AN AUTOMATIC ACQUISITION SYSTEM FOR MEASURING THE DIRECTIONAL CHARACTERISTIC OF MUSICAL INSTRUMENTS

Martin Lahmer, Alexander Mayer

Institute of Music Acoustics
University of Music and Performing Arts Vienna, Austria
martin_lahmer@gmx.at, mayer@mdw.ac.at

ABSTRACT

Obtaining data on the directional characteristics of musical instruments can be both time-consuming and demanding in terms of equipment. This paper explains the construction of an affordable automatic turntable system, for measuring the radiated sound as a function of angle and frequency in one plane. An initial test was carried out on two brass instruments excited by an artificial mouth and two stringed instruments driven by a shaker. The second part of this paper deals with the further processing of the obtained values. As the sound pattern data can be stored in an online database (MySQL), the directional characteristics are accessible via a web-interface. The user is able to display the measurements as single plot (e.g. for each angle), as polar-plot or colormap. This interface represents the first part of a planned Musical Instrument Measurement Database (MIMD) for collecting diverse measurement data of different kind of musical instruments.

1. INTRODUCTION

For the sound of an instrument or even of orchestras sound radiation and the effect of the room is a significant criterion and like other sound sources musical instruments have a more or less pronounced directional dependence of sound radiation. It varies significantly depending on the frequency spectrum. The simplest case is a spheric source radiation when sound is expanded in all directions equally. Usually, this case will occur if the sound source is a "breathing sphere" or it is small in comparison to the radiated wavelength. This occurs at low frequencies and the constant radiation remains virtually unaffected. In the case of higher frequencies the directional characteristic is affected by numerous influences like the position of the player, the direction of the musical instrument, the acoustical consistence of the instrument, etcetera. [1][2].

In Figure 1 the omnidirectional sound radiation for individual frequency regions of some brass wind instruments is given. This measurements were taken by Jürgen Meyer [1]. The spheric radiation depends much on the form of structure and the dimension of the individual bells so long as the bell is the transducer. For instance, the bell of a Tuba is relatively wide in comparison to that of a Trumpet. So a Tuba spreads sound omni directionally at lower frequencies (about 30 Hz up to 90 Hz) compared to a Trumpet (about 180 Hz up to 500 Hz).

In 1970, Meyer and Wogram measured and documented the directional characteristic of Trumpets, Trombones, and Tubas [3]. It turned out that it is necessary to define those angular regions for which the sound level does not sink by more than 3 dB or more than 10 dB respectively below the directed maxima. The 3 dB limit describes the *half width*. This is the difference where the sound intensity is just half the value related to the maximum. For simplification sound pressure above the 3 dB limit was taken as quasi equal. Otherwise a level difference of 10 dB is perceived as approximately one-half the loudness. Figure 2 illustrates the directional characteristic of a Tuba within the 3 dB limit. As it can be seen, the effective radiation angle will narrow if the frequency raises.

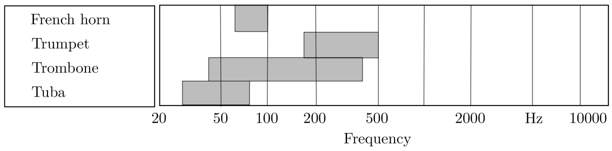

Figure 1: Spheric sound radiation of brass instruments by Meyer [1].

Finally, a quantity called the statistical directivity factor is important for room acoustical considerations. It represents a relationship between sound pressures actually present, to those which would be caused by a sound source of equal total power with omnidirectional characteristics at the same distance. The statistical directivity factor can be given in dependence on direction: Values larger than 1 indicate directions with, on the average, stronger radiation; values less than 1 indicate directions of below average radiation. For example, an ideal dipole reaches a value of approximately 1.7 in the direction of strongest radiation. On the boundary of the 3 dB region, the statistical directivity factor drops to 0.7; on the boundary of the 10 dB region, to 0.3 of the maximum value. For sound level considerations it is advantageous to convert the statistical directivity factor to a dB value. The quantity is designated as directivity index. It specifies how much the sound level is higher in the direction considered than it would be for an omni-directionally radiating sound source of equal power [1].

