Simulation of railway brake plants: an application to SAADKMS freight wagons

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Abstract: The UIC railway braking system is a complex pneumatic plant whose performance and reliability are safety relevant. The plant is controlled by the transmission of pneumatic signals; different train compositions involve large parametric variations of plant response. The problem is critical for long freight trains where the delayed plant response involves heavy longitudinal forces between vehicles. Even for simple compositions of 10–15 vehicles, the number of components involved in the plant response is quite high. The distributor valve, a complex pneumo-mechanic device, is devoted to control the brake response on every vehicle and it is perhaps the most difficult component to be simulated.

Authors have developed simulation models of the pneumatic plant of the UIC railway brake including libraries of pneumatic submodels that can be parametrically calibrated in order to reproduce different train compositions.

In this work, a case study concerning the simulation of a convoy composed by the SAADKMS freight wagon is presented. Simulation results are compared with experimental data kindly supplied by Trenitalia SPA. Model formulation and calibration procedures are shown in order to explain the followed workflow.

Keywords: pneumatic brake, simulation, freight wagons

1 INTRODUCTION

The aim of this work is the development of a model, which is able to simulate the response of a railway brake plant.

In particular, in this article, a case study concerning a train composed by several freight wagons is introduced.

In order to obtain good simulation results, many data concerning various components of the plant are required. Often this data are not available or there is not enough time or resources to find them.

Also in the presented case study, many data concerning the pneumatic plant were not completely known, so the authors have developed a procedure to identify the response of the plant from a reduced set of experimental results available from the Trenitalia SPA.

The proposed procedure may be interesting in order to produce a robust tuning of simulation models against errors due to the uncertainty of parameters.

1.1 The UIC braking plant

The specifications of railway brake plant are imposed by a wide number of international regulations of the Union International des Chemins de fer (UIC) [**1**, **2**]. It is not the aim of this paper to give a complete description of the various features of the plant.

However, a brief introduction is needed in order to understand its basic behaviour. In Fig. 1, a scheme of the typical plant used for freight wagons is shown.

All the vehicles of the train are connected by a pipe 'CG' filled at a pressure of ∼6 bar (absolute) by the pressurized air produced by the compressor group 'SP' on the train locomotive. Every vehicle is equipped with a distributor valve 'D'.

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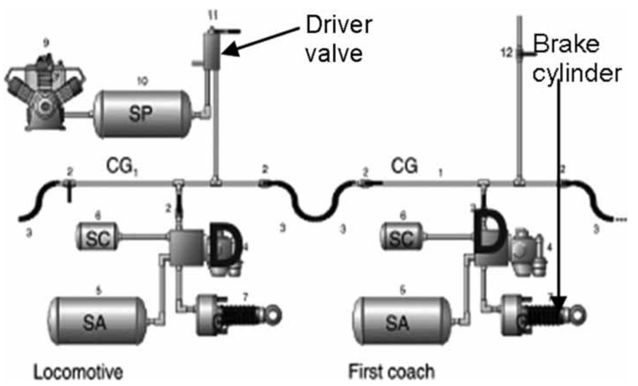

Fig. 1 Simplified scheme of the UIC pneumatic railway plant [**3**, **4**]

The distributor is able to compare the current pressure of the brake pipe with a reference pressure stored in a particular tank called 'command reservoir', 'SC'.

The braking command is generated on the first vehicle at the head of the train: 'driver valve' is used, in order to produce a controlled pressure fall along the brake pipe 'CG'.

The depression wave generated on the first vehicle propagates along the pipe that runs along the train.

On every vehicle, distributor 'D' is able to fill the brake cylinder with a pressure that is proportional to the depression in the brake pipe using the air stored in a special tank called 'auxiliary reservoir', 'SA'.

The 'SA' tank may be filled with a pressure regulator directly from the brake pipe 'CG' or from the additional pipe devoted to the fluid power distribution according to different plant configurations.

