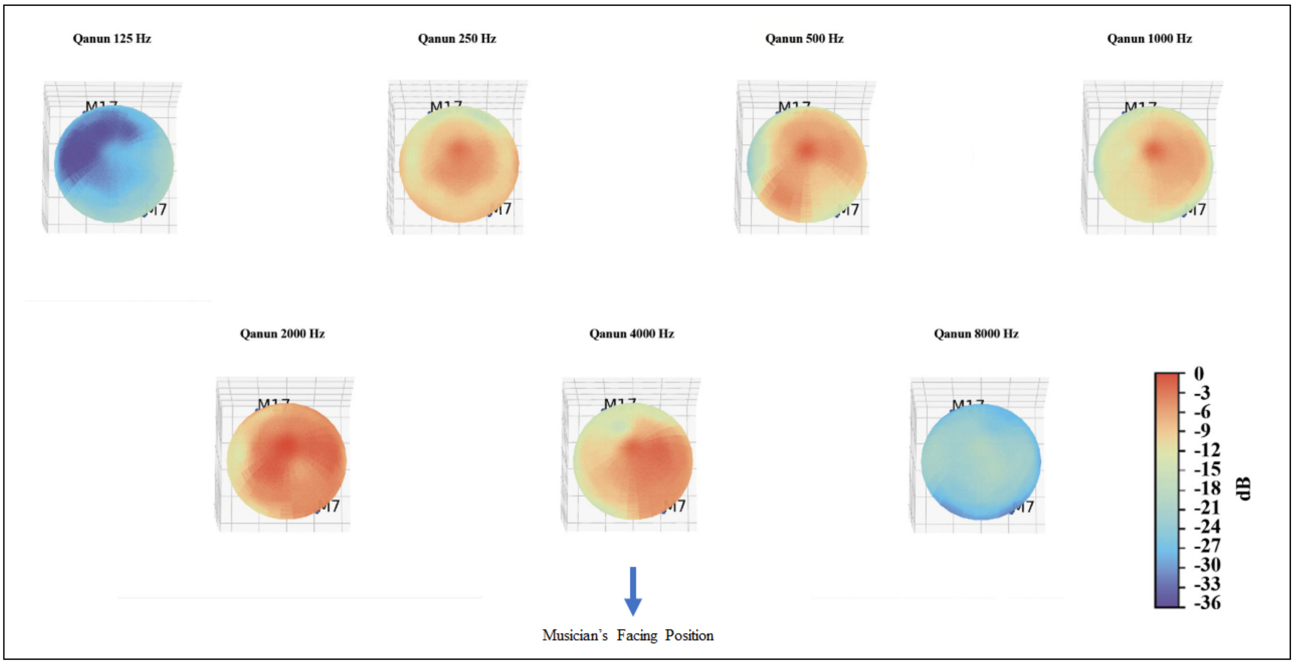

Figure 5. Measurement results for the qanun at each measurement point and octave band.

