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Characterisation of tram noise emission and contribution of the noise sources

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ABSTRACT

The recent expansion of French tram networks and the related local residential complaints mean that a better knowledge of the situations leading to negative reactions from the local inhabitants is required. Hence a research project has been conducted to evaluate and describe noise and vibration emission of trams as well as the perception by the local residents. This paper investigates tram noise emission on common straight track sections, involving two vehicle scales. First the acoustic power and the mean vertical directivity of the total tramset is assessed using an arc of microphones. Then the localisation and the analysis of the main noise sources are performed by means of a cross array during the tram pass-by. Two tram types representing two generations of French rolling stock, both running on two sites with distinct track characteristics, have been investigated considering the effect of speed, tram type, and track type on the noise source contributions and spectral features. Most sources are located in the lower part of the trams, mainly related to rolling noise, with a strong dependence on speed and track type. The tram type dependency, although globally of second importance, influences greatly the noise spectral distribution and behaviour. The HVAC was the only roof-mounted source which could be detected; its contribution towards building storeys becomes significant in configurations of low rolling noise. A tram noise emission model based on the various noise sources has been developed.

1. Introduction

After trams had almost disappeared from the French urban landscape in the 1950s, in those days where cars were considered as the way towards modernity, many large cities are now rediscovering this public transportation mode. For the last 20 years, new modern tram facilities have been helping cities to relieve congestion within centres, while improving their own image through clean-running public transport. Often seen as environmentally friendly, namely non-polluting and silent, trams introduce however a new component within the urban noise scene. Complaints from residents living along the lines prove that they may lead to annoyance and may be perceived as a nuisance. Within the framework of a French research programme in the area of land transportation (PREDIT), a project has been conducted to identify situations perceived as annoying, and to relate physical data concerning noise and vibration to resident perception. It included a psycho-sociological study, based on a survey of residents [1], as well as work packages dealing with vibration [2] and acoustical emission and propagation. This paper concerns the acoustical part of the project.

The tram is a complex large-sized vehicle. In standard models used for predicting noise, it is usually represented by a uniform line source. But the noise radiated by a tram actually results from the contribution of various noise sources (rolling noise, motors, auxiliary electrical equipment, HVAC[1]...) distributed along the vehicle, either spatially compact or widespread, with different physical origins (mechanical, electrical, aeroacoustical...). The development of low-floor vehicles, leading to relocated auxiliary equipment onto the roof, and simultaneously the expansion of HVAC for passenger comfort, define sources which could potentially affect residents living in the storeys of buildings. Whereas some noise sources depend only on the tram equipment, others may result from the track/vehicle interaction. The type of track, as such, is a determining factor for rail and trackbed vibration, and thus for the radiated noise. Besides, the intrinsic parameters of the track, the rail and wheel roughnesses – depending on wear and maintenance – influence rolling noise. The trackbed surface also, through its absorption properties, may influence the noise propagation. Several parameters, among which running conditions such as speed, have an effect on the level and the spectral characteristics of the emitted noise, and consequently the predominance (or the screening) of some sources against others.

Except for studies dealing with specific phenomena such as squeal noise, few scientific papers are available concerning noise emission and noise sources of trams, particularly on French networks. The tram has often been considered globally, without discriminating sources. Such a detailed study was achieved in the

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[1] Heating, ventilation and air-conditioning.

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1980s in the Netherlands, pointing out the respective effect of several parameters (speed, type of track, type of surface...) on the global noise levels of Dutch trams [3]. Other studies (for example [4,5]) report on mean noise level improvement related to track rebuilding, where generally several parameters are simultaneously modified : rail, fastening, surfacing, commercial running speed... More recently vertical directivity was measured on an Italian tram [6] and on the Strasbourg rolling stock in France [7]. Concerning individual sources, a first investigation on the horizontal noise source distribution of the tram of Nantes was carried out in 2000, showing differences between powered and unpowered bogies, as well as frequency variations with the type of track [8]. Lately the European project SILENCE achieved a description of the noise sources of several tram types – two French, one Belgian, and one Italian – specifying the source location and spectra, as well as source ranking [9]. In that project, investigations of tram noise emission involved track types specific to each rolling stock, as well as distinct measuring protocols. The French procedure was based on several array measurements at three speeds. French and Belgian studies concluded to prevalence of rolling noise and the secondary importance – if not insignificance – of roof mounted sources, whereas traction equipment noise was pointed out as predominant on the Italian tram.