Brake is released only if the pressure inside the brake pipe is raised to its original value by the driver valve.

In order to improve the brake system reliability and performances, the brake distributor has been designed implementing many additional features.

In particular, the distributor response is sensitive only to an assigned pressure drop of about 150 m/bar with a minimum gradient of about 100–150 mbar/s.

This reduced sensitivity to the pressure gradients avoids undesired brake activation due to the physiological pressure oscillations of the plant. The maximum braking effort is applied to the cylinder with a pressure drop of about 1.5 bar in the brake pipe.

Also the dynamical response of the distributor is tuned in order to obtain an initial rapid filling of the cylinder followed by a second slow filling phase. This particular behaviour is usually obtained using two particular techniques.

1. *Variation of distributor equivalent pneumatic impedance*: air flows to the cylinder through orifices whose equivalent section is reduced as a cylinder pressure raise. As a consequence, the flow/filling rate of the distributor is regulated according internal brake cylinder pressure.

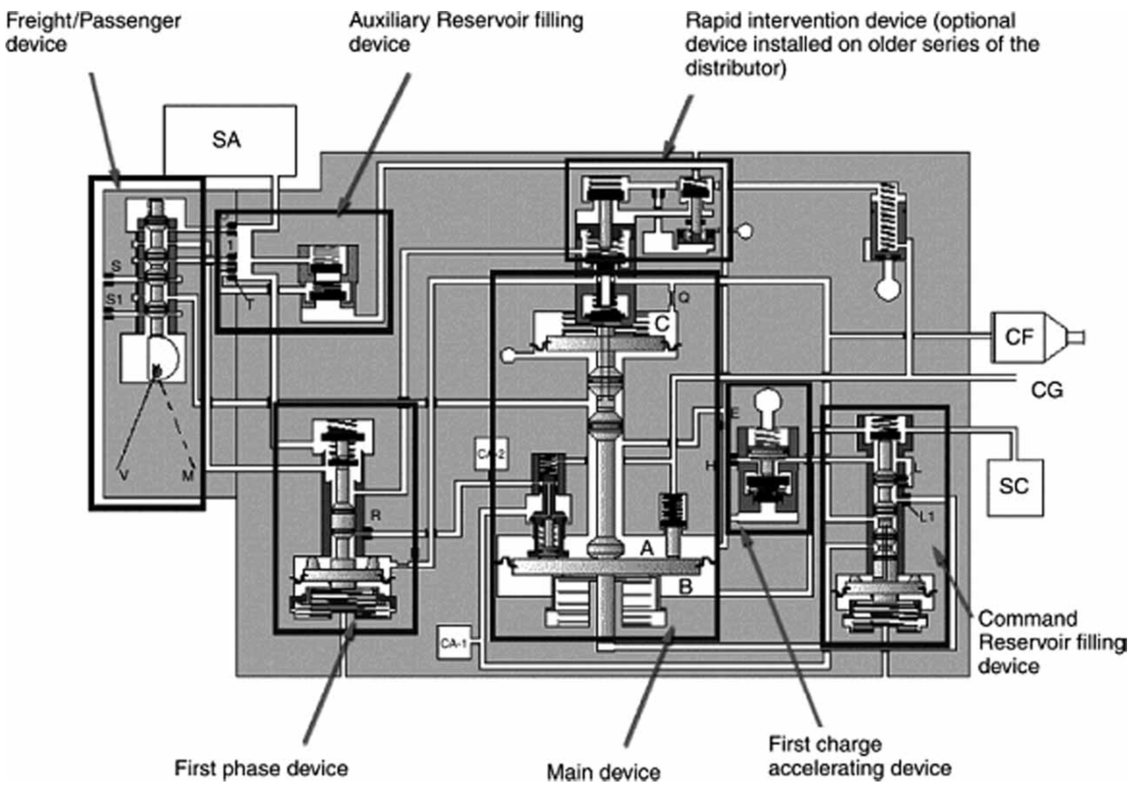

Fig. 2 Simplified scheme of the railway brake distributor [**3**, **4**]

2. *Accelerating capacities*: on long trains, propagation of the pressure drop along the pipe may be slow.

