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Effect of boundary layer development on the dynamics of trains and train-like articulated systems travelling in confined fluid

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ABSTRACT

The effect of boundary layer development on the dynamics of trains of flexibly interconnected rigid cylinders subjected to fluid dynamic forces is investigated theoretically. Each cylinder in the model is flexibly coupled to the other cylinders and is supported by springs, such that it has both translational and rotational degrees of freedom. The kinetic, dissipation, and potential energies of the system and the generalized forces associated with the fluid dynamic forces acting on the system, such as inviscid fluid dynamic forces, viscous frictional forces, and form drag, are obtained first. Then the equations of motion are derived in a Lagrangian framework. The effect of the boundary layer development is taken into account by integrating variable viscous frictional coefficients into the equations of motion, instead of taking them to be constant. This is part of a broader study into the dynamics of high-speed trains running in a tunnel, or more generally of a train-like system travelling in a coaxial cylindrical tube and subjected to aerodynamic forces associated with lateral motions of the cylinders. The results of this study show that the system becomes less stable if the boundary layer is considered to be developing from the head toward the tail of the train. In addition, the average values of equivalent sand roughness k_S^* for high-speed Japanese trains are estimated from the previous data obtained from running experiments.

1. Introduction

Some work has recently been conducted for trains and train-like articulated systems travelling in confined fluid, especially its dynamics, wave propagation, flow-excited vibration and mode localization (Sakuma et al., 2008a,b, 2010a). It was found that the ratio between the viscous frictional drag coefficients in the longitudinal and normal directions, C_T and C_N, has a considerable effect on the stability of the train. In these studies, it was assumed that the values of the frictional drag coefficients C_T and C_N (defined in Section 2.4) were constants along the whole train. If the length of train is infinite, this assumption may be reasonable. However, for finite-length trains, the variation of the frictional coefficient along the train should be taken into account, because the boundary layer develops from the head toward the tail of the train. Since the length of actual trains is finite, in this paper the effect of the developing boundary layer will be taken into account; thus, the constant coefficients of frictional drag, especially $C_T =$ cst. in the longitudinal direction, will be replaced by one which is a function of the distance from the head of train, $C_T(x)$. The expression of $C_T(x)$ will be obtained by estimating average values of equivalent sand roughness k_S^* for high-speed Japanese trains. Then, we shall examine the effect of this refinement on the dynamical stability of the train. As shown previously (Sakuma et al., 2008a), since the dynamical behaviour of the train is sensitive to the ratio of viscous frictional coefficients, the revision of C_T (and C_N) from constant to a function of x, may affect the stability of the train.

Only a few papers exist for the dynamics of slender bodies including trains and train-like articulated systems in flow, in which the variation of the fluid forces due to boundary layer development along the body has been taken into account. For example, the dynamics of a continuous, not lumped parameter, beam subject to external axial flow with variation of the hydrodynamic forces due to axial boundary layer development along the beam has been studied by Hannoyer and Païdoussis (1978). In that study, the effect of the boundary layer was taken into account by utilizing a reduced velocity in the expression of the inviscid hydrodynamic force, but not by variable viscous frictional coefficients. In order to analyze the fluid–structure interactions on structures of finite length more precisely, variable frictional drag coefficients should be taken into account instead of constant ones. In this study, it is attempted to clarify the effect of axial boundary layer development on the dynamics of slender bodies, including trains and train-like articulated systems, by replacing the constant frictional drag coefficients by variable ones. Here, the local

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frictional drag coefficients along the train are estimated from the previous data obtained from running experiments (Hara et al., 1968) through the estimation of average values of equivalent sand roughness for high-speed Japanese trains, which are then integrated into the equations of motion; this constitutes another contribution of the present study.

Some work has been done on the measurement of the frictional drag of actual trains travelling in tunnels. A method of measuring the aerodynamic drag of trains was devised by Hara (1961, 1965). The aerodynamic drag obtained through this method is the force acting on the side surface of a train, including the forces acting on the components on the roof and under the floor of the train. Average frictional drag coefficients of high-speed and conventional trains running in tunnels were obtained by this method from running test data (Hara et al., 1968; Maeda et al., 1988). In these studies, values of equivalent sand roughness, k_S^*, were not discussed. The dependence of drag on the blockage ratio of cross-sectional area of the car to that of the tunnel was theoretically analyzed (Vardy, 1996). It was shown that the average frictional drag coefficients of trains in tunnels vary approximately linearly with the blockage ratio, and this dependence increases with increasing train roughness, i.e., equivalent sand roughness. In the analysis, three different values, $k_S^* = 1$, 5, and 20 mm, were employed. Later, the average frictional drag coefficients were estimated from measurements during routine operation (Vardy and Reinke , 1999). The effect of the developing boundary layer on the frictional drag coefficient of streamlined trains in tunnels was investigated by three-dimensional computations (Sima, 2006). In the computations, the values of $k_S^* = 0.5$, 1, and 5 mm were employed. It was shown that friction on the train is significantly higher on the forward part of the train, but it reduces to a fairly constant value in the distance taken for the growing boundary layer to accelerate the flow in the annulus between the train and the tunnel.

