Numerical Analysis on Pressure Characteristics of the Pipe system of Train

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ABSTRACT

With modern computational fluid dynamics method (CFD), air-charging models of the air brake pipe system and auxiliary reservoir are built. Compared with one-dimension model, no empirical formula is introduced to solve branch pipe fields for two-dimension model. A modified operator-splitting method is presented to solve the coupled equations of pressure and velocity, and numerical simulation shows that it is very stable. Compare the numerical results with empirical data of heavy haul trains in home and abroad so as to prove the correctness of the theory and algorithm presented. This paper gives theoretic reference to the experiments of braking effects of heavy haul trains, and forms a basis for development of complete freight train air brake system simulation.

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1. Introduction

Railway braking has become important because it directly relates to train's running safety. In a long time, the study on brake mainly adopts experimental method. However, the experimental method needs high cost and long cycle. Moreover, due to the limitation of impersonality conditions, the full system and a good many factors can't be considered entirely. Along with the development of computer technology, computational fluid dynamics (CFD) and computational mathematics, methods combining computer simulation technology with experiment have been widely used to do research on train air brake system in home and abroad [1][2][3][4][6][10].

In 2003, CARS and KRRI started the cooperation project of Numerical Simulations and Test Validations of Freight train air brake systems and began to study together. This paper introduces the research results we got so far and the recent development.

2. Freight train air brake system

A railway air brake system is basically comprised of two systems: a train system and a vehicle system. The train system includes a driver's brake valve in the locomotive and a train pipe running along the train length. The vehicle system comprises an distribution valve, brake cylinder, an auxiliary reservoir and relevant devices. Fig. 1 provides the schematic sketch of a pneumatic brake system for freight trains.

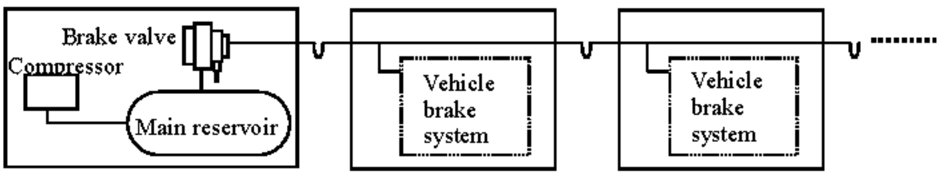

Fig. 1 schematic sketch of pneumatic brake system for freight trains

Train air brake system is so complicated that we have to divide it into several subsystems when conducting simulation study. CARS and KRRI agreed to divide it into train piping system and vehicle brake system. Numerical study on piping has been finished so far and based on which the simulation of auxiliary charging process is being done.

3. Numerical Model for piping

Charging process is the emphasis of study on piping model. To effectively simulate charging process, this paper simplify train pipe on every vehicle into one main pipe and one branch pipe. The --------------------------------------

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influence of bends, hoses and angle cock on the flow state inside train pipe can be simulated equivalently by adjusting the friction coefficient of inner pipe wall. The layout of train pipe model is shown in Fig.2. This model is equal to the case that vehicle brake has no adverse current toward main pipe.

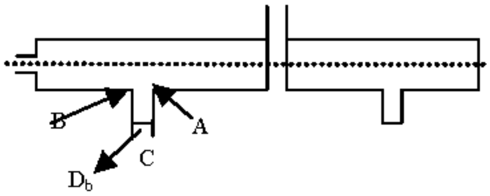

Fig.2 layout of train pipe model

3.1 One-dimension Mathematical Model

Since the axial size of brake pipe is much bigger than the radial size, and the axial flow influence is much bigger than the radial flow influence, the flow inside brake pipe is regarded as one dimension. The air inside the pipe changes violently as time goes on, so it's a typical non-stationary flow. Assuming that pipe wall is rigidity and no air gravity, governing equations comprise of the ideal gas equation, equations of continuity and momentum.

$$\rho = \mathrm{k} * p^{1/n}$$

(3.1)

$$\frac{\partial p}{\partial t} = -u\frac{\partial p}{\partial z} - np\frac{\partial u}{\partial z} - P_L$$

(3.2)

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{4f}{2D}|u|u$$

(3.3)

where ρ, p, u, t, z, D, n are density, pressure, velocity, time, space coordinate, pipe inner diameter and polytropic index respectively.

P_L in equation (3.2) is the leakage that can be measured

$$P_L = \frac{\partial(\delta p)}{\partial t}$$

(3.4)

In equation (3.3), $4f$ is the product of pipe wall friction coefficient and equivalent damping coefficient.

$$4f = \mu * c_f$$

(3.5)

where μ is pipe wall friction coefficient, c_f is the equivalent damping coefficient of bends.