In order to accelerate the propagation of the brake signal, every distributor is equipped with special auxiliary capacities. When the distributor detects a pressure drop along the pipe, orifices between the brake pipe and these capacities are opened.

Capacities are filled with air coming from the brake pipe causing a local pressure drop.

Thus, the action of accelerating chambers produces a rapid pressure drop that accelerates the response of the distributor and the filling of cylinders.

Additional secondary features of the distributors ignored in this paper are also implemented.

As a consequence, the resulting structure of the device is a very complex system of chambers, springs, calibrated orifices as visible in Fig. 2.

2 DISTRIBUTOR MODEL: DESIGN AND CALIBRATION

Although the distributor is a quite complex pneumo-mechanic component, authors have tried to model it following different methodologies.

First, the authors have tried to physically reproduce any subcomponent of the distributor in order to completely catch the physical behaviour of the system [**3**].

This first 'pure physical approach' leads to very accurate models but also involves many disadvantages.

1. The resulting model is quite complex; as in a train, there is a distributor for every vehicle, the required computational resources may be high.
2. Many data concerning design and behaviour of the system are needed. All this records have to be taken from technical drawings, results of experimental tests, etc. Sometimes all this data are not completely available. Also in this test case, data concerning the installed distributor were only partially available.

Also the distributor can be modelled as a 'black box system' with a physical behaviour that follows a programmed logic. This second approach can be followed to build models that need very limited computational resources.

For this work, authors have preferred a third 'hybrid' approach: main subcomponents of the distributor are physically modelled as chambers, spring, and orifices. Thus, the physical behaviour is better reproduced. Also the secondary effects due to the mass–flow interaction of the distributor with the brake pipe can be better understood.

Additional logical features are modelled using simplified logical functions.

The resulting model is a compromise between the physical accuracy and the model performances.

Also the model can be easily customized to fit the behaviour of different kind of distributors.

This 'hybrid' approach was made easier by the use of a commercial simulation tool like Imagine Amesim™ that supports the creation of customizable subsystem from a wide library of validated pneumatic, mechanical, and logical submodels.

Extensive use of a wide diffused and validated commercial code was very useful to produce a library of parametric models, which are able to simulate the response of various components of the UIC pneumatic braking plant. This work is an ideal extension of the first Matlab Simulink™ models developed by Pugi *et al.* [**3**] inspired by some very interesting works in reference [**5**].

In particular, the authors have redesigned models in order to speed-up execution and have refined the tuning procedures on experimental data.

Further efforts have been done to optimize the number of parameters that have to be tuned to improve the reliability of simulation results.

In particular, the procedure used for the design and the tuning of brake distributors models is organized as follows.

1. '*Imposed pressure tests*': a pre-existing, validated model of distributor is tuned or modified in order fit experimental data in '*imposed pressure tests*' whose procedure will be explained in the following sections.
2. *UIC-like testing procedures*: response tests with imposed conditions are simulated in order to verify that the modified distributor is able to satisfy the specifications imposed by the UIC regulations in force (for example, UIC 541 and UIC 540).

   If these verifications are not satisfied, further modifications are applied to the model, and the calibration described in the previous point '*imposed pressure tests*' is repeated.
3. *Plant simulation*: finally, the distributor models are assembled with a lumped model of the brake pipe to simulate the plant of a train with known composition. Preliminary tuning of the brake-pipe model is mandatory for this activity.

If experimental data are available, additional validation tests are carried on.

2.1 Imposed pressure tests

To perform the imposed pressure tests, the user has to know the response of the tested distributor against a known imposed brake pipe pressure profile. Usually, the experimental data are available.

