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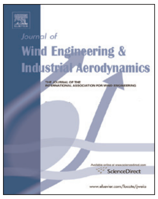

Perforated exit regions for the reduction of micro-pressure waves from tunnels

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ABSTRACT

The effectiveness of long, perforated exit regions in reducing pressure disturbances from railway tunnels is assessed. Such disturbances always occur, but their amplitudes are usually small. For the particular case of high speed trains, they can reach levels that would cause annoyance in the absence of suitable counter-measures. This risk is especially large in the case of long tunnels. The mechanisms causing the disturbances are described and the potential effectiveness of perforated exit regions as a counter-measure is demonstrated. It is shown that the effectiveness is sensitive to the number, size and distribution of pressure relief holes along the exit region, but that the most important parameter is the combined area of all of the holes. This parameter controls the balance between external disturbances alongside the perforated region and disturbances beyond the exit portal. It is also shown that the amplitudes of the external disturbances are strongly dependent upon the amplitude and duration of wavefronts arriving at the exit region as well as upon their steepness. This contrasts with the behaviour found for tunnels with simple exit portal regions.

1. Introduction

The radiation of micro-pressure waves (MPWs) from railway tunnels has received close attention since the first bullet trains in Japan (Ozawa et al., 1991; Ozawa, 1992). These pressure disturbances are much smaller than pressure waves inside tunnels, but they can annoy people who are not using the railway itself. The most likely sources of annoyance arise from low frequency components of MPWs. These can excite structural features that are sensitive to vibration, notably doors and windows of nearby buildings. In rare cases, higher frequency components in the audible range can occur and are loosely referred to as “sonic booms”. The disturbances were first detected during commissioning trials on the early Shinkansen network and some examples were quite strong (Ozawa and Maeda., 1988; Ozawa et al., 1993; Matsubayashi et al., 2000). However, remedial measures were soon implemented and it is unlikely that strong examples will occur anywhere in future – because designers are now aware of the phenomenon.

Understanding of the underlying physics of the phenomenon is good, but the ability to predict the likely amplitudes of MPWs accurately is less good. This is because there is a strong dependence on the amplitude–frequency characteristics of internal wavefronts that cause them when reflecting at a tunnel portal. In all tunnels, these depend strongly on the detailed shapes of train noses and tunnel entrances. In long tunnels, they also depend strongly on the nature of the tunnel lining and on fixtures and fittings along the tunnel. Another big complication is that, even if the predictive ability were excellent, an important hurdle would remain, namely identifying suitable acceptability criteria for MPWs. As with most noise-related phenomena, this is a subjective matter that cannot be addressed satisfactorily by technical analysis alone. Criteria that are appropriate for a tunnel in one location might not be suitable for a tunnel in another location. For generic design purposes, the most common approach is somewhat pragmatic, with comparisons between alternative designs being made on the basis of a single-valued criterion, namely the maximum amplitude of the MPW, regardless of its frequency distribution. In these cases, a standard reference location is usually chosen, typically 20 m or 25 m from the centroid of the plane of the relevant tunnel portal and, perhaps, at an angle of 45° to the plane (Ravn and Reinke, 2006; Degen et al., 2008; Gerbig and Degen, 2012; Hieke et al., 2011). More detailed, frequency-dependent, criteria are coming into use for the assessment of measured pressures and these can be chosen to suit the site-specific usage of the region

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List of symbols

c	speed of sound [m/s]
e	total energy per unit volume of air [J/m^3]
$\mathbf{F},\mathbf{G}$	matrices defined in Eq. (1)
H_{slot}	slot height (wall thickness) [m]
L_1	simulated length of tunnel upstream of perforated region [m]
L_{tun}	length of tunnel plus perforated extension [m]
MPW	micro-pressure wave
N_{slot}	number of slots
p	absolute pressure [Pa]
R_G	gas constant [J/kg.K]
R_{tun}	radial tunnel [m]
r	radial coordinate [m]
T	absolute temperature [K]
t	time coordinate [s]
u,v	velocity components in x,r directions [m/s]
$\mathbf{U},\mathbf{W}$	matrices defined in Eq. (1)
W_{slot}	width of roof slot [m]
X_{slot}	distance between slot centres [m]
x	axial coordinate [m]
Y_{ref}	distance between MPW reference line and nearest part of tunnel [m]

Greek characters

ρ	air density [kg/m^3]
γ	ratio of principal specific heat capacities [dimensionless]

close to the any particular tunnel (Degen et al., 2008; Gerbig and Degen, 2012; Hieke et al., 2011).