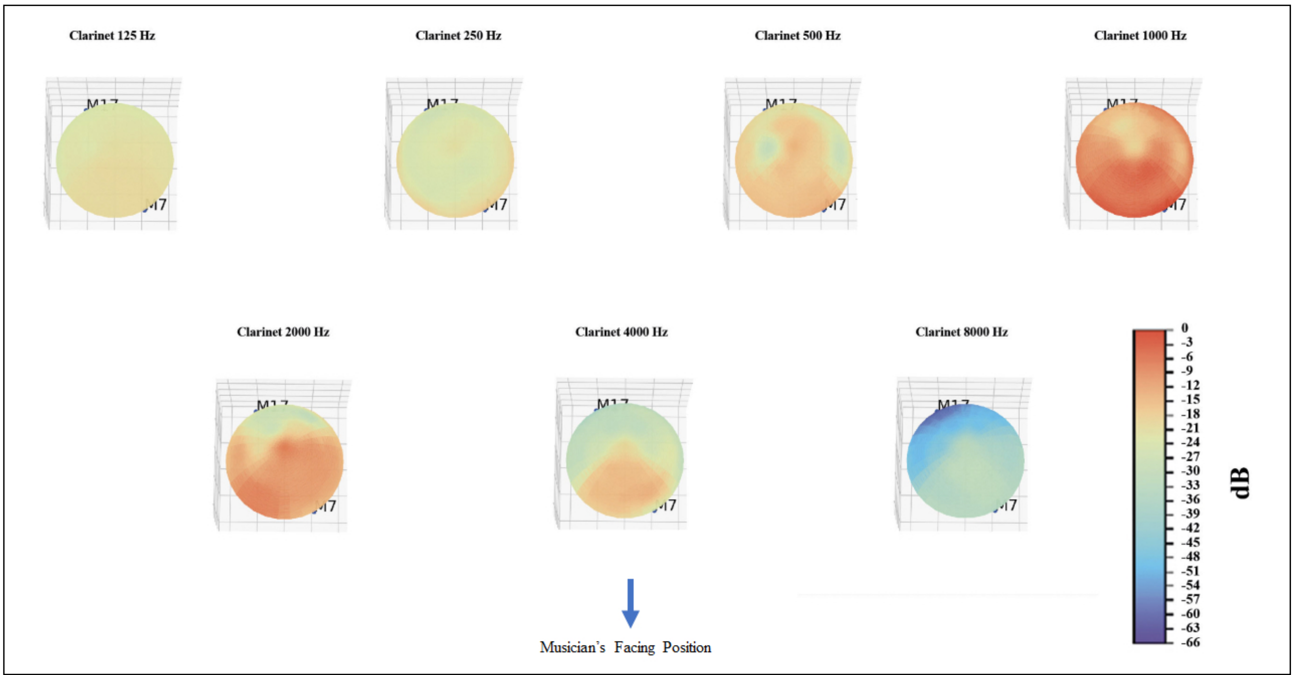

Figure 6. Measurement results for the clarinet at each measurement point and octave band.

directivity at low frequencies, while at high-frequencies there is a more prominent directivity as expected.

- The most obvious directivity information for the tanbur is observed at 4000 Hz and 8000 Hz although it has low sound pressure levels. This makes a difference as against other instruments. The highest sound pressure level values are around 500 Hz and 1000 Hz, and the propagations in this octave band are homogeneous.
- The oud reaches the highest sound pressure levels in low-frequency bands, while it creates a lower sound pressure level at high-frequencies. For all octave bands, it could be observed that there is ambiguous and similar directivity information.
- When examining the differences between the instruments according to octave bands, the qanun shows a non-homogenous propagation at 125 Hz, while other

