Noise controlling by means of intensity of acoustic radiation measurements

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Abstract. Noise control in working places often involves the design of acoustic treatment of enclosures and the design of proper devices able to reduce vibration of surfaces in machinery and structural borne propagation. However, in order to optimize the efficiency of the treatment, it would be very useful to properly relate the vibration with total sound emission. From a general point of view, it is quite important to determine the relation between vibration surfaces and total sound (or noise) emission. The same problem could be also studied for several other sources, such as loudspeakers or musical instruments. We employ the Intensity of Acoustic Radiation (IAR), a novel, corresponding parameter introduced recently, that relates modal analysis with sound production. This parameter is defined as the space-averaged amplitude of cross-spectrum between sound pressure caused by the movement of the vibrating surface and the velocity of the vibration of the surface itself. To measure IAR, an omnidirectional microphone is placed in a fixed position at a short distance over the surface, while an accelerometer is mounted at the same points utilized during modal analysis. IAR showing a very high correlation between Frequency Response Function (FRF) and sound production of the surfaces is, therefore, able to describe the relationship between vibration and noise emission.

1. Introduction
Working places are part of the built environment with a defined use and timetable [1]. Ensuring high-quality design and high comfort levels in the working place is often a matter of energy field [2], while simulation tools are available nowadays to check at the same time thermo-physical properties [3], occupant behavior [4], lighting conditions [5] and acoustic performance [6]. The above aspects allow identifying building behavior [7]. On-site measurements are crucial to test the real performance of the integrated devices [8] as well as investigating the link between design and reality [9]. This threshold is not related only to the building itself, as a designed product but also to the boundary conditions assumed as starting point for the project, i.e. reliable data to collect [10]. Boundary conditions analysis is the most challenging part when renewable energy integration is foreseen [11] or high-level modeling is carried out at building level [12]. Acoustic comfort is often ignored and assumptions made on the context description as well as on the future design requirements result to more detailed energy considerations for innovative solutions [13] or for the urban environment [14]. Noise plays a key role related to the surroundings [15] and for the comfort of future users [16]. Moreover, where the designed space or object has acoustic as its main use such as opera house [17], theater or even musical instrument [18], acoustic measurements must be carried out, following specific rules to be highly reliable. Similar attention must be paid to the mechanical devices installed in the environment.
enhancing the comfort levels as well as to the dedicated linear and not linear analysis techniques [19] to describe phenomena such as noise.

In mechanical noise prediction, modal analysis and acoustic radiation are very often used to study the vibro-acoustical behavior of mechanical parts of complex machines. Furthermore, relevant 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 must exist. Previous studies [20, 21] indicated a negative correlation between acoustic radiation and Frequency Response Function (FRF) of membranes or plates in instruments such as pianos and harpsichords. Perhaps one of the reasons for the negative correlation is the complexity of pianos and harpsichords and understanding their sound radiation could have been hampered by their complex structure. Noise reduction and controlling may be considered as special cases of general optimization problems, arising in different scientific areas, such as photoacoustics or even medical imaging [22, 23, 24]. Starting from these experiments, another researcher has recently defined a new vibro-acoustic parameter able to describe the relation between modal patterns and sound emission [25].

This parameter, called Intensity of Acoustic Radiation (IAR), was determined considering kettledrums and other percussion musical instruments, where sound generation and modal analysis are strongly related. In the present paper, the application of IAR has been extended in mechanical noise production, and the results are presented.

2. Noise radiation

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

\[ \sigma = \frac{W}{\rho_0 c S \langle \nu_N^2 \rangle} \]  

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, \( \rho_0 \) is the air density, and \( \langle \nu_N^2 \rangle \) is the space-averaged value of the time-averaged normal distribution of velocity [26]. 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. Several researchers have studied the soundboard of the piano using different measurement methods.

Wogram [27] used the parameter \( F/v \), defining \( F \) as the excitation force and \( v \) as the resulting velocity at the point of excitation. Suzuki used the “surface-intensity method” [20], defined as:

\[ I = \text{Re}[p(a/j\omega^*)/2] \]  

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.

