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Development of an experimental facility for measuring pressure waves generated by high-speed trains

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ABSTRACT

An experimental facility was developed for investigating pressure waves generated by high-speed trains. The facility launches a 1/30 scale model conforming to the actual shape of the train and enables measurements to be carried out with the same geometric configurations at full scale. The train models are launched using compressed air. A mathematical model is developed to predict the performance of the experimental facility. This model allows the optimum values of the design parameters of the facility to be determined in order to achieve a given target velocity and to control the launching velocity by adjusting the pressure of the compressed air. Measurement of the flow in the experimental facility shows that the facility performs as designed by the mathematical model and is capable of launching a train model at velocities greater than 500 km/h. Pressure waves generated by a train moving into a tunnel are measured, and the experimental data agree well with field measurements. The effect of the train nose on the strength and form of the pressure waves is also discussed.

1. Introduction

High-speed trains were first developed in the 1960s, and operated at speeds of up to 210 km/h. Increased speeds are required to meet the growing demand for rapid mass transportation. The latest Shinkansen, a bullet train in Japan, runs at 360 km/h. Magnetically levitated (Maglev) trains have been experimentally operated at 500 km/h also in Japan. A train running at this speed can cause various aerodynamic problems, one of which is the generation of a low-frequency noise.

When a train runs near structures such as tunnels and buildings, subsonic flow around the train interacts with the structures. This interaction generates pressure waves, which then results in the propagation of low-frequency noise to the surrounding environment. The most notable problem is caused when a train moves into a tunnel. A train compresses the air in the tunnel generating pressure waves both inside and outside the tunnel. Inside the tunnel, a compression wave forms and travels towards the tunnel exit. It finally becomes a "tunnel sonic boom" leaving the tunnel exit. This problem emerged when Shinkansen began to be operated in the 1960s, and Ozawa et al. (1991) experimentally and theoretically studied this problem. Meanwhile, outside the tunnel, another pressure wave is directly emitted from the tunnel entrance when the train enters. This pressure wave, termed "entrance wave" in this study, will be noticeable with the increase in speed of high-speed trains (Tanaka et al., 2001). The frequency of these pressure waves is typically less than 10 Hz.

For experimental study of the pressure waves generated by a train, an apparatus is required that launches a train model along a track where fixed structures, such as a tunnel, may be placed. For dynamic similarity, the train model should run at the same Mach number as the full size train. Thus, developing a device to launch a train model at such high speed is one of technical issues, and various techniques have been developed in the past. Saito et al. (2006) used rotating disks to launch a projectile into a duct for measurement of the tunnel sonic boom. A 1/97 scale projectile was launched at 500 km/h in their experiment. Ricco et al. (2007) used a crossbow-like mechanism to launch 1/87 scale models with circular and squared cross-sections. Another possible method is to use compressed air, which is considered to be capable of launching a train model faster than the rotating disk. Takayama et al. (1995) used this method and achieved 360 km/h for a 1/200 scale model.

In past studies, train models or projectiles have been produced with a simplified shape, such as a cone and a paraboloid. This is for fundamental studies to obtain an understanding of the phenomena and, partially, because of the limitations of experimental facilities in accommodating realistic train geometries. The shape of trains and tunnels, however, affects the pressure waves. For example, Bellenoue et al. (2002) reported that the peak values of the pressure wave depend on train shape, even if trains have the

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Nomenclature

Symbol definition

C_D	drag coefficient of the train model
C_p	pressure coefficient
d	hydraulic diameter of the acceleration tube
g	gravitational acceleration
L_{nose}	length of the train nose
M	mass of the train model
p	pressure
p_0	atmospheric pressure
Q	flow volume
R	gas constant
s	cross-sectional area
t	time
T	temperature
U	speed of the train
u	velocity
V	volume
x_m	displacement of the train model
γ	heat capacity ratio
λ	coefficient of pipe friction
μ	friction factor between the train model and the track
ξ	pressure loss coefficient
ρ	density of the air
τ	non-dimensional time

same distribution of cross-sectional area. Thus, for accurate estimation of the strength of the pressure waves, it is important to use train models of actual shape. Pope (1991) and Da Costa et al. (1991) developed experimental facilities that can use precisely formed train models, but their launching speeds are 200–300 km/h and are not fast enough for the latest high-speed trains.