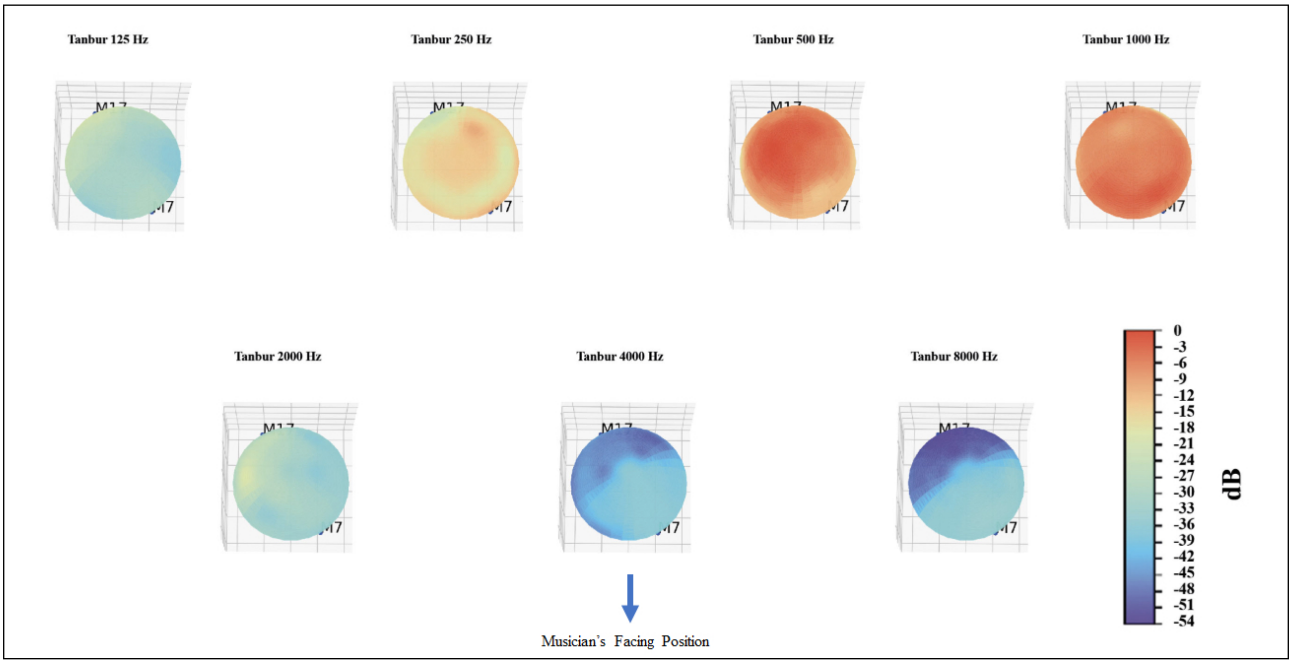

Figure 7. Measurement results for the tanbur at each measurement point and octave band.