Obtaining the data on the directional characteristics of musical instruments can be done in various ways. The basic method will use a single microphone, the test item has to be turned in defined angles, for each being excited at the frequency bandwidth of interest. If multichannel recording is possible, a multitude of microphones can be placed on a ring or better on a sphere around the test item. For measurements excluding the influence of the surrounding room, both set-ups should be placed inside an anechoic chamber. This paper describes the implementation of a single microphone automated measuring system. After setting up the system the device-under-test will be excited and rotated without human supervision. As carrier a massive turntable was equipped with step-motors. Lastly, the storage and the processing of measured data and the control of the turntable and its step-motors have to be combined externally outside the chamber by a computing system. Here a Personal Computer (*PC*) with *LabVIEW* from *National Instruments* was used. With it, the PC is capable of communicating with the

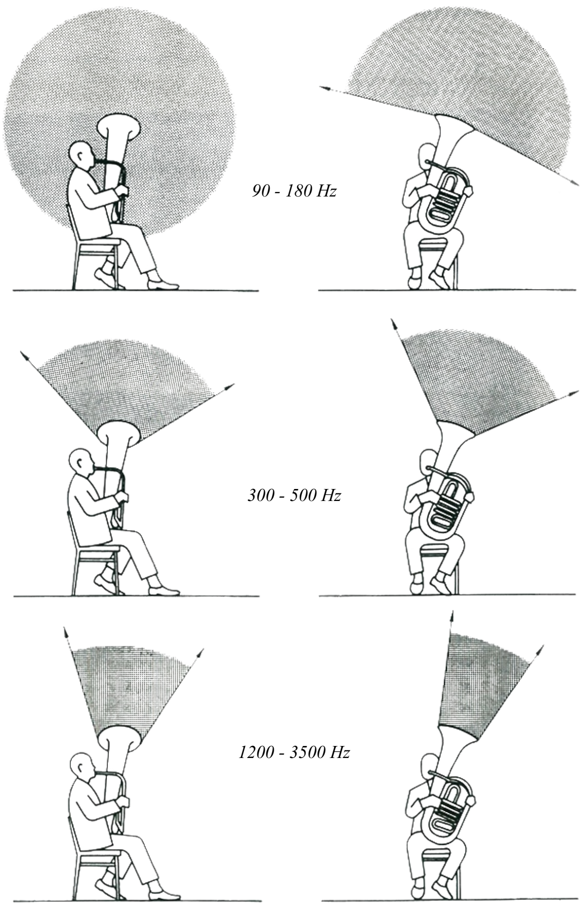

Figure 2: Main radiation area (0 to -3 dB) of a Tuba by Meyer [3].

Step-Motor-Control (*SMC*), executing the acoustical measurements and processing the acquired information.

2. TURNTABLE-SYSTEM WITH STEP-MOTORS

For this project an existing turntable was chosen for modification. It consists of a huge bearing ring of a semi-trailer coupling with a diameter of about 65 cm which was attached on a heavy metal-frame. The actual table board can be placed on the bearing ring by four screws, however, other installations can be mounted on the bearing ring too. For instance, a stable construction with a Tuba to be measured is shown in Figure 3. This build-up was made of a flexible assembly kit with mounting rails. It was the final mechanical set-up for the acoustical acquirement of Tubas.

2.1. Mechanical Design

For automatic motion it is necessary to install at least one motor onto the turntable construction. To ensure conformity between required effort and engine performance the tensile force was measured at the outer edge of the bearing ring with a spring balance. It turned out that the mean force was at about 200 N, however, the top force was measured at about 400 N at some points of the wheel. This can be explained by the fact that the semi-trailers coupling ring is not ideal and possesses higher friction losses at several points. Multiplied with the radius of the ring (33 cm) the resulting maximum load torque amounts 132 N m.

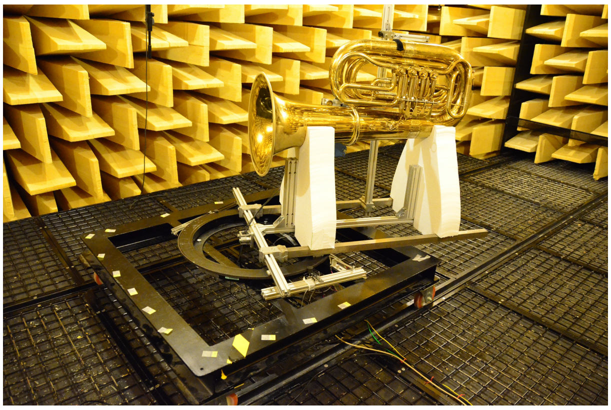

Figure 3: Turntable system with a stable construction for fixing a Tuba.