2. Theoretical model of the dynamics

The lumped-parameter Timoshenko-beam (LTB) model with constant frictional coefficients C_T(cst.) and C_N(cst.) has been developed by Sakuma et al. (2008a,b). In this section, instead of C_T(cst.) and C_N(cst.), variable frictional coefficients $C_T(x)$ and $C_N(x)$ will be obtained based on the estimation of average values of equivalent sand roughness for high-speed Japanese trains, and then integrated into the equations of motion of the LTB model.

2.1. Description of the system and assumptions

In order to achieve a description of the overall motion of a train passing through a tunnel, a large number of simplifying idealizations have to be introduced both in the mechanics and fluid mechanics of the system.

First, assumptions in mechanics are described. Simulation of translational and rotational motions of train dynamics commonly involves seventeen or more degrees of freedom for each car and interaction between wheels and rails (Miyamoto, 1994). Since the main concern of the present study is to examine the effect of the aerodynamic forces on trains and train-like articulated systems,

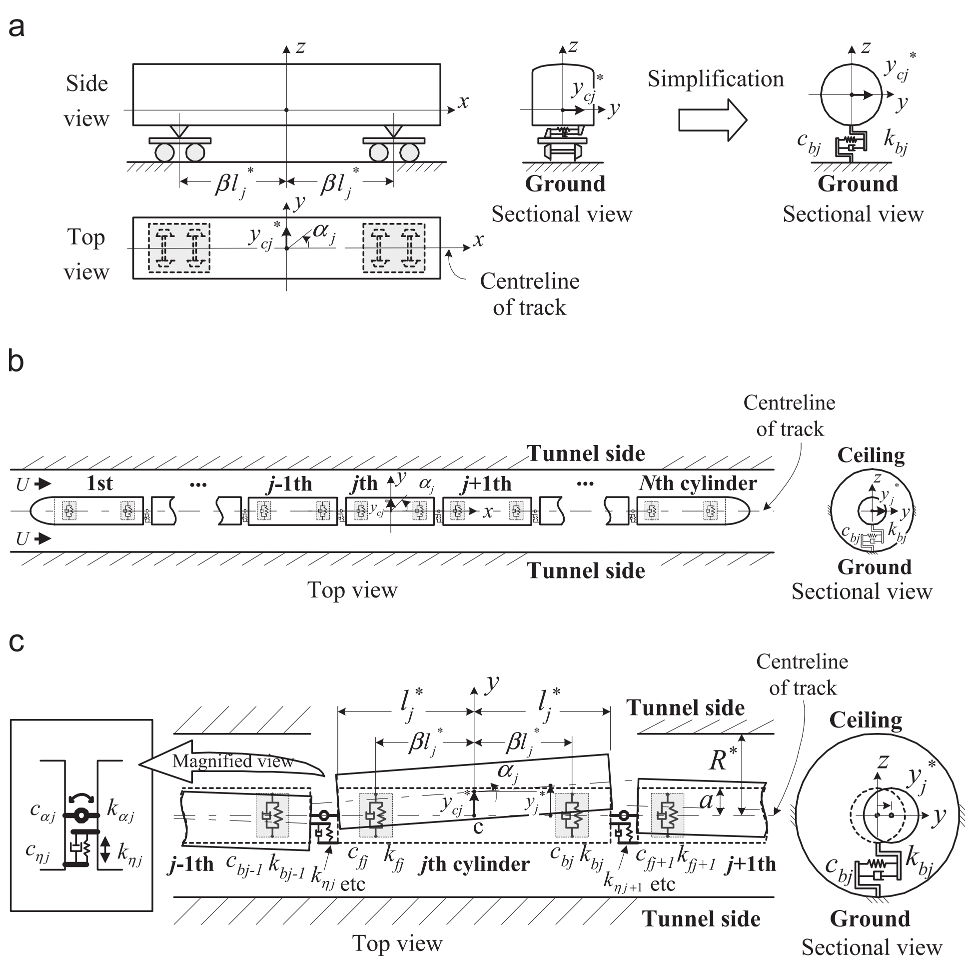

Fig. 1. Geometry of (a) a vehicle and a simplified cylindrical car, (b) N interconnected rigid cylindrical cars, and (c) the jth oscillating cylindrical car in the cylindrical duct. The variables with an asterisk are dimensional quantities.