In this study, an experimental facility is developed that launches a scale model of actual train shape. Compressed air is used for launching a train model, and the performance of the experimental facility is modelled mathematically. This model permits the optimum design parameters of the experimental facility to be determined to obtain a given target velocity and to control the launching velocity by adjusting the pressure of the compressed air. The target velocity in this study is 500 km/h. The mathematical model is validated by measuring the flow and pressure in the experimental facility and comparing the performance of the experimental facility with that predicted by the mathematical model. Pressure waves generated by train models entering a tunnel model are measured and compared with field measurement data for validation of the experimental facility. The effect of train nose shape on the pressure waves is also discussed.

2. Experimental facility and its mathematical model

2.1. Experimental facility

Figs. 1 and 2 show the experimental facility. The scale is 1/30th. Past studies, for example, Ogawa and Fujii (1997), show that the effect of viscosity on pressure waves generated by a train is not significant, and scaling for the Reynolds number is not taken into account in this experimental model. The facility consists of mainly three parts: a launching system, a test section, and a brake tube, as shown in Fig. 1.

The launching system, consisting of an air tank and an acceleration tube, uses compressed air to accelerate a train model. Compressed air is stored in the air tank that is connected to the acceleration tube. A train model is placed inside the acceleration tube, where compressed air exhausting from the air tank propels the train model. After ejected from the acceleration tube, the train model moves through the test section on a track made of metal rails. It then enters into the brake tube, which gradually stops the train model with the air compressed by the train model itself. By placing models of fixed structures, such as a tunnel model, in the test section, the pressure waves generated by the train model passing through the structures can be measured.

Both the acceleration tube and the brake tube have a square cross-section. This requires that the body of train models also has a square cross-section to gain improved utilization of the thrust from the compressed air. If an experiment of a fully realistic train model is conducted, a square spacer is used to propel the train model from behind. After the train model is launched from the acceleration tube, the spacer is detached from the train model. Train models are made from polystyrene and precisely formed by a computer-aided modelling machine from CAD data of full size trains as shown in Fig. 3.

2.2. Mathematical model of the airflow in the launching system

The design parameters of the launching system determine the velocities achieved by the train model. These parameters are the pressure and the volume of the air in the air tank, the length of the acceleration tube, and the mass of the train model. Determining them without studying the airflow in the system could result in poor launching performance. The airflow behaviour in the launching system has been modelled mathematically to obtain the optimum values of the design parameters required for achieving the target velocity.

The flow from the air tank through the acceleration tube is modelled as shown in Fig. 4. The flow field is divided into four zones. Zone 1 is the stationary air inside the air tank. A valve is attached to the air tank, and zone 2 is the flow through this valve. Zone 3 is the flow in a chamber next to the valve. This chamber provides a space for opening the valve. Zone 4 is the flow in the acceleration tube. In the following, a sub-index of variables is applicable to each zone.

When the valve opens, the air exhausts from the tank through the valve. Initially, the pressure in the air tank is high, and the flow from the tank is choked at the valve. Thus, the mass flow rate from

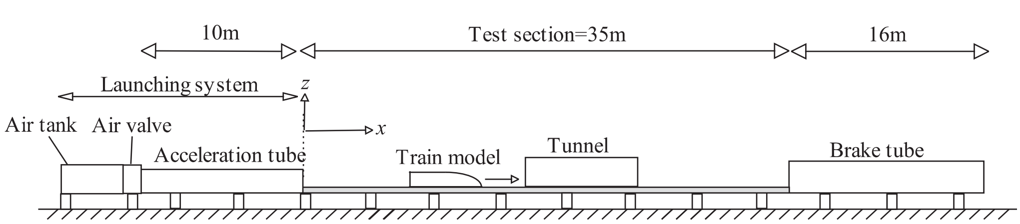

Fig. 1. Schematic figure of the experimental facility.