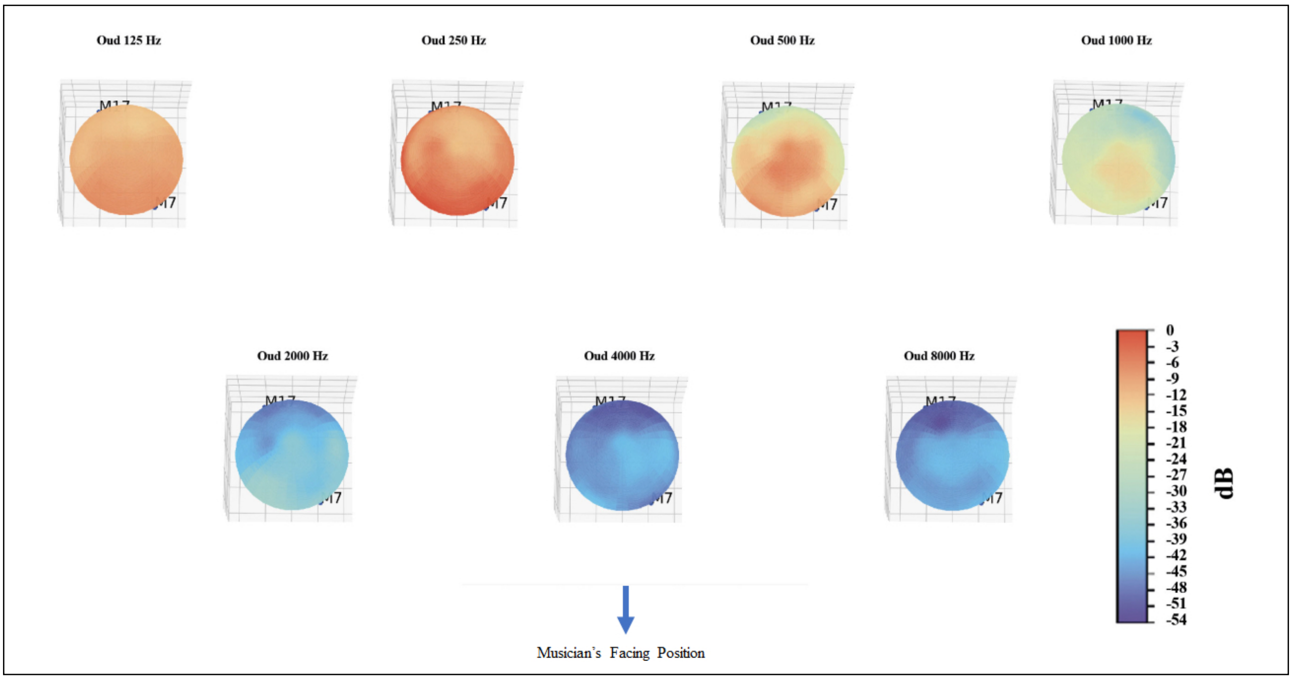

Figure 8. Measurement results for the oud at each measurement point and octave band.

instruments show a propagation close to homogeneous. The oud has the highest sound pressure level of around 125 Hz.

- The frequency zone in which the oud characteristically reaches the highest sound pressure levels is 250 Hz. The clarinet demonstrates a fairly homogeneous propagation. The qanun and tanbur have similar directivity compared to other instruments.
- The frequency region where the tanbur reaches the highest sound pressure values is 500 Hz, and it shows a propagation close to homogeneous. Other instruments reflect more prominent information of directivity and could be stated to be demonstrating similar characteristics.
- They are frequency regions where the clarinet and tanbur reach the highest sound pressure levels. While