This calibration procedure is quite simple: brake pipe pressure profiles from the experimental data are imposed as input to the distributor model; then the simulated response of the distributor is compared with experimental one; finally the distributor model parameter are modified with an iterative procedure in order to obtain a good agreement between the experimental data and the simulation results.

Often this procedure is done using automatic optimization toolbox available in the Imagine [**6**] Amesim™ environment.

In this work, a case study concerning the SAADKMS freight wagon is described.

In particular, data are referred to some experimental test on a train composed by 30 SAADKMS freight wagons; data were kindly supplied by Trenitalia [**7**].

In Figs 3(a) and (b), some results are compared with corresponding experimental data: pressure profiles of the brake pipe are very different according the position of the corresponding vehicle along the train showing all the delays associated to the pressure wave propagation from the first wagon (Fig. 3(a)) to the last one (Fig. 3(b)).

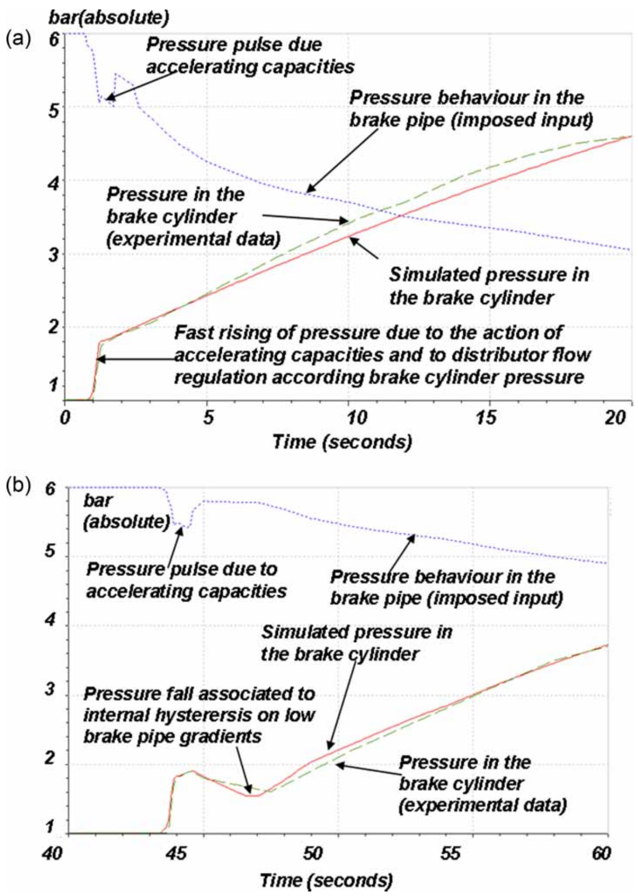

Fig. 3 (a) Comparison of real and simulated pressure response of the distributor with a fast brake pipe depression (first freight wagon near to the head of the train) and (b) comparison of real and simulated pressure response of the distributor with a smooth brake pipe depression (30th freight wagon very far from the head of the train)

As visible in figures, the model of the distributor shows a good agreement with the experimental data.

In particular, in order to reproduce a slow pressure drop visible in Fig. 3(b), the authors had to model internal friction effects of the device.

Behaviour of the last wagon is very sensitive to these non-linear phenomena since corresponding the brake pipe pressure gradient is smaller.

It is interesting to notice in Figs 3(a) and (b), the impulsive effect on the brake pipe pressure associated to the filling of accelerating chambers.

This effect cannot be modelled in this tuning procedure, as it depends on mass–flow interactions with the brake pipe that is modelled as a known imposed pressure profile. As a consequence, calibration of the mass flow pulse associated to accelerating capacities has to be performed after the tuning of the brake pipe model described in section 3. However, this procedure is very useful since it possible to calibrate most of the typical parameters of the distributor in a fast way.

2.2 UIC-like testing procedures

The UIC [**1**, **2**] regulations in force prescribe several tests that the distributor has to pass for homologation purposes.