Therefore, the selected motor must meet this criterion, so that the platform can rotate smoothly. A few stepper motors with a nominal holding torque of 44 N cm were available at the institute. It should be mentioned that the holding torque nearly corresponds to the driving torque at lower stepper frequencies. Since comparing these torques results in a high discrepancy, a convenient power transmission had to be found. For this use a nearly 1:300 gear reduction was calculated by dividing load torque by the motor torque. A geared belt drive was chosen to achieve the required power transmission. Figure 4 shows a hypothetical example of a gear belt drive which connects the bearing ring on the turntable-construction with a toothed belt wheel placed on the axis of the stepper. With 12 teeth and a belt pitch of 5 mm the belt wheel has a perimeter of 60 mm. This leads to a radius of 9.549 mm. It was possible to attach a timing band with 411 teeth and a length of 2055 mm onto the edge of the semi-trailers bearing ring. So a provisional "belt pulley" was created with a radius of about 327.063 mm since the complete diameter of the turning ring is 654 mm.

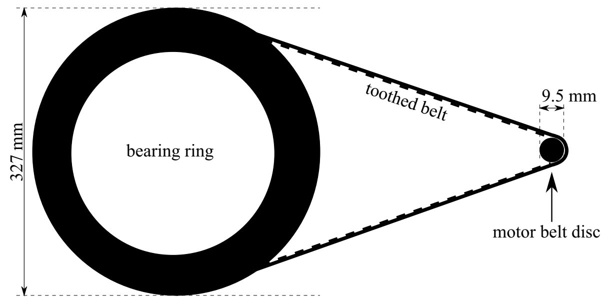

Figure 4: Example of a gear belt drive with a reduction of about 1:35.

As a result of this, the Gear Ratio (GR) which is also known as mechanical advantage, can be calculated where the input belt wheel has radius r_i and the output belt wheel has radius r_o, or rather the number of output teeth (N_o) is divided by number of input cogs (N_i):

$$GR = \frac{\omega_i}{\omega_o} = \frac{r_o}{r_i} \approx \frac{N_o}{N_i} = \frac{411}{12} = 34.25. \qquad (1)$$

As it can be seen in Equation (1) the resulting mechanical advantage ($GR = 1 : 34.25$) is too small to drive the turntable's bearing. Furthermore, the gear will not be able to stabilize the system if the motor is turned off. For that reason, another gearing mechanism had to be combined with the pre-designed system. In this case, a worm gear for further reduction was selected. The self-locking feature and the property of achieving a high gear transmission ratio are few advantages of worm gears. For this use, a worm with a module of 1.0 was purchased. A module of 1.0 signifies dimension of a cog. The more force is applied on the cogs the higher should be their module. Since the worm is a special form of a helical gear the angle of the helical toothing is defined by the winds around the wheel axle. The cog/tooth is referred to in this case as a gear or a start. One start indicates that one rotation of the worm screw will rotate the worm wheel by one cog. A higher gear/start stands for a faster turn and vice versa. To complete the worm gear an adapted worm wheel had to be combined. Here, one with 20 teeth and a hub diameter of 23 mm was used. Comparing the amount of teeth of the worm wheel (N_{wheel}) with the starts of the worm (N_{worm}) will lead to the gear transmission ratio:

$$GR = \frac{N_{wheel}}{N_{worm}} = \frac{20}{2} = 10. \tag{2}$$

Equation (2) depicts that the mechanical advantage of the planned worm gear accomplishes a ratio of 1:10. So the worm gear and the belt drive were united and finally, the collective gear ratio reached a reduction of 1:350. Of course, this was only an ideal result because friction losses of the advanced gearing mechanism derogated the transmission.

The principal composition of the gear unit is charted in Figure 5. This graph shows how the torque is transmitted from the step motor to the terminal turntable ring in ground plan on the left side. First, the force is transported over the motor shaft to the worm. After this, it is converted 1:10 to the connected worm wheel thereafter, over an axis the power is finally transferred to the turntable's gearing ring by the driving wheel. This last transmission had a ratio of 1:35. Thereby the direct transmission ratio of 1:350 can be calculated. For completeness the sheer plan of the gear mechanism is shown on the right side of Figure 5. It also shows the transmission of power from the step motor with its worm gear, via worm wheel and the connected axis, to the closing driving wheel connected with the bearing ring.