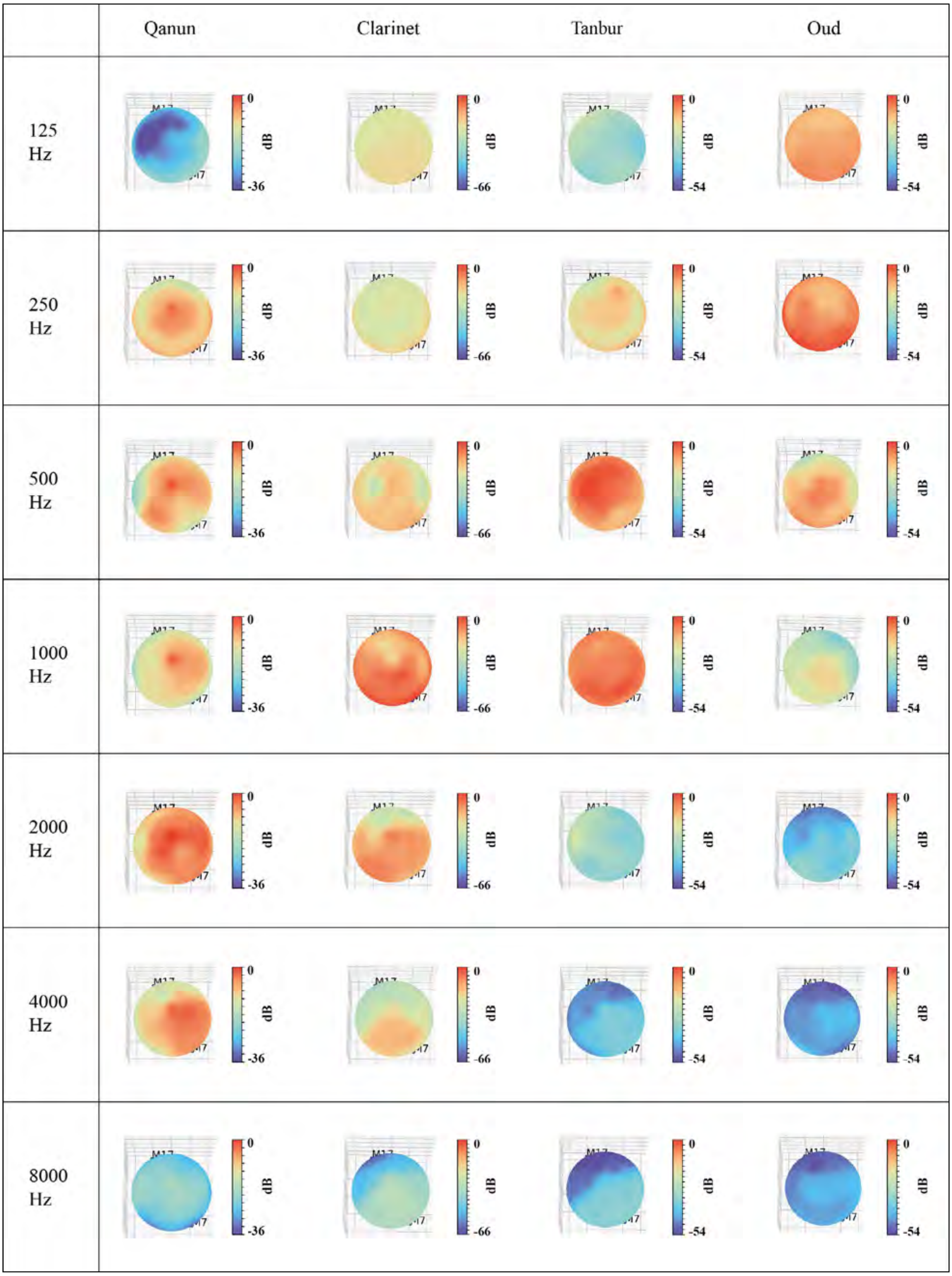

Figure 9. Measurement results for all instruments at each measurement point and octave band (All scales are separate for each instruments).

directivity information for tanbur is homogeneous, regional concentrations are observed in other instruments. For example, it is possible to refer to a prominent propagation in the direction of view for the oud.

- There is a significant decrease in sound pressure levels for the tanbur and oud compared to other low-frequency regions. The clarinet shows a prominent sound propagation characteristic towards the point of view at this frequency. The oud also shows similar propagation characteristics as the clarinet. The qanun has reached the highest sound pressure level in frequency zone measurements within itself.
- Propagation characteristics for all instruments have been sharper than for lower frequencies. Although the sound pressure levels of oud and tanbur decrease to lower and medium frequencies, the propagation zones are clearly visible. Clarinet and qanun demonstrate sharp propagations but in different directions.

The propagation characteristics of clarinet and tanbur are quite similar. The qanun has a homogeneous propagation, although it demonstrates a high-frequency zone that does not have propagating characteristics. Although the oud shows characteristics close to homogeneous, it is possible to demonstrate a distinct area for the propagation zone.

CONCLUSION

For the acoustic performance of the halls, it is extremely important to consider the directivity characteristics of the sound sources during the stage and orchestra design. This topic which has been studied for most Western music instruments has unfortunately not been discussed in detail for Turkish music instruments until today. In the study, the directivity information of four different Turkish music instruments has been obtained. According to the findings, it has been determined that instruments with different acoustic properties show different directivity behaviours. In addition, the directivity behaviour of the same instrument also varies in different octave bands. Considering the musician factor, whether the low-, medium- and high-frequencies have similar or different general behaviours for different instruments can be interpreted within the scope of the study. With this approach, it is obvious that instrument type, positioning and placement are very important for acoustic performance places with different purposes. It can be said that instrument directivity is a very important parameter especially in designing concert halls. In addition, this study aims to contribute to the development of measurement approaches required for directivity research of Eastern music instruments. With future studies, determining the directivity characteristics of other Turkish music instruments that are not discussed within the scope of the study is important in terms of the contribution to the literature.

Acknowledgments

This study was created from the doctoral dissertation supported by Yıldız Technical University Scientific Research Projects Coordination Unit with the FDK-2019-3681 project. The author would like to thank the YTU BAP Coordination Unit.