These tests are performed after the tuning with imposed pressure profiles as a further model validation; the procedure is quite simple and can be automated. Also the corresponding models require reduced computational resources, so this test are a good tool to verify errors due to over-fitting of experimental data or to understand if there is something wrong in the population of tests used for the tuning of the distributor.

The UIC-like tests are organized in the following way:

1. *Sensitivity tests*: the sensitivity to impose brake pipe pressure profiles is verified. The distributor has to be insensitive to pressure gradients lower than 50 mbar/s, corresponding to a brake pipe pressure drop of 0.3 bar in 60 s. On the other hand, the distributor has to be sensitive to a pressure gradient of 100 mbar/s corresponding to a brake pipe pressure drop of ∼0.6 bar in 6 s. When the gradient is applied, the activation of the distributor has to start within 1.2 s.
2. *Step response tests*: the pressure input of the distributor is excited with rising/falling pressure step in order to verify the distributor response both in braking and release phases. The rising step is from an initial value lower than 4.5 bar (corresponding to full braking) to a final one of 6 bar; the falling

Table 1 UIC-like test results

Insensitivity test: verified	Sensitivity test: verified activation after 0.2 s (prescribed max 1.2 s)
Settling time for falling step = 18.5 (prescribed 18–30 s)	Settling time for rising step = 48 (prescribed 45–60 s)

one is a pressure drop >1.5 bar from an initial pressure of 6 bar.

Response is evaluated in terms of settling time that has to remain confined in assigned tolerances.

In Table 1, some results concerning the response of the distributor model used for the SAADKMS freight wagons are shown.

3 BRAKE PIPE MODEL CALIBRATION

3.1 Some preliminary considerations

As visible in Fig. 1, the brake pipe 'CG' runs along the train.

Brake pipe is responsible of the transmission of the pressure signal used by distributors as the reference command for the regulation of the clamping effort on brake cylinders. As a consequence, a good modelling of pipe response is very important to fit experimental data.

The pipe is modelled as a lumped system composed by a great number (from 30 to 150) of Imagine [**5**] Amesim™ C-RI elements in order to obtain a good simulation of the pipe model behaviour.

The C-RI is the acronimous of '*capacitive, resistive, inertial*' element.

These kinds of elements are preferable, as they can be used for the simulation of wave propagation effects along the pipe.

In the example of Fig. 4 is shown how the use of different number of lumped elements may affect the simulated response of the brake pipe.

The data used for the case study of Fig. 4 are as follows.

1. *Pipe geometry*: a length of the pipe 300 m, a diameter of 25 mm, and a relative roughness of 0.01 are simulated.
2. *Initial conditions* ($t = 0$): air in the pipe is initially quiet (no flow) with an homogeneous pressure of 6 bar.
3. *Description of the case study*: at simulation time '0' one end of the pipe is opened so the air inside of the pipe is free to flow to atmosphere; flow in the opposite end of the pipe starts only when the depression wave from the open extremity arrives.

As flow starts the pressure at the close end of the pipe begins to fall.

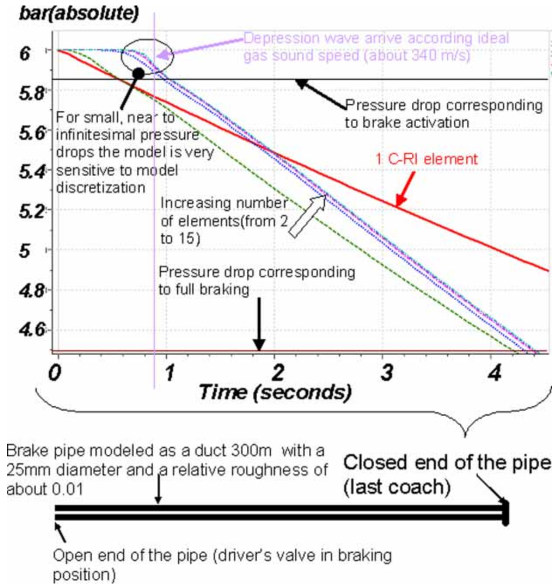

Fig. 4 Comparison of results obtained with models that have different number of elements to discretize the system

As visible in Fig. 4, the calculated pressure profile at the closed end of the pipe is very sensitive to the number of C-RI elements used to discretize the system.

