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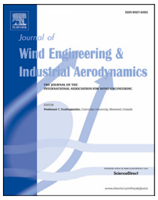

Experimental and theoretical study of the pressure wave generation in railway tunnels with vented tunnel portals

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ABSTRACT

The aim of this study is to enhance the knowledge of the generation of pressure waves in railway tunnels and to adopt a method of predicting the influence of vented tunnel portals.

Pressure waves in railway tunnels generated by the entry of a train into a tunnel entail many disadvantages and therefore have to be reduced.

The experimental study was performed at the Tunnel Simulation Facility Göttingen, a moving-model rig. The influence of the train velocity, size and the head length, as well as the influence of the geometry of the tunnel portal and the number and size of portal vents on the pressure waves were investigated regarding the minimisation of the pressure gradient inside the tunnel. The air outflow through the vents was studied using PIV, especially the amount of air leaving the portal through each vent and the geometry of the stream tube.

Furthermore, an acoustical analogy was used to predict the pressure-time history inside a model tunnel equipped with the different types of tunnel portals during the passage of the train. Empirical parameters, which are necessary for the estimation, were assessed both theoretically and experimentally. The given theory was adapted to a realistic train with underbody.

1. Introduction

During the tunnel passage of a train, a complex system of pressure waves is generated. These pressure changes lead to loads on the structures of the train and tunnel, decrease the comfort of the train's passengers and may even steepen resulting in the so-called tunnel boom, a phenomenon that might be disturbing for people outside the tunnel, close to the exit portal. Newly built tunnels are twin-bore single-track tunnels with a small-sized, narrow cross-section. Due to this fact and the fact, that the speed of trains is to be increased even more in the future, the number of pressure-wave dependent problems will increased within the next years. Therefore, countermeasures are needed to ensure operational reliability and to reduce maintenance expenses. The main parameter, which determines the negative impacts of the pressure waves, is not the pressure amplitude but the pressure gradient. As, depending on the initial pressure gradient, the pressure waves may steepen during their propagation along the tunnel, the initial slope of the pressure is crucial for the effect of the waves. An overview over several studies is also presented by Baker in (Baker, 2014).

In Japan the pressure-wave depending problems became evident in the 1960s. In 1961, Hara investigated the pressure amplitude using the basic equations of gas-dynamics (see (Hara, 1961), (Maeda et al., 1993) or (Ozawa, 1979)). This theory reproduces the amplitude of pressure waves in railway tunnels very well, even though it does not include several parameters like the effect of boundary layers at the train and tunnel wall. However, it does not give an idea of the pressure-time history and therefore of the pressure gradient, which is the crucial factor for the steepening of pressure waves and therefore the appearance of a tunnel boom.

The pressure-time history and the pressure gradient can be analysed using an approach developed by M.S. Howe (see e.g. (Howe, 1998a), (Howe et al., 2003), (Howe et al., 2006) or (Howe and Iida, 2003)). The approach is based on an acoustical analogy and provides information about the interaction between the train and the tunnel. Hence, the influence of the portal geometry on the pressure gradient can be assessed. Howe studied different kinds of tunnel portals with the intention to decrease the initial pressure gradient of the waves. The shape of the portal was adapted to ensure a slow rise of the pressure (see (Howe et al., 2000).). Additionally, Howe studied vented portals. Because of the vents, the pressure increase inside of the tunnel takes a longer time leading to a smaller pressure gradient. Howe's acoustical theory was confirmed by experiments with generic, axisymmetric train models.

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Investigations of the reflection of pressure waves at both tunnel portals (Vardy, 1978) or the scattering of waves at side branches (Fukuda et al., 2001) provide further essential information of the pressure-time history. In 2002, the TRANSAERO-Project took place, in which transient aerodynamics of trains like the train-tunnel passage were studied numerically and experimentally (see (Vardy and Brown, 2002) and (Réty and Grégoire, 2002)). Three years later, the tunnel boom was observed for the first time in Europe in the newly-built German Euerwangtunnel (presented in (Tielkes et al., 2008)) resulting in further studies of the pressure waves in railway tunnels. In Europe, several norms have to be fulfilled to operate a train or a tunnel (see (Directive 2008/232/EC, 2008) and (European Committee for Standardization, 2010)). These norms specify a maximum pressure amplitude inside railway tunnels during the passage of a high-speed train. Newly build tunnels in Germany are equipped with vented tunnel portals or other countermeasures against the high pressure gradient (like presented in (Deeg et al., 2013)).

However, most vented tunnel portal are equipped with a large quantity of vents, which are closed to optimize the portal efficiency. Test runs are performed to identify the best vent configuration.

In this paper, studies of the generation of the pressure waves in railway tunnels are presented. The three train models used are 3D-models with wheels and an underbody flow, whose effect on the pressure waves will be studied. A vented tunnel hood with rectangular windows, which is supposed to reduce the initial pressure gradient, is studied with the intention to detect the most efficient portal vent configuration. For that purpose, the pressure inside the tunnel was measured depending on the geometry of the tunnel portal. To investigate the effect of the number and position of the vents, the outflow was analysed quantitatively using an optical measurement technique. Furthermore, the pressure-time history was estimated theoretically using the acoustical approach, which was extended for a realistic train with underbody in order to verify the experimental results and to enhance the knowledge about several empirical parameters, which are essential for the estimation of the pressure-time history inside of the tunnel.