For one-dimension model, solve the pressure and velocity of branch pipe by combining equal pressure model and governing equations (3.1)~(3.3). The velocity at joint of main pipe and branch pipe will be modified when computing the velocity of flow in branch pipe in this way. Solve the governing equations by explicit algorithm, so the integral influence of branch pipe on the main pipe embodies in the next step. The algorithm may not converge because local correction is too big. Considering the length of branch pipe is very small compared with the main pipe, we can decouple the solution of main pipe and branch pipe by combining numerical method with analytic method. The branch pipe's influence on main pipe is implemented by increasing the equivalent damp coefficient in momentum equation. Take the head loss into account. See Fig.2, we assume the pressure difference Δp between branch pipe entrance point B and corresponding main pipe center point A, the velocity u_1 at branch pipe entrance satisfy Darcy formula [11].

$$\Delta p / \rho = c * \frac{1}{2}(u_I)^2$$

(3.6)

where coefficient c can be obtained from empirical formula or utilizing the parameter inversion method. Supposing flow velocity at the branch entrance is u_{I}, we can get the pressure difference Δp by Darcy formula, with which and the pressure at main pipe center point A, the pressure at branch pipe entrance point B can be obtained immediately.

$$p_{\mathrm{B}} = p_{\mathrm{A}} + \Delta p$$

(3.7)

Solve with explicit algorithm. The flow velocity at branch pipe entrance is the value of previous step and the flow velocity at end point of branch pipe is zero. With governing equations (3.1)~(3.3), the pressure and air velocity of branch pipe can be obtained by the same method which is used for the main pipe processing.

As the governing equations are partial differential equations, it's very difficult to obtain the analytic solution. Numerical methods are used to solve them commonly. The numerical methods currently used are characteristic line method, finite difference method, finite volume method and finite element method. Compared with other methods, the explicit finite difference method in Literature [3] is the simplest method to program. We use modified explicit finite difference method to solve the above-mentioned problem, see reference [6] for detailed information.

3.2 Two-dimension Mathematical Model

The airflow in train pipe should be a 3-dimension model. Considering the axial size of the pipe is much bigger than the radial size, and the axial flow influence is much bigger than the radial flow influence inside the pipe, the flow inside the pipe is regarded as one dimension in references [1]~[6]. Just as expatiation in above literatures, simplifying the model in this way is reasonable and the computation is greatly simplified. The disadvantage is decoupling the branch pipe with main pipe factitiously and using some analytic formulas to compute the pressure and velocity of branch pipe. How to set the parameters in analytic formulas need further study. We construct two-dimension model by extending the one-dimension model mentioned above. In two-dimension model, the decoupling of branch pipe and main pipe ca be obtained naturally and it is not necessary to introduce into any analytic formula. Moreover the additional computation work is very small.

Assuming that pipe wall is rigidity and no air gravity, the 2-dimension governing equations consist of state equation, equations continuity and momentum.

State equation $\rho = \mathrm{k} * p^{1/n}$

(3.8)

Continuity equation considering leakage $\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \mathbf{U}) = -p_{\mathrm{L}}$

(3.9)

Momentum equation

$$\frac{\partial(\rho \mathbf{U})}{\partial t} + \nabla \bullet (\rho \mathbf{U}\mathbf{U}) = -\nabla p - \mathbf{F}_c$$

$$\mathbf{F}_c = \begin{pmatrix} \frac{f_4}{2} |u| u & 0 \end{pmatrix}^{\mathrm{T}}$$

(3.10)

where $\nabla, \nabla \bullet$ are gradient operator and divergence operator respectively and in two-dimension rectangular coordinates, they can be written as follows:

$$\nabla = \begin{pmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} \end{pmatrix}^{\mathrm{T}}, \qquad \nabla \bullet = \frac{\partial}{\partial x} + \frac{\partial}{\partial y}$$

(3.11)

For equations (3.9)~(3.11), $\rho, p, \mathbf{U}=(u\ \ v), t, p_L$ are density, pressure, velocity, time and leakage quantity respectively. n is polytropic index and f is the product of pipe wall friction coefficient and equivalent damping coefficient.

SIMPLE [5] algorithm is usually used to solve pressure-velocity coupling fluid dynamic equations (3.8)~(310), but the selection of some relaxation factor are very empirical. So we adopt operator-splitting method [7] to solve these equations. To assure the stability and toughness of the algorithm, the pressure-velocity coupling hyperbolic equation is replaced by parabola equation about pressure. Considering that compared with finite difference methods it is easier to be extended to arbitrary irregular region, finite volume method is applied to discretize in space. See reference [10] for detailed information.