In particular, different results are obtained according to the number of used lumped elements.

A minimum number of five sequences of C-IR elements have been used to simulate with acceptable tolerances the time at which the maximum service braking (corresponding to a depression of ∼1.5 bar) is applied to brake cylinders.

A good simulation of other events like brake activation requires a greater number of elements (10–15), since braking activation is associated to a small pipe pressure drop (∼0.15 bar) and to a precise gradient (>100 mbar/s).

As a general principle, simulation of phenomena that are associated to smaller time scales and higher gradients involves the use of a finer model; a finer model involves a higher ratio between the number of elements and the pipe length.

However, the distributor has a finite bandwidth and precision of response, so an excessive number of elements to discretize brake pipe may be useless.

As a consequence, a certain skill is required to optimize the number of elements used in order to obtain a good compromise between accuracy and execution times.

3.2 Model tuning on the SAADKMS case study

When this work has been written by the authors, approximate information concerning the piping layout of the train used for the experimental campaign were available. The equivalent length of the pipe was known only in an approximate way, also pressure losses introduced by bends, junctions, and other irregularities of the plant were roughly estimated.

Experimental data from Trenitalia [**7**] were referred to a particular train composition described in Fig. 5.

As clearly visible in Fig. 5, pressure measurements of the brake pipe were available only on the first and the last wagon.

The distributor of the intermediate coach (Mis2. in Fig. 5) was isolated during experimental test so the coach can be modelled as a longer pipe connection between the two adjacent wagons.

Also there are no information concerning the driver valve used to activate the brake on the head locomotive.

As a consequence, only the brake pipe between the two available pressure measurements is modelled (see Fig. 5 for more details); the pressure profile recorded on the first wagon during the experimental test is imposed on the calculus node corresponding to the first wagon, and then the calculated pressure profile calculated for the last wagon is compared with available records.

Simulations are repeated with an iterative procedure in order to tune some uncertain parameters like equivalent lengths of pipes and the relative roughness.

The procedure converges when a good agreement between the calculated brake pipe pressure of the last wagon shows a good agreement with the corresponding experimental data.

As the aim of this fast procedure was to roughly estimate these unknown parameters, mass–flow interactions with distributor are neglected.

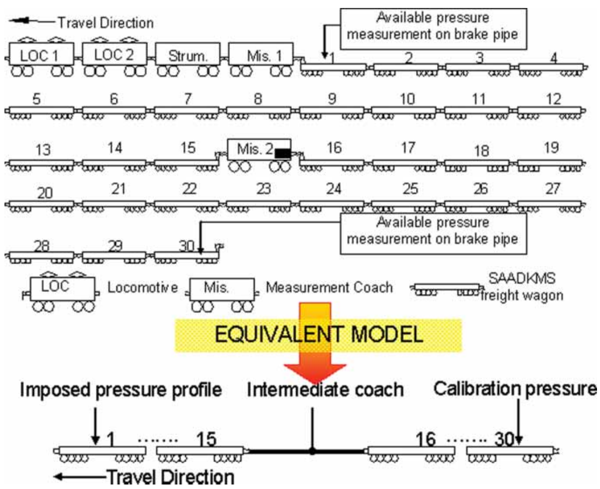

Fig. 5 Layout of the train used for experimental tests and corresponding equivalent model used for calibration–validation tests