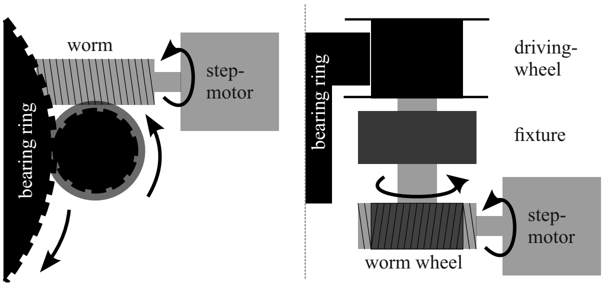

Figure 5: Principle of the designed gearing mechanism. Left: ground plan, right: sheer plan.

As mentioned above, the bearing ring of the semi-trailer's coupling ring is not ideal and so the outer edge of it is not absolute circular. To compensate these unevenness of the ring the motor was not fixed stable onto the mounted driving belt instead, it was pulled against the edge by a spring. The needed load of the spring gained the mechanical losses of the system. So it was decided that an additional motor should reinforce the existing engine. The total torque was doubled and the stepping losses were compensated by the mutual engagement of both engines.

The translated torque of both engines ($2 * 0.44\ Nm = 0.88\ Nm$) on the driving belt of the ring is now 308 Nm which conforms the required expenditure of energy (about 132 Nm) more than enough. It has to be taken into account that the angular velocity of the turntable system is slowed by the reduction of a factor of 350 (cf. Formula of gear ratio with ω_i as motor velocity and ω_o as output velocity in Equation (1)). That leads to increasing the rotational speed of both motors simultaneously to balance the velocity decrease. As mentioned above, increasing the stepper frequency leads to lowering the step motor torque. In addition, unbalanced load could destabilise the system and induce disparate force actions on the bearing. That would require a higher torque of the gear and accordingly of the step motors. After all, it is of use to have an overpowered system which can deal with possible force problems.

2.2. Step Motor Control Interface

The Step Motor Control (*SMC*) - Unit is responsible for the automatic process of regulating the step motor drive. The unit has following tasks to do:

- Controlling the two stepper motors by stimulating convenient signals.
- Communicating with the supervising processor unit over a serial interface.
- Monitoring, whether step losses and accordingly degree losses would occur.
- Providing a manual control of the turntable with buttons and a seven-segment display.
- Managing the power for all integrated components.

As micro-controller an *Arduino Mini* - Board(rev5) was applied for controlling all tasks the SMC have to do. It is a small micro-controller board assembled with an *ATmega328*, intended for use on breadboards. Since the whole acquisition concept is a research project, in addition, that such board is relatively cost-efficient, the Arduino Mini seems to be the most adequate solution for this cause. For the SMC two *A4988 Stepper Motor Driver Carrier* from *Pololu Robotics and Electronics* were selected. The driver board features adjustable current limiting, over-current and over-temperature protection, and five different micro-step resolutions (down to 1/16-step). Since a high gear reduction is applied, there is no use of micro-stepping and only the full-step mode should be executed. It operates from 8 35 V and can deliver up to approximately 1 Ampere per phase without a heat sink or forced air flow, or 2 Ampere per coil with sufficient additional cooling. The SMC applies the Electronic Industries Alliance (*EIA*) standard RS-232 as serial interface. As main function the serial communication has to exchange several instructions from and to the supervising computer.

2.3. Exciting Brass Instruments

For oscillating the air column in the tube of brass wind instruments a convenient stimulation system is required. Therefore, a loudspeaker had to be adapted for this use. Since also Tubas with an immense volume of air should be measured, a low frequency speaker with a rated output power of 50 Watt from *RS-Components* was chosen. It has an impedance of 8 Ohm and a diameter of 5.25 Inch. This large-dimensioned speaker was covered in a box made of plywood. A circle of the size of the membrane was cut out of the front plate besides a holed plastic cone was placed over the hole in order to focus the sound energy. The mouthpiece of the brass instrument could be mounted with clips, and between both parts a rubber ring was placed for tightening. Additionally, a probe microphone which serves as reference, was integrated in the plastic cone as near as possible to the mouthpiece plane. It is a 1/8 Inch pressure microphone (type: 40DP) from *G.R.A.S.* which has a linear frequency range (± 1 dB) from 10 Hz up to 30 kHz. Figure 6 shows the completed High Air Pressure Artificial Mouth (HAPAM) box in blue.