4. Numerical Model for auxiliary reservoir charging

When release, the train pipe is connected to auxiliary reservoir. So it's necessary to construct numerical mode combing brake pipe and auxiliary reservoir so as to simulate the charging process of auxiliary reservoir. Under the precondition of precision, we simplify the air brake system reasonably. The brake system of the individual vehicle consists of one brake pipe, one branch pipe, two connection pipes between reservoirs, control valve, auxiliary reservoir and brake cylinder. The physical model is given in Fig. 3.

In this model, the locomotive brake is simulated by boundary function and the flow status in brake pipe is obtained by calculation based on above-mentioned two-dimension model. The status of control valve depends on the pressures of brake pipe, auxiliary reservoir and brake cylinder. During the charging process the brake cylinder doesn't act, so only the status of auxiliary and control valve is take into account.

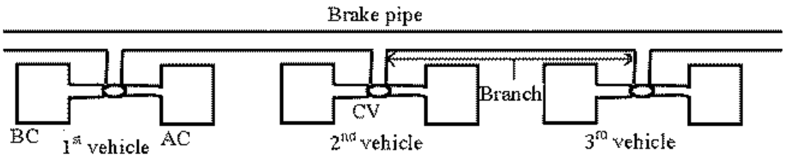

Fig. 3 simplified physical model of train air brake system

Assuming that the pressure is constant and no gravity, the governing equations of auxiliary reservoir consist of energy conversation equations and state equation.

Bernoulli's theorem $\Delta P = \frac{1}{2} c u^2$ (4.1)

State equation $\rho = \mathrm{k} * p^{1/n}$ (4.2)

therefore $dm = \frac{V_c}{RT} dp$ (4.3)

where ΔP, u, dm, V_c, dp are pressure difference between branch pipe end and auxiliary reservoir, air velocity flowing into auxiliary reservoir, increased air mass in auxiliary reservoir, auxiliary reservoir capacity and the pressure increase in auxiliary reservoir. The parameter c in Bernoulli's theorem relates to the size of inlet opened by the control valve. During the charging process, pressures at the branch pipe end and in auxiliary reservoir determine the size of inlet opened by the control valve.

For train pipe and branch pipe models, we use operator-splitting method to solve pressure-velocity coupling fluid dynamic equations (3.8)~(310). In every time step, there are two steps to solve pressure and velocity, but it doesn't need alternate iterative solvers.

In case of auxiliary reservoir model, when in time step n, the following equation is obtained

$$dP_{cb} = P_c^n - P_b^n \quad (4.4)$$

where P_c^n and P_b^n are auxiliary reservoir pressure and branch pipe end pressure respectively.

According to Bernoulli's theorem

$$dP_{cb} = \frac{1}{2} c u^2 \tag{4.5}$$

the velocity of flow u into auxiliary reservoir can be obtained.

Decouple the calculation concerning branch pipe and auxiliary reservoir. For branch pipe, we use operator-splitting method to solve fluid dynamic equations (3.8)~(310). When u is obtained, the pressure P_b^{n+1} at the end of branch pipe can be worked out. In case of auxiliary reservoir, dm, the mass of air flowing into auxiliary reservoir in one time step can be obtained with u. Then we can get P_c^{n+1} using start equation.

5. Numerical simulation on charging process

For pipe model simulation, computation conditions are consistent with that of [3] on the whole, so as to validate the model, algorithm and code by using test data in [3]. Locomotive is not considered in the model. The pressure in the first vehicle is used as input pressure, assuming it can be approximately represented by an exponential curve. Rationality of algorithm and reliability of the code are validated through making comparisons of the pressure-time curves of the last vehicle.

The model consists of 57 vehicles. The length of each vehicle is 10.6 m, the length of hose 0.75*2 m, the computational length of brake pipe 689.7m, the diameter of main pipe 31.75 mm, the friction coefficient of the internal wall of pipe 0.03, constant in state equation k=1.2887e-5, no leakage. The equivalent damp coefficient c_f of bend and cock is the same as [3].

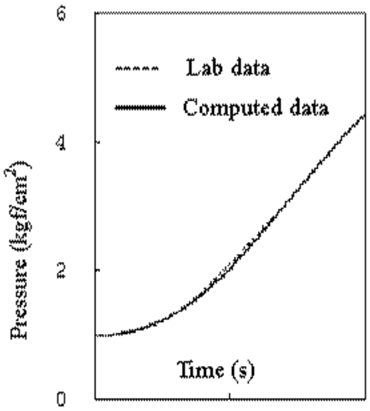

Fig. 4 Recharging after emergency brake (one-dimension)

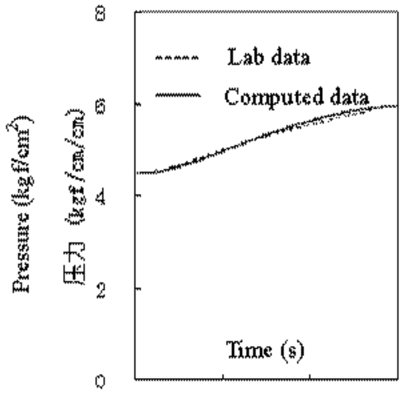

Fig. 5 Recharging after full service application (one-dimension)