- *This article is based on the PhD Dissertation entitled as An Approach to Determining the Acoustic Characteristics of Turkish Music Instruments and Evaluating Their Effect on Hall Design by Yalın Özgencil and continues under the supervision of Prof. Dr. Neşe Yüğrük Akdağ at Yildiz Technical University, Department of Architecture in 2022.*

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

REFERENCES

Ackermann, D., Böhm, C., Brinkmann, F., and Weinzierl, S. (2018). The acoustical effect of musicians' movements during musical performances. Acta Acustica United with Acustica 105(2019):356–367.

Açın, C. (1994). Enstrüman Bilimi. Yenidogan Basımevi.

Benade, A. H. (1976). Fundamentals of Music Acoustics. 1st ed. London: Oxford University Press.

Berg, R. E. and Stork, D. G. (2005). The Physics of Sound. San Francisco: Pearson Education, Inc.

Causse, R., Derogis, P., and Waresful, O. (1995). Radiation of musical instruments and improvement of the sound diffusion techniques for synthesized, recorded or amplified sounds. Proceedings of the International Computer Music Conference. Banff, Canada, 359–360.

Cook, P. and Trueman, D. (1998). A database of measured musical instrument body radiation impulse responses, and computer applications for exploring and utilizing the measured filter functions. Proceedings of the International Symbiosis Musical Acoustics. Leaven-Worth WA, USA, 303–308.

Dalenback, B. I., Kleiner, M., and Svensson, P. (1993). Audibility of changes in geometric shape, source directivity, and absorptive treatment - Experiments in auralization. Journal of Audio Engineering Society 41:905–913.

Değirmenli, E. (2017). Türk Müziği Telli Çalgılarının Akustik Analizlerinde Kullanılan Yöntemler. Gazi Üniversitesi Fen Bilimleri Dergisi Part C: Tasarim ve Teknoloji 5(2):23–35.

Erkut, C., Tolonen, T., Karjalainen, M., and Valimaki, V. (1999). Acoustical Analysis of Tanbur, a Turkish Long -Necked Lute. Paper presented at the International Congress on Sound and Vibration, Denmark.

Fletcher, N. H. and Rossing, T. D. (1997). The Physics of Musical Instruments. New York: Springer-Verlag.

ISO Standard 3745:2003. (2003). Acoustics - Determination of sound power levels of noise sources using sound pressure — Precision methods for anechoic and hemi-anechoic rooms. International Standards Organization.

Martin, D.W. (1942). Directivity and the acoustics spectra of brass wind instruments. Journal of Acoustics Society of America 13:309–313.

Meyer, J. (1978). Acoustics and the Performance of Music. Frankfurt/Main: Verlag Das Musikinstrumenter.

Meyer, J. (1993). The sound of the orchestra. Journal of Audio Engineering Society 41:203–213.

Otondo, F. and Rindel, J. H. (2004). The influence of the directivity of musical instruments in a room. Acta Acustica United with Acustica 90:1178–1184.

Patynen, J. and Lokki, T. (2010). Directivities of symphony orchestra instruments. Acta Acustica United with Acustica 96:138–167.

Pollow, M., Behler, G., and Masiero, B. (2009). Measuring directivities of natural sound sources with spherical microphone array. Proceedings of Ambisonics Symposium 2009, Graz, Austria, 25–27.

Rossing, T. D., Moore, R. F., and Wheeler, P. A. (2002). The Science of Sound. Third edition. Prentice Hall.

Sabine, W. C. (1964). Collected Papers on Acoustics. Reprinted by Dover Publications, Inc.

Vigeant, M. C., Wang, L. M., and Rindel, J. H. (2007). Investigations of multichannel auralization technique for solo instruments and orchestra. 19th International Congress on Acoustics, Madrid.

Wang, L. M. and Vigeant, M. C. (2004). Objective and subjective evaluation of the use of directional sound sources in auralizations. 18th International Congress on Acoustics, Kyoto, Japan. IV:2711–2714.

Weinreich, G. (1997). Directional tone color. Journal of the Acoustical Society of America 101:2338.