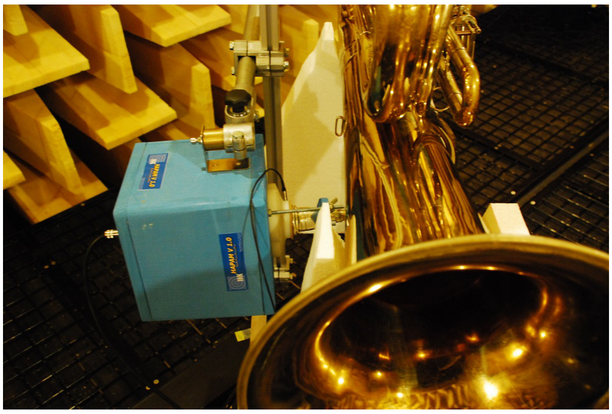

Figure 6: HAPAM mounted on a Tuba.

2.4. Exciting Stringed Instruments

For exciting stringed instruments a *Brüel & Kjær Measurement Exciter Type 4810* in conjunction with an impedance head (*PCB 288D01*) was chosen. The strings are damped by soft foam, the push rod was placed on the bridge of the musical instrument. As excitation reference the force output of the impedance head was evaluated.

2.5. Final Measurement Set-Up

A *ROGA RG-50 ICP*® 1/4 Inch probe microphone is placed in front of the musical instrument to be rotated and measured. It has a linear frequency response (± 1 dB) from 30 Hz up to 4 kHz. Since lower frequencies should be measured too, it should be noted that the microphone has an accuracy of ± 1.5 dB down to 4 Hz. It is connected with the suitable *PCB Series 440* sensor signal conditioner with gain of 1x, 10x, 100x. The G.R.A.S. microphone which interacts as reference in the excitation device HAPAM, is connected with a *BSWA Tech Co. MC702* pre-amplifier. Both pre-amplifiers were connected with a port which is linked with a 19 Inch rack terminal tower outside the chamber. For the measurement of stringed instruments the HAPAM and the reference microphone was exchanged to the above mentioned shaker and impedance head setup. The input signal for HAPAM's loudspeaker or the shaker is amplified by *Orion Profi Mosfet Amplifier* from *Zoffmusic*. Next, a converted XLR connector supplies the SMC with power besides the communication is realised over a RS-232 link. For analog data transfer a data acquisition interface card (DAQ) from *National Instruments* which is compatible to LabVIEW came into use.

2.6. Supervising Computer Program with LabVIEW

Controlling the rotation of the step motor controller and conducting the measurements were applied by a program based on designing software *LabVIEW*. The cycle of the acquisition can be divided in several parts. First of all, a top layer sequence can be defined. This level describes functions from the initialisation to the conclusion of the measured data abstractly. It can be said that the top layer also provides information about the process of the SMC's micro-controller program by the reason that both program cycles work synchronously. The second layer describes one acoustical measurement at a given position of degrees. It is encapsulated in the top layer between approaching of the desired positions of the turntable. It will be applied while the end position has not been achieved. The third and last one is the data processing layer which computes all acquired information.

3. MEASURING PROCEDURE

After setting up the music instrument and corresponding excitation device onto the turntable, all connections to the PC must be set. Now the user will be able for setting up the desired measurement parameters, like step-angle θ, full or half circle, excitation bandwidth B and the duration of measurement d. According to the bandwidth and duration the software generates a logarithmic or linear stepped sine signal, depending on the chose of the user. The sampling frequency as the buffer size of the DAQ - device is fixed by fs = 50000 samples per second and the buffer size B = 5000 samples. As each output buffer will contain the data of a sine at one frequency, the length of duration influences directly the number of output buffers and therefore also the frequency resolution. As soon, the start button is hit, the software ensures, that the turntable moves to the position $\theta = 0$ degrees. As soon the position is reached, the SMC prompts the control-software to start excitation and recording of the response. As soon, the stepped sine excitation ends, also the recording comes to stop. The SMC receives the command to increment the position by the stepp-angle θ. This procedure repeats until the the last position has been reached. In the first glance the obtained data is stored as transfer response into a text file.