2. Methods

2.1. Theoretical description of the pressure changes

When a train enters a tunnel with a vented hood, several pressure waves are generated, which can be described and analysed separately. The different pressure changes are identified in Fig. 1. When the train enters the portal hood, the entry pressure wave P_E is generated. Each passage of a vent of the portal leads to a pressure contribution P_W due to the outflowing air. The passage of the junction between hood and tunnel is the reason for the pressure change P_J because of the change in cross-sectional area. Furthermore, growing boundary layers of train and tunnel go along with the pressure increase P_D. The pressure changes cannot be studied separately during the experimental tests. This is only possible for the influence of the vents and for the influence of the junction when comparing a tunnel with or without unvented hood.

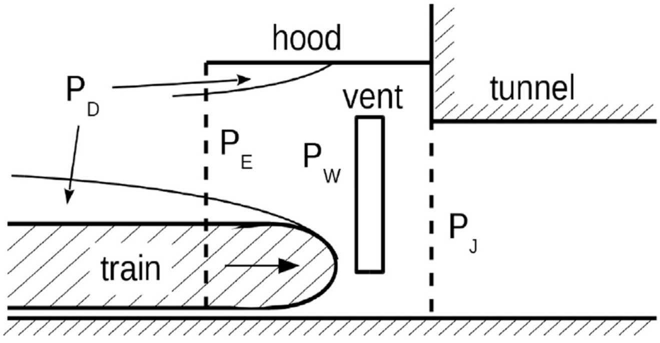

Fig. 1. Components of the pressure-time history.

All calculations are executed for an observation point inside of the tunnel several tunnel diameters away from the entrance.

A theoretical description of the pressure changes inside of a railway tunnel with vented portal was done according to M.S. Howe (for example see (Howe et al., 2006) and (Heine, 2015)).

The pressure rise P_E is generated as a result of the train entering the tunnel portal. This pressure change can be estimated using an acoustical analogy based on the theory of Ffowcs Willliams and Hawkings (see (Ffowcs Williams and Hawkings, 1969)), the derivation is explained in (Howe, 1975) and (Howe, 1998b)

$$P_E = \frac{\rho_0 U^2}{A_h(1-M^2)}\left(1+\frac{A_0}{A_h}\right)\cdot\int_{-\infty}^{\infty}\frac{dA_z(x+U\cdot[t])}{d\xi}\,\frac{\partial\varphi_h(x,0,z)}{\partial x}dx \tag{1}$$

with ρ_0: density of undisturbed air, U: train velocity, A_h: cross-sectional area of the tunnel hood (respectively A_t: cross-sectional area of the tunnel in the absence of a hood), M: Mach-Number regarding U, A_0: (maximum) cross-sectional area of the train, A_z: cross-sectional area of the train (variable with the distance from the train nose) ξ: distance of the train nose, $\partial\varphi/\partial x$: compact Green's function characterising the influence of the hood portal.

The information about the tunnel geometry and size is provided by the Greens function. This function can be obtained by estimating the potential φ_h of a hypothetical flow streaming out of the tunnel. The tunnel was mirrored to simulate the influence the ground. The geometry of the tunnel without hood used to estimate the flow potential is shown in Fig. 2 (upper part). The source was placed deep inside the tunnel right before the closed end to ensure an almost undisturbed flow over most of the tunnel length. Flow sources at all corner points of the grid (which is shown in the lowest image in Fig. 2) were numerically adjusted so that it can be assumed that there is no flow through any of the surfaces.

The flow potential was estimated by calculating the influence of each source point on the line where the center point of the train will move ($y = 8.3$ cm above the ground for a tunnel height of about 31 cm). The spatial derivative of the flow potential was scaled, so that inside of the tunnel it equaled 1. The result was the one-dimensional approximation of the influence of the three-dimensional tunnel on the train.

The train was described with the help of a line source and the train head was assumed to be elliptical to simplify the analysis of different train shapes and geometries.

The pressure-time histories were estimated using GNU octave V3.8, which is a free alternative to MATLAB. The tunnel was discretised, the length of each cell is 1 mm. The time step was adjusted to the train velocity, so that the train passed one grid cell per time step. The integral of (1) was discretised and summed up for a certain observation point, which was included in the retarded time [t] leading to the pressure-time history at the observation point.

The pressure amplitude for an infinitely long train and tunnel and a sufficiently long time difference between the train's entry into the tunnel and the measurement time, is calculated to be

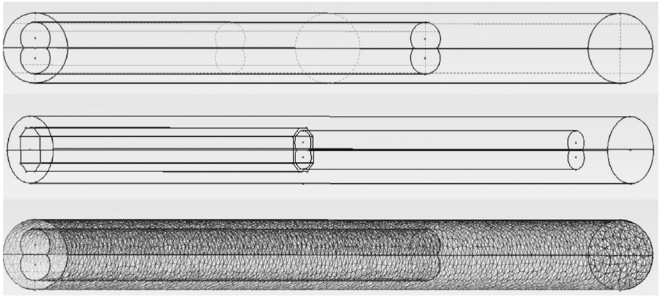

Fig. 2. Determination of the flow potential, upper image: geometry of the tunnel, middle image: geometry of the junction, lower part: grid of the tunnel.