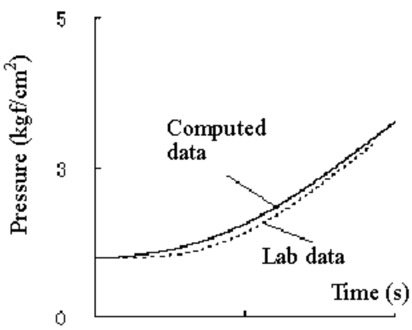

Fig. 6 Recharging after emergency brake (two-dimension)

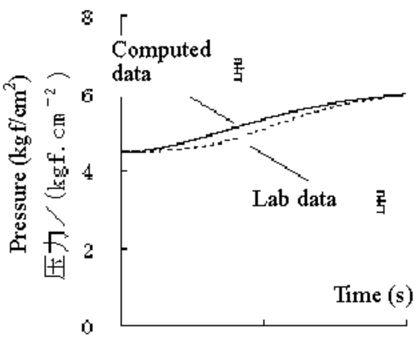

Fig. 7 Recharging after full service application (two-dimension)

Recharging performances after emergency brake application and full service application are shown in Fig.4 and 5 (for one-dimension model), 6 and 7 (for two-dimension model), respectively. The dashed line represents test data, which is obtained by processing the test data in [3] with cubic spline interpolation method. These figures show that numerical results of the pressure-time curve of the last car are consistent with test results. So we can say that simulation results are reasonable, and the code is reliable.

For auxiliary reservoir charging model, simulations are conducted with the dame parameters and conditions described in reference [12], that is the *Research report for test study on 4000-5000t heavy haul train brake technology* by CARS. Basic parameters are: length of brake pipe for each vehicle 13.35m, hose length 0.75*2m, diameter 1.25 inch; branch pipe length 1.5m, diameter 1 inch; the length of connection pipe between auxiliary reservoir and distribution valve 1.6m, diameter 1 inch.

Train with 21 vehicles, 103-type brake, auxiliary reservoir capacity 60L, quick release reservoir 11L, and regime pressure 5kgf/cm^2. The auxiliary reservoir charging process of first and last wagon is shown in fig. 8 and 9 respectively, in which the dashed lines are lab data from reference [12]. It is evident form these figures that in case of the initial charging curves of the first and last car for train with 21 wagons, the computer-predicted results are in good agreement with laboratory data during the first 150 seconds. At the last stage of charging, the computer-predicted pressure increases faster because the final pressure is assumed to be 5kgf/cm^2 for simulation.

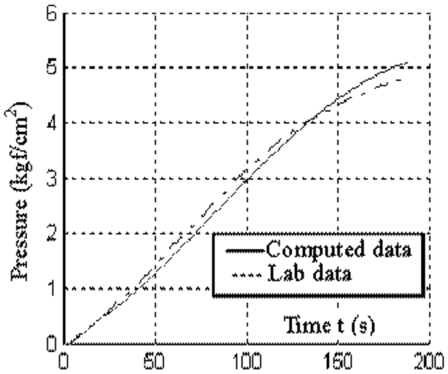

Fig. 8 auxiliary reservoir charging process for the fist vehicle

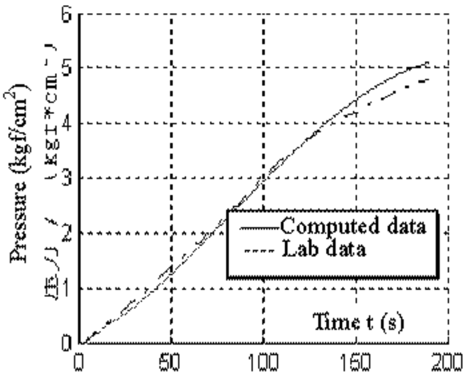

Fig. 9 auxiliary reservoir charging process for the 21st vehicle

6. Conclusion

Two air-charging characteristics models of the heavy haul train air brake pipe system, that is one-dimension model and two-dimension model, and auxiliary reservoir charging model are built. The solution methods are give. A modified operator-splitting method is presented and numerical test shows the algorithm is more stable than the classical simple algorithm. Moreover the time step may be very big, which greatly improves the practicability of theory and algorithm.

Train air brake system comprises train air pipe brake subsystems and vehicle brake valve subsystems. Only train air pipe brake subsystem and auxiliary reservoir is discussed in this paper. The model and brake performance of whole vehicle brake valve subsystems is our next study aim. The theory and program of this paper provide a very strong basis for future study.

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