3.1. Transfer Response

The Transfer Response relates output sound pressure to input sound pressure. Since the transfer response is similar to the acoustical admittance of a musical system, it also can be associated with the input impedance [4]. Further measurements of the directional sound radiation on brass instruments were based on the acquisition of single transfer responses (Equation (3), where n is the index of frequency and θ the angle of measurement).

$$T_{brass}[n,\theta] = \frac{p_o[n,\theta]}{p_i[n]} \tag{3}$$

Considering the transfer response measured on stringed instruments [5] the output sound pressure is related to the input force of the shaker onto the bridge and can be described as:

$$T_{string}[n,\theta] = \frac{p_o[n,\theta]}{F[n]} \tag{4}$$

Both methods describe the resonance profile of the music instrument. Each transfer response is now transferred into an binary format and stored as measurement dataset in an*MySQL* online database. The dataset represents a collection of vectors T[n,θ]. As for the directivity measurement the resonance profile is not of interest, but the variation in terms of radiation angle θ, all data is normalized to one measurement. For the analysis presented the transfer data of $\theta = 0$ degree has been chosen as normalization reference. The normalization factor K[n] is derived by Equation (5), all vectors will be normalized by Equation (6).

$$K[n] = \frac{1}{T[n, 0]} \tag{5}$$

$$T_{norm}[n, \theta] = K[n] * T[n, \theta] \tag{6}$$

All calculations are done by the web-server, the most algorithms are programmed using *PHP*, a server-side scripting language. *JAVA Scripts* where used, where fast user-interaction is required. As user-interface a common web-browser is needed. All line-graphs are translated to the web-browser readable XML-based vector image format *SVG*. For displaying colour-maps, the written script transfers the data into portable network graphics (*PNG*).

4. WEBINTERFACE

In the first glance the web-interface was only meant to display and share the data of the directivity patterns recorded. Soon the idea of a Musical Instrument Measurement Database (*MIMD*) came into mind, where different kind of measurements of music instruments can be stored (current url: `http://iwk.mdw.ac.at/am/mimd`). The present version of *MIMD* can handle and display input impedance and transfer response measurements. Directivity graphs can be calculated by referring to a collection of corresponding transfer response data.

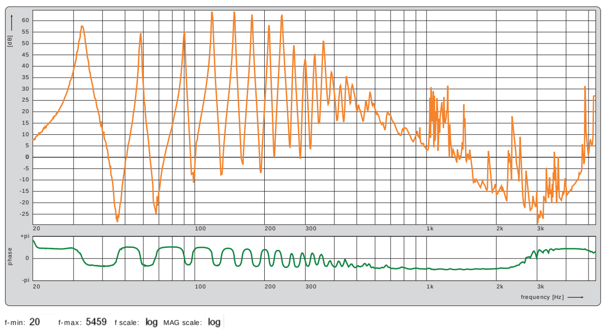

Figure 7: Input impedance of a tuba in B

4.1. Single Measurement Display

The acoustic input impedance of brass wind instruments is often used to specify and analyse quality indicators as the intonation [6]. The results of BIAS measurements can be loaded and displayed (Figure 7). Other than the graphic output of the BIAS Software the web-interface will also plot the corresponding phase graph below the impedance plot. The user can adjust the graphic output in terms of frequency bandwidth and linear or logarithmic scaling on both axis. As the data is displayed as a vector graph, lossless zooming in is only limited by the frequency resolution of the measurement. In the current state of the software the graph can only be downloaded as svg-file. Future programming will allow to load more than one measurement data sets to allow a direct comparison of impedance curves. The algorithm can also be used to display admittance measurements of stringed music instruments. As the transfer data is stored in the same data-format as the acoustic impedance, the tool can also display the single transfer data (Figure 8). For taking single point measurements interactively a moveable measurement bar is planned.