Furthermore, Giordano [21] used the parameter \( p/v \), where \( p \) is the sound pressure measured in near field and \( v \) is the velocity of the soundboard. It’s 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 a negative correlation.

On the other hand, several researchers proposed different methods and parameters for predicting sound radiation over structures. Among them, Scamoni [28] and Piana [29] employed of the wave propagation approach in order to predict the link among vibrational and acoustic behaviors in sandwich structures.
3. Intensity of acoustic radiation - IAR

Starting from the experiment described, a new parameter called *Intensity of Acoustic Radiation, IAR* has been defined as the space-averaged amplitude of cross-spectrum between sound pressure caused by the movement of the vibrating surface and the velocity of the vibration of the surface itself:

\[ IAR = \langle P(\omega) \ast V(\omega) \rangle \]  

(3)

The *Intensity of Acoustic Radiation* resulted strongly correlated with FRF function, and for this reason was defined as a new parameter, which differs from other similar ones, especially for vibrating systems.

![Comparison between FRF and p/v](image1)

![Comparison between FRF and p*v](image2)

*Figure 1.* Comparison between IAR, p/v and p*v for a kettledrum.

An omnidirectional microphone is necessary for the measurements. In the case of tympani, the microphone must be located in a fixed position at about 25 cm over the surface, i.e. about one-fourth of the wavelength of the frequency corresponding to the earliest mode. The measurements must conduct in a moderately 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 is conducted by moving the transducers through the instrument enhance the measurements.

In the case of mechanical noise emission, the measurements are conducted in a normal reverberant environment, as in the case of an industrial warehouse. The distance from the vibrating component and
the microphone is fixed at about 20 cm or less since noise emission normally consists of frequencies over 1 kHz.

4. Measurements of IAR in machine noise emission
During the design of a new model of elevator, an Italian Company found an overall noise production originating from the prototype, which was much higher than the previous model. Since they had simply enhanced some mechanical components of the engine, they were unable to determine the reason for the increase of noise emission. The technical staff initially suggested adding some absorbing materials close to the new components, however, no reasonable results were achieved. Moreover, they also observed an increase of vibration in some parts but did not find any relation with sound emission.

Starting from these analyses, experiments for the measurement of vibration and noise emission were planned. The experiments were firstly conducted separately, in order to quantify the overall values of vibration and noise emissions in the elevators.

![Figure 2. Measurements of IAR in an elevator.](image1)

![Figure 3. Measurements of IAR for the 3 components of the elevator.](image2)
In a second step, the measurements were addressed to underline the mechanical causes of the noise emission. Due to the complexity of the mechanical parts of the machine, the analysis could not be undertaken considering the engine and mechanical components globally.

In order to find the mechanical components that provoked noise emission, a different approach, in terms of acoustic intensity, was planned.

The IAR was, therefore, measured in different conditions of the machine, as depicted in Figure 1 and 2. The measurements of IAR were repeated in different configurations of vibration sources, in order to characterize the relationship between every single vibration of each component of the engine and the total noise emission of the engine. Finally, the measurement of IAR verified that the cause of noise emission was a component of the braking system in the elevator. This is to demonstrate that when designing high-performance buildings [30], even historic [31], the designer must be keen in detail to make the building performing well in all the indoor comfort aspects without ignoring the mechanical devices operating in it. In Figure 3 we present the graphs of the measurements for 3 different components of the elevator: n.3 corresponds to the braking system.

5. Conclusions
In this paper, the measurements of IAR, previously applied in musical acoustics, have been firstly applied in mechanical noise generation in complex mechanical structures. IAR links vibration (velocity) of mechanical components of complex structures with their sound emission. Furthermore, IAR could also properly describe the frequency characteristics of noise generation since it also relates the frequency response function with vibrating velocity of mechanical parts. The definition of IAR may potentially help to enhance measuring tools for noise emission since it can easily predict the efficiency of vibrating surfaces that generate sound emission. Moreover, since the evaluation of IAR requires a reverberant environment, the measurements could be easily performed in the real space that contains the noise source, as in the case of industrial warehouse, without requiring any movement of the source in other rooms (as the anechoic room). This could be unrealistic in most of the other cases, due to dimensions and weight complexity limitations.

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