EVALUATION METHODS OF EXTERNAL AIRBORNE NOISE EMISSIONS OF MOORED CRUISE SHIPS: AN OVERVIEW

Antonino Di Bella
Dep. of Industrial Engineering, University of Padova, Via Venezia 1, 35131 Padova, Italy
e-mail: antonino.dibella@unipd.it

The evaluation of noise emissions of a ship is a problem particularly complex. The difficulties are related to the characteristics and to the ways of relating to potential receptors of the source itself. The analysis of noise emission and propagation from a vessel can be divided in several parts, essentially based on the medium of sound energy propagation and on the environmental reference: internal (airborne and structural propagation) and external (airborne and underwater propagation, vibration effects on harbour structures inducted by wave motion).

While internal and underwater sound propagation can be effectively evaluated by standardized test methods for many types of vessels, the assessment of external noise propagation requires more attention, because measurement methods do not always fit to the type of vessel and to operating procedures of navigation and mooring. From this point of view, a very interesting case is that of the large cruise ships. In recent years, the gross tonnage rose sharply and the form factor has been modified to allow the housing of an increasing number of passengers. Therefore, several aspects related to acoustic emissions are involved, such as the increase of funnels height and number of sources on the ship sides, mainly ventilation outlets. The consequences are particularly noticeable when the ship is moored, often because its height overlooks the port facilities and the effect of noise produced by power supply and ventilation systems can be significant on the surrounding urban areas. The paper addresses the actual framework regarding ship noise, comparing different measurement techniques and evaluation methods, with reference to airborne noise emission in the external environment of moored large cruise ships.

1. Introduction

The problem of noise emitted by moored ships focus not just on technical aspects of acoustic measurements, but involves also several factors that may depend on the type of vessel and activities carried out in the port area, taking also into account the surroundings. While the assessment of noise on board commercial vessels, with regard to the prevention of risks arising from excessive exposure, is regulated at supranational level according to the resolution of the International Maritime Organization\(^1\), a global approach is not applied to airborne noise emissions outside the ship\(^2\). The control of environmental noise related to port activities, nevertheless, has to comply with the broader framework of the national directives and regulations.
2. Problems of cruise ships noise measurement and modelling

The European Directive 2002/49/EC\(^3\) suggests to mapping harbour areas by measurement methods applied for industrial noise in accordance with ISO standards\(^4\). Consequently, the airborne noise emissions outside the ship that propagate in port area have been analyzed for a long time mainly from the point of view of industrial sources that operate in production environments, as in the case of commercial vessels (bulk, tanker, container and general cargo ships) and related infrastructure for handling and transport goods (cranes, roads, railways, pipelines, etc.). The acoustic emission of moored cargo ships, Ro-Ro and Ro-Pax is usually evaluated during harbour activity and can include all the sources on the ship and on the dock\(^5,6\).

This kind of evaluation makes it possible to verify compliance with local regulations but does not handle the noise problem in advance by modelling. The Directive 2002/49/EC, also suggests what are the technical standards that must be used in the modelling calculations according to the typology of source. For industrial noise the reference technical standard is ISO 9613-2\(^7\). It is intended to modelling of outdoor sound propagation without any reference to specific sources of noise and is based on knowledge of the sound power emitted by the source, its shape and directivity.

These three elements are necessary to make any kind of assessment on the noise emitted from a sound source, together with information on the geometry of the site, which helps to define the Digital Ground Model. However, for a particular type of vessel, shape is taking a leading role in the ability to correctly define the sound power and directivity. Indeed, the maximum gross tonnage of cruise ships, and consequently the size, has grown exponentially in recent years, as shown in Fig. 1.

![Figure 1. Tonnage variation of the cruise ships put into service since 1947. The growing trend of gross tonnage (exponential dashed line) is based on the larger cruise ships launched in each year (black dot) and is compared with the gross tonnage of the total number of new cruise ships in service per year (white dot). New world’s largest cruise ships under construction (grey dot) are also reported. Source: Main Cruise Line Companies.](image-url)
Comparing the data on the gross tonnage of the individual cruise ships to those of the total tonnage of new cruise ships put into service every year it is possible to note the tendency, particularly accentuated in recent years, to the realization of a lower number of cruise ships but larger than earlier (Fig. 2). The threshold of the gross tonnage of 100000 tons was exceeded in 1996 and since then have been launched more than 50 large cruise ships with an average capacity of about 3200 passengers. In 2009 a cruise ship with a gross tonnage of over 200000 tons and a capacity of 5400 passengers has been put into service.

![Figure 2](image-url)  
**Figure 2.** Trend (dashed line) of the total tonnage of cruise ships from 1947 to 2013. The evaluation is based on the total number of new cruise ships put into service every year. Ocean liners are included only if they also functioned as cruise ships. Source: Main Cruise Line Companies.

The analysis of the size of cruise ships recently built with a gross tonnage greater than 100000 tons shows that the average length is greater than 300 m, with a beam (width at the widest point as measured at the ship's nominal waterline) of more than 42 m (Fig. 3). This corresponds to a maximum height of the funnels which can vary between 50 m and 70 m.

These aspects should be taken into consideration in the choice of methods of assessing the sound power. The size and shape of the vessel, as well as the position of the prevalent sound sources, does not allow, in the majority of cases, the direct evaluation of the sound power emitted.

The noise sources of a moored cruise ship can be located at the exhaust pipes (main engine and auxiliary engine) at the top of the funnels and in the ventilation system outlet (from engine room and decks). When a ship is moored to a pier, not all noise sources are switched off. The noise from engine room is reduced because the main engine is idle and only auxiliary engines are working for production of electricity. While engine room ventilation system is operating at reduced capacity, ventilation noise from decks and cabins is unchanged (Fig. 4).9

From the point of view of the modelling and control of noise emissions, the effect of noise sources to the receivers strongly depends on the position of the moored ship in relation to the screens in the harbour area (docks, buildings, cranes, etc.). For the acoustic modelling of an harbour
area it is extremely important to take into account the ground effect, both for surface of the water and for the docks, and the screening effect due to the buildings between the ship and the receptors. The large size of modern cruise ships and the conditions of mooring in the harbour, with the simultaneous presence of several ships and handling activities on the docks, makes difficult the task of monitoring and measurements of noise levels at fixed points of control within the port itself, as well as the determination of the sound power produced by each vessel.

Figure 3. Comparison between length and beam (width at the widest point as measured at the ship's nominal waterline) of cruise ships recently built with a gross tonnage greater than 100000 tons. Source: Main Cruise Line Companies.

Figure 4. Position and activity of the main noise sources on board of a moored cruise ship.
3. Review of methods for the assessment of sound power emitted by moored ships

The knowledge of the power spectrum of the noise sources is necessary for any kind of assessment of the effects induced by noise on potential receptors. It can be obtained by means of noise measurements. On site noise measurements, using established techniques and specific equipment, can be considered the most accurate option, but the standards for the determination of the sound power do not fit to sources of large dimensions with the accuracy required for the use in simulation models. This is one of the reasons why nowadays there are still few data in the literature on the total sound power emitted by the big cruise ships. The options are therefore to consider the ship as a sum of the individual sound sources, measured individually on board the ship\textsuperscript{9}, or to obtain the sound power level by on site measures, according to different technical standards, and reverse analysis with numerical models\textsuperscript{8,10}. The first option is limited by the possibility of direct access to the vessel and to the feasibility the measure itself, as it is necessary to determine with sufficient accuracy the envelope surface around the source, in order to be able to correlate the different measurements of sound pressure. The second option requires the possibility to apply different measurement techniques and to be able to set up a grid of measurement points of sound pressure levels induced by the vessel that is representative of the actual propagation characteristics of the site. Moreover, with the size increase of the ship, it is necessary to introduce several control points even at a considerable distance from the ship itself.

If direct access is possible, the measurement standards of ISO 3740 series\textsuperscript{13} can be used. Among them, the ISO 3744 standard\textsuperscript{14} appears the most suitable procedure to derive the noise sources power level of a ship. In this standard, is specified a method for estimating the sound power level produced by a source in terms of sound pressure level on a measurement surface enveloping the source. Using the methodology described in the standard is possible to characterize one by one each on board noise source. Even ISO 3746 standard\textsuperscript{15} may be useful for the evaluation of small sources on board, but the results obtained are limited to the overall value of sound power, without frequency spectrum, and with less accuracy.

There are other ISO standards which are specific for airborne sound emitted from ships and boats, but these international technical standards define only procedures to carry out acceptance and monitoring tests and don’t have the aim of an acoustic characterization based on sound power emission. The ISO 2922 standard\textsuperscript{16}, relevant for all vessel types with the exception of recreational crafts, proposes to characterize the noise pollution of stationary vessels by sound pressure level values measured by an array of microphones placed along the ship’s side\textsuperscript{17}. The standard defines that the position of microphones has to be fixed at a distance of 25 m from the ship’s side and at several points around the vessel. No other information can be drawn from this standard, making it ineffective when the noise levels at some distances need to be estimated. Furthermore, the ISO 14509 standard series\textsuperscript{18,19,20} is relevant for small recreational crafts, but only pass-by measurements of moving vessel are considered.

The most common condition is one in which it is not possible to access to the moored ship or where there are many ships in port. In this case it is necessary to solve the problem in a different way. The typical approach is a process of reverse calculation starting from experimental measurements carried out according to different standards for environmental noise measurement. Starting from the determination of the acoustic contribution of a sound source at given points, it is possible to obtain a reliable assessment of the input data for the acoustic model\textsuperscript{8,21}.

Concerning the measurement points, it is important to distinguish between reference, verification and reception points:
• a “reference point” is a point of measurement near the source that makes it possible to estimate the sound power level of noise sources (paying attention, for example, to noise source directivity);
• a “verification point” is a significant point for checking the correctness of the hypotheses about geometrical features (e.g. presence of reflections and/or obstacles) and acoustical features of the site (e.g. meteorological conditions, ground characteristics);
• a “reception point” is the point of measurement chosen near a receiver that is considered significant for checking the assessment of the acoustic emission of a noise source.

The evaluation method typically consists in a reverse procedure, starting from the sound pressure level due to an equivalent sound power of a point source placed at the top of the funnels. For the inverse calculation, formulas described in ISO 9613-2 standard can be used after making several assumption about site geometry and sound sources position. Then, the optimization of the inverse calculation and the approximation of the sound power of the point source is based on reduction of the difference between the sound pressure level calculated and that measured at points of verification and reception (Fig. 5).

The effectiveness of reverse calculation methods, which combine techniques of assessment and measurement requirements already present in several national and international standards, is well stated by several cases study\textsuperscript{8,10} and can be adapted to different combinations of shape and directivity of the source, as in the case of Ro-Ro, in which the area of the loading ramps, during the operations of embarking or disembarking, can be effectively modelled as radiating surface.

![Figure 5. Outline of the reverse procedure for the evaluation of the sound power of moored ships from measurements of sound pressure level.](image)

Other procedures may be applied by merging different methods of measurement or technical standard guidelines, such as, for example, by redefining in an appropriate way the reference surface of the sound source or using devices, as microphone arrays handled by cranes\textsuperscript{11} or a fixed grid of acoustic monitoring stations\textsuperscript{8}, in order to characterize the acoustic emissions of moored ships. Some of these techniques may be used effectively in shipyards, in order to allow the acoustic characteriza-
tion of each vessel and to use the obtained data to constitute a database that can be used for acoustic planning purpose or noise control in harbour areas.

In recent years the importance of these issues have become noticeable and several research projects have been launched with the aim to investigate the most effective ways of measurement and assessment of noise from ships\textsuperscript{22,23,24}.

4. Conclusions

Most of cruise ports are close to urban areas, in particular in Europe and in the Mediterranean basin, and the problem of noise due to the activities of navigation and mooring of large vessels can become relevant for noise pollution control.

The acoustic maps can be used for the evaluation of different acoustic scenarios, at urban planning stage, and also to define acoustic buffer zones according to national regulations about noise of transport systems, and for the noise control with reference to local requirements.

In all these cases the knowledge of the sound power emitted by moored cruise ships is essential for a proper evaluation and control of environmental noise. However, there are currently no technical standards that can define unambiguously the methods for the determination of the sound power of very large sources, such as cruise ships in a complex environment like an harbour.

The need for a technical standard for the characterization of large vessels is evident for the growing importance on a worldwide scale of the cruise tourism industry and the impact that this can have on the urban environment in the vicinity of the port areas.

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