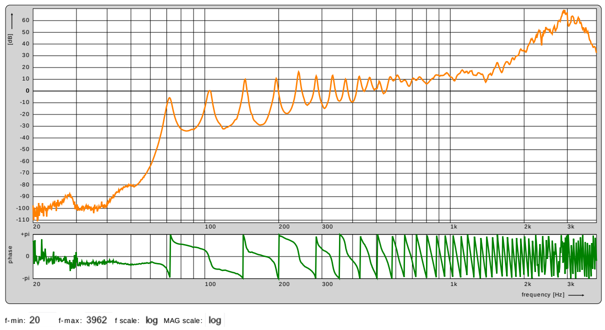

Figure 8: Single transfer respond of a tuba in B

4.2. Directivity Pattern Display

To observe the directivity pattern the user can choose of two different plot-types. A polar-plot diagram offers a two dimensional vector graph at one frequency (Figure 9). Using a slide-bar above the graph the value of frequency is changeable. As here a quick response to the user changes is essential the data is transferred to the client computer. A *JAVA Script* handles the graphic output and updates the plotted svg-graph corresponding to the set value of frequency. For a total view of the directivity data, a two dimensional color map or directivity sonogram was chosen as output (see Figure 10). The output pixel-map can be adjusted by the user. By default the highest appearing amplitude is mapped to the color red, the lowest to blue. By defining a value for "Ceiling" all amplitude values above, will be mapped to the same red-color value. By imputing a value higher than zero into the "Floor" input field, all amplitudes below this limit will be mapped to the same blue-value. All existing amplitude values in between this two limits will be mapped linearly to the color-field displayed below the main graph. Also a limitation of the frequency bandwidth is possible by changing the values of "f-min" and "f-max". A fifth input field provides a remapping of the data whether the zero-degree line is centred horizontally or at the top or bottom limits of the pixel-map.