MPWs are created whenever a pressure wave reflects at an open end of a duct. In a dominant majority of cases, however, their amplitudes are far below levels likely to cause nuisance. Possible exceptions include, for example, guns and vehicle exhausts as well as railway tunnels, but only the latter are considered herein. In part, this is because of the special geometrical configurations of each possible application and, in part, it is because of the widely different frequency–amplitude characteristics in the different applications. This, together with practical constraints, has a major influence on the nature of potentially useful remedial measures. In the case of railway tunnels, by far the most common method of reducing MPWs radiating from tunnel *exit* portals is the construction of special extension regions at *entrance* portals. This highly effective counter-measure is logical because (i) the amplitudes of MPWs depend strongly on the steepness of pressure waves approaching the exit portal, (ii) the particular case that is most commonly troublesome is a wavefront generated during train-entry to a tunnel and (iii) it is relatively easy to design entrance regions that will ensure that nose-entry wavefronts do not exceed an acceptable steepness.

The use of special entrance regions to combat MPW development becomes questionable in the case of long tunnels – for two key reasons. First, the nose-entry wavefront is a compression wave and so, in slab-track tunnels that are popular in today's high-speed railways, it steepens as it propagates (Mashimo et al., 1997; Fukuda et al., 2006; Miyachi et al., 2008). The required entrance length to compensate for this effect can become excessive—over 200 m in some (unpublished) cases. Second, long tunnels often have shafts for ventilation, pressure relief or access and these are additional sources of wavefronts when trains cross them. Extended entrance regions have no influence whatsoever on these internally-generated waves and it would rarely be practicable to provide equivalent extended regions at such locations. Possible ways of countering wavefront steepening during propagation can be envisaged, but the most obvious response is to explore the possibility of providing remedial measures at the exit portal itself. Measures at this location have the potential to be effective for all incident wavefronts, irrespective of their origins.

The literature includes papers describing a range of exit alleviation possibilities. These range from passive devices involving large chambers that are loosely reminiscent of vehicle exhaust silencers/mufflers (Aoki et al., 1999; Sockel and Pesave, 2006; Kim et al., 2004; Raghunathan et al., 2002) to active devices that create a tailored response to the specific characteristics of each incident wavefront. Active devices utilise the concept of "anti-noise" in one form or another (Raghunathan et al., 2002; Vardy, 2008; Matsubayashi et al., 2004). They have the strong theoretical advantage of being potentially highly effective and yet compact, but also the disadvantages of being reliant on the reliable availability of power and potentially being capable of exacerbating the situation in the event of malfunction. Herein, attention focusses on a *passive* measure, namely the provision of long, perforated extensions at exit portals (Fig. 1). These have a special advantage over many other counter-measures, namely that they might also provide benefit as extended *entrance* regions when trains travel in the opposite direction. This is relevant even in single-track tunnels because railway operators commonly require the capability of operating at full design speed in either direction even if such capability is intended only for back-up purposes.

The remainder of this paper begins with a brief outline of the theoretical methodology and a summary of the physical behaviour expected in the absence of remedial measures. Then, the performance of a base-case perforated extension is considered, including an assessment of the dependence of such regions on the dominant characteristics of incident wavefronts (amplitude and steepness). Thereafter, the focus is on the effectiveness of alternative configurations of the perforated region – namely its size and the distribution of holes in its walls. Finally, conclusions of relevance to practical design are presented.

2. Theoretical approach

The detailed performance of any particular exit region will depend upon the geometrical configuration of the region and also

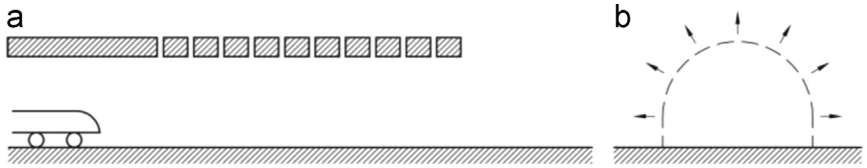

Fig. 1. Indicative geometries for perforated exit regions. (a) Longitudinal geometry. (b) Indicative cross-section.