The main objective of the present work is to specify tram noise emission, as well as the influence of several track, tram and running parameters, other parameters being equal. Noise linked to specific situations such as standstill, transient (switches, braking or moving off), or squeal in curves are outside the scope of this paper. Common conditions of running on straight track sections are considered. The first part of the work is developed in Section 2 and describes tram noise emission in free-field conditions, relying on a wide measurement campaign on the tram network of Nantes, France. Measurements include microphones in an arc for investigating noise power and vertical directivity of the whole tramset, as well as a two-dimensional microphone array for exploring the main noise sources (position, noise level, spectrum). Detailed tram noise emission is explored through several parameters – type of tram, type of track and surfacing, running speed – both for the overall tram and for the individual sources. In Section 3 of this paper an empirical model of free-field tram noise emission is developed, relying on the equivalent noise sources associated to actual source areas. Model outputs are acoustic descriptors such as time signature, frequency spectrum or standard acoustic indicators. Use is made of this model for investigating the contribution of the main noise components (rolling noise, traction noise, HVAC).

2. Description of tram noise emission

Tram noise emission is approached at two distinct levels: the vehicle is firstly considered as a whole emitting object, emission information being taken through total acoustic power and vertical directivity ; then the main noise source areas are investigated.

2.1. Tram and site configurations

The measurement campaign forms the foundation of the acoustical study, and intends to state the actual noise emission for various common configurations of French tram networks.

Two measurement sites were chosen as representative of usual closed track structures (Fig. 1): the first one is equipped with a classical track (sleepers, stiff rubber pads – stiffness 280 MN/m) and a grass surfacing, the other one has sleepers and soft pads (DPHI – stiffness 95 MN/m) and is covered by a paved surface. Thus the former offers an acoustically partly absorbent surface, whereas the latter is reflective. In each case, track structure and type of surface converge *a priori* to the same acoustical trend, either quieter or noisier. Both sites are fitted with grooved rails 35 GP (mass 55 kg/m). Insulation between rail and paving is made of polyurethane foam. For each site, the rail condition can be considered as satisfactory. The roughness could only be measured at large wavelengths (0.1–1.25 m), which fit the vibration frequency domain studied in parallel [2] but concern the sole lower part of acoustic frequencies: in this range, the roughness was lower than the limit curves of the reference rail of EN ISO 3095:2005 [10].

Two types of tram were measured on both measurement sites (Fig. 1). The first tram (TFS, Alstom), here named *tram A*, is representative of rolling stock from the beginning of tram renewal, that is 1985–1995. It is composed of three modules, the middle one with a low floor, and has two powered and two unpowered bogies. Its total length is 39.15 m. It is equipped with DC motors, and has no HVAC. The second tram (Incentro, Bombardier), named *tram B*, is representative of the more recent tram generation (after 1995). It has a full low floor and three bogies, among which two are powered with independent wheels (one motor for each wheel, asynchronous motors). Its length is 36.14 m. The HVAC, as well as much auxiliary equipment, is roof-mounted. One tramset was available for each tram type, the same for every measurement site. Except for a slight flat on one wheel of TFS, the wheels were in good maintenance state on both trams. Both tram types have resilient wheels of 0.66 m diameter, disc braking systems and shielded bogies.

During the measurement period, the trams were running in both directions on the same track line. Records concern pass-bys at constant speeds, from 20 to 50 km/h, on a straight track section. Complementary measurements were also made at standstill, for studying auxiliary equipment noise.

2.2. Overall tram noise emission

2.2.1. Principle

The assessment of the noise power emitted by a tramset is based on the measurement of the noise field radiated through a virtual half-cylinder, as represented in Fig. 2.

In this approach, the tram is considered as an acoustic uniform line source of length L, with a constant directivity around its axis, located on an horizontal plane. We call $W_{/m}$ the elementary power per unit length of the line source. In the case of an absorbent ground, the apparent acoustic power $W'_{/m}$ emitted by the tram is lower than the actual tram power $W_{/m}$, and depends directly on the type of track surface.

The noise pressure is measured on the lateral surface of a half-cylinder of radius r and length L, whose axis coincides with the line source. We consider first the pressure radiated by an elementary line source section of length dx at abscissa x, received at point M of abscissa x_M located on the cylinder:

$$p^2(x_M) = \frac{\rho c}{2\pi} \frac{W'_{/m}}{r^2 + (x - x_M)^2} \, dx \tag{1}$$

For the whole tramset of length L, considered as a line of incoherent elementary sources whose abscissa range from $x_0 - L/2$ to $x_0 + L/2$, the squared pressure measured at point M is:

$$\begin{aligned} p_L^2(x_M) &= \frac{\rho c}{2\pi} \int_{x_0-L/2}^{x_0+L/2} \frac{W'_{/m}}{r^2 + (x - x_M)^2} \, dx \\ &= \frac{\rho c W'_{/m}}{2\pi r} \left[\arctan\left(\frac{x_M - x_0 + \frac{L}{2}}{r}\right) - \arctan\left(\frac{x_M - x_0 - \frac{L}{2}}{r}\right) \right] \end{aligned} \tag{2}$$

When integrating the squared pressure over the whole outside area S_{ext} of the half-cylinder, whose abscissa coincides with the extent of the line source: