The characterisation of Musical Instruments by means of Intensity of Acoustic Radiation (IAR)

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In the physics of Musical Instruments sound radiation is usually related to modal analysis. In violin acoustics, normally sound generation of a good instrument is physically measured considering the X mode (2) and the ring mode (5) of the top and back plate.

On the other hand, several Authors (for example Wogram, Suzuki and Giordano) have considered sound (acoustic) radiation for acoustic characterisation of vibrating components of musical Instruments. Nevertheless, no strong correlation with modal analysis was found, and therefore further researches were requested.

In this paper a new acoustical parameter recently defined, the Intensity of Acoustic Radiation (IAR) is introduced and experimentally measured on different musical Instruments. The IAR considers mechanical vibration of surface (e.g. soundboards) and sound generation of the musical Instruments. It is therefore able to quantify the sound efficiency of musical Instruments. Finally, the results of experimental measures of IAR are compared with results obtained of other techniques, as modal analysis.

1 Introduction

In musical acoustics modal analysis and acoustic radiation are very often used to study the vibro-acoustical behaviour of musical instruments. Furthermore, some other techniques have been developed starting from these fundamental methods, as holographic interferometry. Sound radiation is strongly related to modal patterns, and therefore a correlation between resonance frequencies in vibrating structures and sound production should exist. Previous studies of Suzuki (1986) and Giordano (1998) found a negative correlation between acoustic radiation and Frequency Response Function (FRF) of membranes or plates in instruments such as piano and harpsichord. Perhaps one of the reasons of the negative correlation was the complexity of pianos and harpsichords, and understanding their sound radiation could have been hampered by their complex structure. On the other hand, percussion instruments are relatively simple musical instruments, and the study on frequency response, modal analysis, acoustic radiation and the correlation between FRF and sound radiation should be found easily. The comparison between experimental modal patterns and previously published results could suggest the most appropriate measurement technique for characterizing vibro-acoustical properties of musical instruments.

A new vibro-acoustical parameter, able to properly relate sound production and FRF, is required especially for tympani, where sound generation and modal analysis are strongly related. Applications of this extend beyond musical acoustics into the modelling of musical instruments in auditoria.

2 Acoustic radiation

The efficiency of acoustic radiation is a measure of the effectiveness of a vibrating surface in generating sound power. It could be defined by the relationship:

$$\sigma = \frac{W}{\rho c S \langle v^2 \rangle}$$

in which W is the sound power radiated by a surface with area S, which could be obtained by integrating the far-field intensity over a hemispherical surface centered on the panel, and $\langle v^2 \rangle$ is the space-averaged value of the time-averaged normal distribution of velocity (Fahy, 1989). From this general definition various measurement methods useful for the study of sound emission could be obtained. Previous studies on this argument have been conducted on the soundboards of the piano and of the harpsichord. K. Wogram, H. Suzuki and N. Giordano studied the soundboard of the piano using different measurement methods.

Wogram used the parameter $F/v$, defining $F$ as the excitation force and $v$ as the resulting velocity at the point of excitation (1980). He reported that it exhibits a maximum at a frequency near or below 1 kHz, and that it falls sharply below 100 Hz, and above 1 kHz. He found that it falls typically by a factor of 10 as the frequency is varied from 1 to 5 kHz.

Suzuki used the “surface-intensity method” (1986), defined as:
where \( I \) is the average intensity in time, perpendicular to the vibrating surface, measured in near field (about 30 cm from the radiating surface), \( \omega \) is the angular frequency, \( \text{Re} \) and \( * \) are the real part and the complex conjugate of a complex number, \( p \) and \( a \) are the pressure and the normal acceleration at the measuring point.

Giordano used the parameter \( p/v \), where \( p \) is the sound pressure measured in near field and \( v \) is the velocity of the soundboard (1998). In all the measured points \( p/v \) is greatest at about 1 kHz, and it falls off below a few hundred hertz and above 5 kHz. Is important to notice that all of these studies have one result in common: the resonance frequencies did not coincide with those of acoustic emission; on the contrary they often had negative correlation.

### 3. Intensity of Acoustic Radiation (IAR)

IAR is defined as the space-averaged amplitude of cross spectrum between sound pressure caused by the movement of the vibrating surface (the membrane) and the velocity of the vibration of the membrane itself.

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IAR(\omega) = P(\omega) * V(\omega)
\]

An omnidirectional microphone is necessary for the measurements, and should be located in a fixed position at about 25 cm over the instruments, and about one-fourth of the principal dimension of the instrument. Furthermore, the measurements should be conducted in a slightly reverberant room, where reverberation time helps to average radiation of sound caused by early modes. At higher frequencies the room acoustics do not influence the measurements. Moreover, the space-averaging of the data conducted by moving the transducers thorough the instrument enhance the measurements.

### 4. Experiments

Measurements of IAR were performed in two different percussion instruments. In the first case, two kettledrums were analysed. The first was a plexi-glass Adam 25-in (about 65 cm) kettledrum with a Remo mylar skin and a central reinforce, tuned to approximately 166 Hz (corresponding to E). The second was a copper 25-in (65 cm) Ludwig kettledrum with a mylar skin and no central reinforce, tuned to approximately 145 Hz (corresponding to D). In the second case, a special idiophone was analysed. It is a special ethnographic musical instrument. The instrument (called carabattola) used to be played during the holy week before Easter in certain rural villages in Italy. Actually the instrument is not more played, since it was forbidden from Catholic Church in 1950s for not clear reasons. It should be underlined that this instrument gives not proper a real sound (as normally one could expect), but rather a background noise, partially similar to the noise of a grater.

In both cases (kettledrums and carabattola) the measurements of IAR were also accomplished with modal analysis. Sound pressure \( p \) was measured in near field, at 25 cm from the instruments, as previously reported by Suzuki and Giordano. In order to properly measure radiation of sound, the distance between the radiating surface and the microphone should be one fourth of the wavelength, and hence 25 cm was considered a good compromise for low and high frequencies.

#### 4.1 The tympani

The measurements in the tympani were conducted in two different ways. In the first case, a hammer was used with an accelerometer. In the second case, a shaker substituted the hammer. In both cases the microphone was located in the same position.

In the figure 1 (A and B) the results are reported.
Furthermore, up to 15 modes were studied, in order to check the results with previous researches. In the figures 2 and 3 the first three circular and four radial modes are respectively reported.

### 4.2 The carabattola

The *carabattola* is a very rare ethnographic musical instrument. It was played only in the holy week before Easter, and perhaps the origin of that instrument is Byzantine. The player holds the instrument with his handler, and turns quickly the *carabattola* left and right. The movement causes a clapper to hit in rapid sequence alternatively two metallic little circles, located on the wood. Therefore the clapper becomes similar to a knocker, and the sound comes up. The measurements in the *carabattola* were conducted in a similar way that in the tympani. The shaker excited the instrument in one of the two metallic circles, and the microphone was positioned about 25 cm above. All measurements were carried on in the same room as of the tympani.

Also in this case modal analysis was conducted. Since sound generation differs considerably from the tympani, the results are quite different. In figure 3 the IAR is compared with $p/v$ ratio and with FRF. The graph is limited to 1 kHz because of the increasing of modal density at higher frequencies. In figure 4 are reported some modal patterns measured in the instrument.

In the *carabattola* the matching between IAR and FRF is not so extremely marked as in the case of kettledrum. Nevertheless, the negative correlation between FRF and $p/v$ is not so evident. This should be explained with the special kind of sound emission of the *carabattola*, which differs considerably form the tympanum.
5 Analysis of measured data

Considering the two different musical instruments here analysed, the following results could be summarized. In the case of the tympani, the negative correlation between \( FRF \) and \( p/v \) are very high, and in the same time the two graphs of \( FRF \) and \( IAR \) are almost coincident.

In the case of \textit{carabattola} the results are different, as the mechanism of sound generation differs from the tympanum. The first four modal patterns of the \textit{carabattola} are reported in figure 4. From the analysis of these patterns, it should be noted that the metallic plate where the knocker hits the instrument influences the movement of the sound chest. Considering the relation between \( FRF \) and \( p/v \), it could be observed that there is only partially a negative correlation, especially at medium-low frequencies. At the same time, comparing the two graphs of \( FRF \) and \( IAR \), they result to be only partially correlated. It is likely that the two graphs are shifted of a little frequency interval, even though they are much more correlated each other rather than \( FRF \) and \( p/v \).

In other words, the tympanum generates sound mostly from the membrane, and the vibration of the membrane causes a very clear perception of pitch. Nevertheless, in the \textit{carabattola} the chest and the metal knocker generate the sound, which is not perceived as a specific pitch.

Considering the relation between \( IAR, FRF \) and \( p/v \), in the case of the tympani they are very correlated, since almost all sound generation comes from the membrane (where velocity \( v \) is measured) whereas in the \textit{carabattola} the correlation is not so evident, since sound generation comes not only from the wood.

The \( IAR \), therefore, resulted a parameter able to properly relate vibration of plates or membranes and sound production. In the case of the tympani this relation is
remarkable, whereas in the *carabattola* the relation is not so marked. In the first case IAR and FRF are very correlated, in the second case they are only partially correlated.

## 6 Conclusions

Acoustic radiation measurements and modal analysis were conducted in two different kinds of percussion instruments, two tympani and a *carabattola*. The measurements were conducted as suggested by many Authors in previous papers. In both cases the instruments were excited by means of a shaker, connected with a thin metallic bar. In previous paper the shaker resulted better than the head-impedance hammer for frequency results up to 3 kHz, since the resonance of the bar connecting the shaker to the instruments was found at about 3 kHz. The mappings of individual vibration modes for all the instruments were very clear, and in the case of the tympani the frequency ratios agreed approximately with the theoretical ones. A high degree of correspondence was obtained for the circular and mixed vibration modes, whereas the diametric modes yielded frequencies slightly lower than the theoretical ones. In the *carabattola* the mappings of modal patters resulted not so clear as in the tympanum, due to the typical sound produced.

In all musical instruments acoustic radiation was measured in two different ways. In the first case the complex ratio ($p/v$) between sound pressure and the vibration velocity of the main vibrating elements of the instruments was calculated. This is the method used by Giordano. In the second case the space-averaged amplitude of cross spectrum ($p \cdot v$) between sound pressure, measured at a fixed point at 25 cm far from the instruments, and the vibration velocity of the membranes or of the chest, was calculated. This is the new parameter called intensity of acoustic radiation (IAR). Comparing the graphic of FRF and $p/v$, it can be observed how the resonance frequencies are often in opposition to those of acoustic emission, in accordance with previous studies conducted on soundboards of the piano. Applying IAR, the resonance frequencies correspond perfectly to those of sound emission, and the curves of the two graphics are very similar. This is particularly evident in the case of tympani. The IAR parameter is well related to frequency response function and for this reason is preferred to $p/v$. It is a medium parameter between acoustic intensity and acoustic radiation, and so is suitable to measure the sound generating characteristics of musical instruments with vibrating soundboards. This parameter can be used to qualify and define the directivity of musical instruments, which is important for architectural acoustics, as well as for auralization processes.

## References