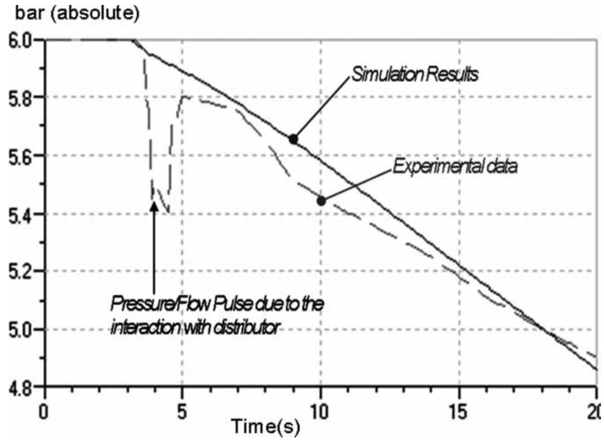

Fig. 6 Brake pipe calibration, comparison with experimental data, results referred to the last wagon

Thus, the pneumatic plant of wagons is reduced to the lumped model of the pipe.

In Fig. 6, results of this iterative procedure are shown.

Clearly, the pressure drop caused by the interaction between the distributor and the pipe cannot be reproduced.

4 BRAKE PLANT SIMULATION

4.1 Model layout

After both the pipe and the distributor model have been calibrated, a full plant is modelled, and the results are compared with available experimental test.

The plant reproduced is the same used for the brake pipe calibration procedure described in Fig. 5.

However, in this simulation, all the elements of the plant like brake pipe distributor and cylinders are modelled.

The mass interaction between the distributor and the brake pipe is simulated with an imposed flow pulse applied to the brake pipe when the distributor is activated.

To produce this pulse, an equivalent capacity-orifice system is used. When the distributor is activated, a calibrated orifice is opened between the pipe and a calibrated chamber. Air from the brake pipe suddenly fill the chamber causing a local, transient, pressure drop in the brake pipe, emulating the typical shape visible in Fig. 6.

The volume of the capacity and the diameter of the orifice are adjusted to obtain the desired effect.

Simulation of the interaction between the pipe and the distributors may be negatively influenced by the number of elements chose to discretize the system, as very fast transients are involved.