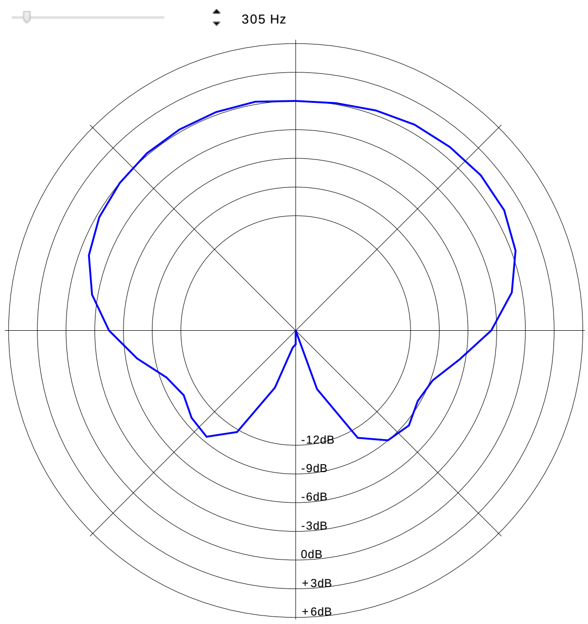

Figure 9: svg pattern of a tuba in B at 305 Hz

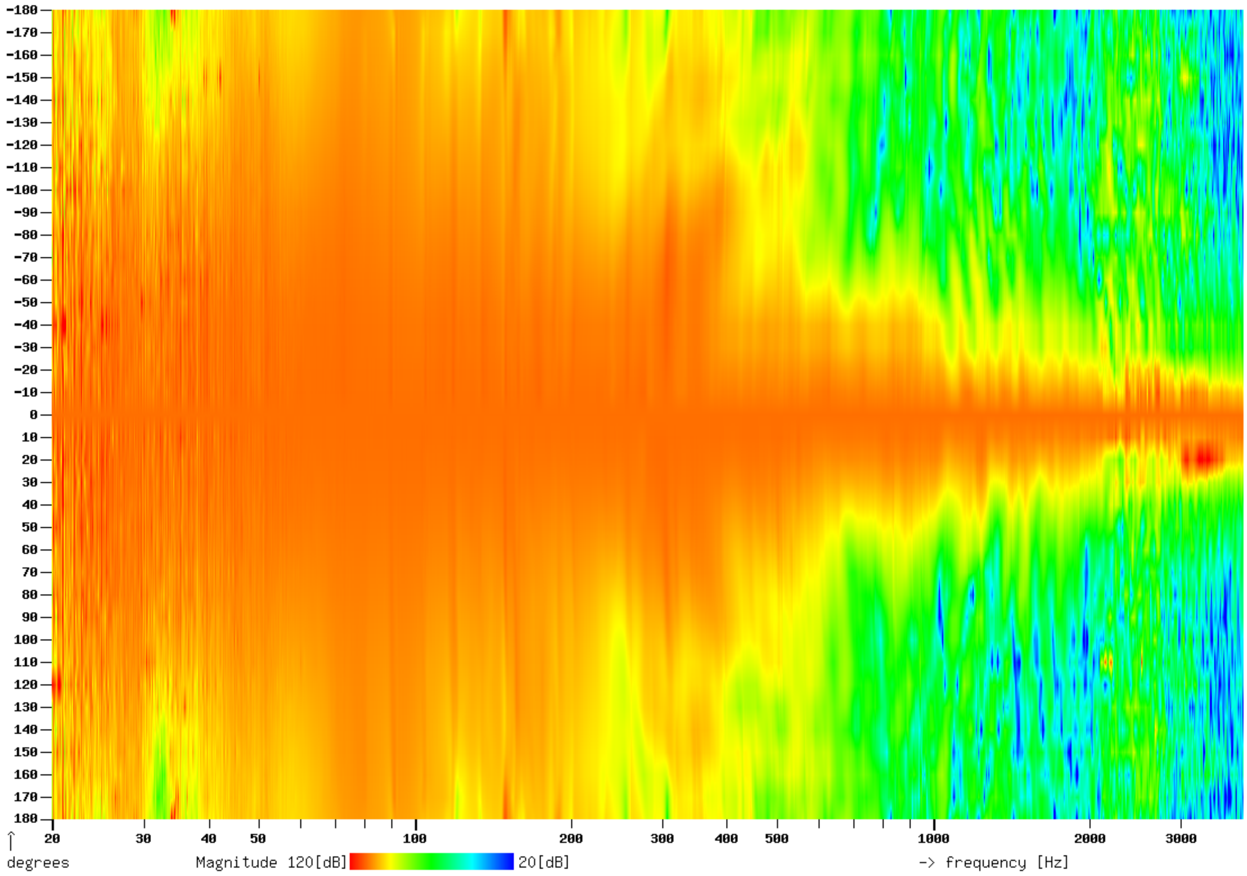

Figure 10: Directivity sonogram of a Tuba in B, Ceiling: 120 dB, Floor: 20 dB, f-min: 20 Hz, f-max: 3962 Hz and 0 degree measurement positioned in the horizontal centre.

5. CONCLUSION

The presented hardware in conjunction with the developed software offers a widely user-friendly device for measuring two-dimensional directivity patterns of brass wind- and stringed instruments. An extension to obtain directivity data in three dimensions is planned.

The current version of the web-interface allows to display several kinds of single measurement data as well directivity patterns. Future features will include data exporting functions and multi-curve display. Depending on the response to the presented database, extensions for collecting construction data of music instruments, general descriptions, sounds and photos will be processed.

6. REFERENCES

[1] Jürgen Meyer and Uwe Hansen, *Acoustics and the Performance of Music: Manual for Acousticians, Audio Engineers, Musicians, Architects and Musical Instrument Makers*, Springer Science+Business Media, LLC, 5 edition, 2009.

[2] Jürgen Meyer, "Musikalische Akustik," in *Handbuch der Audiotechnik*, pp. 123–180. Springer-Verlag Berlin Heidelberg, 2008.

[3] Jürgen Meyer and Klaus Wogram, "Die Richtcharakteristiken von Trompete, Posaune und Tuba," *Das Musikinstrument*, vol. 19, pp. 171–80, 1970.

[4] Stephen Elliott, John Bowsher, and Peter Watkinson, "Input and transfer response of brass wind instruments," *Journal of the Acoustical Society of America (JASA)*, vol. 72, no. 6, pp. 1747–1760, 1982.

[5] Paul Geissler, Otto Martner, Carsten Zerbs, and Martin Schleske, "Psychoacoustic investigations on the possibility of aurally identical violins," in *Proceedings of the Stockholm Music Acoustics Conference 2003, SMAC 03*, Stockholm, 2003, KTH Speech , Music and Hearing, vol. 1, pp. 59–62, Roberto Bresin.

[6] Werner Winkler and Gregor Widholm, "Bias - blas instrumenten analyse system," in *15 Jahre Institut für Wiener Klangstil (1980-1995)*, Eduard Melkus, Ed., pp. 95–106. Institut für Wiener Klangstil, Wien, 1996.