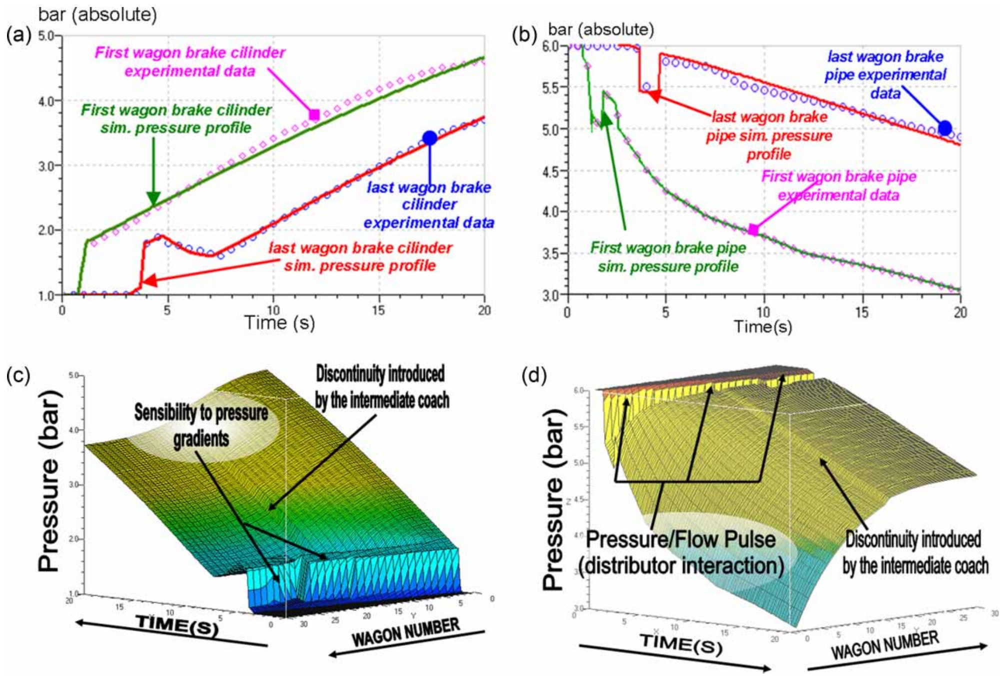

Fig. 7 (a) Comparison between simulated cylinders pressures and available experimental data, (b) comparison between calculated brake pipe pressure profiles and available experimental data, (c) pressure profiles of brake cylinders along the train, and (d) brake pipe pressure along the train

As a consequence, the pipe is discretized with a high number of C-RI elements, about 150.

4.2 Simulation results

The simulation model reproduces the following conditions: a pressure profile recorded from experimental data is imposed on the first wagon; pressure profile of the pipe and cylinders along the train and in particular on the last wagon are compared with the corresponding experimental data. In Figs 7(a) to (d), some results are shown. In particular, in Figs 7(a) and (b), the brake pipe and cylinder pressure profiles are compared showing a very good agreement between the simulation results and the experimental data. In fact, pressure profiles are well reproduced; also delay due to the transmission along the brake pipe are almost the same. In Figs 7(c) and (d), some additional results concerning pressure distribution along the train for both brake pipe and cylinder are shown. As clearly visible, results are quite realistic, since several typical phenomena of the real plant are clearly recognizable.

5 COMPARISON WITH RESULTS OF OTHER SIMULATIONS TOLLS

In past research activities, the authors have worked with a commercial software, I.V.E. [**8**] E-Train™ that has been specially designed for the simulation of the UIC railway brake and the calculation of longitudinal efforts.

Thus, as a natural extension of this work, authors have tried to compare the performances of the two tools.

Computational time and resources required by E-Train™ are smaller, since both the brake pipe and the distributor models are quite simplified.

However, even with a specialized tool like E-Train™, a long calibration phase is necessary to fit the experimental results.

E-Train™, in fact, is customized for a relative narrow application field.

For this reason, tools for automatic models tuning are not available.

Moreover, the E-Train™ is not an open code so special calibrations to fit particular pressure profiles are not easy.

As a consequence, the calibration phase is long and requires a certain user skill.

In Fig. 8, some results obtained with the E-Train™ software and with the Amesim models developed by the authors are compared.

Both the software are able to fit experimental data; however, the Amesim model, thanks to a wide number of configurable parameters and to the higher model complexity, gives more accurate results in the simulation of the brake cylinder pressure profile of the last freight wagon.

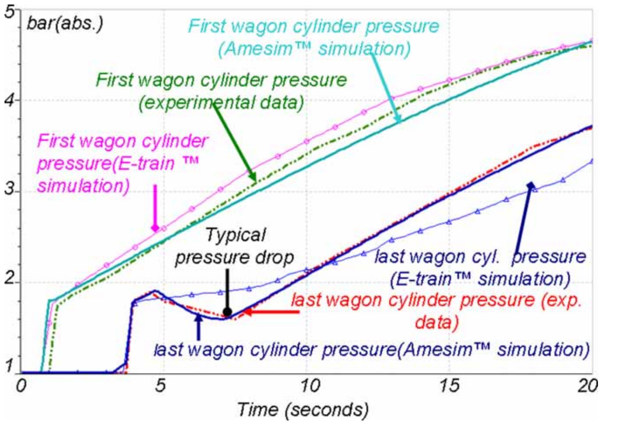

Fig. 8 Comparison of experimental data and simulation results with different simulation software

In particular, during the calibration phase of the E-train model, it has not been possible to fit the typical pressure drop clearly recognizable in experimental data.

In order to compensate this fitting trouble, the authors were forced to increase pressure drops on the brake pipe but the obtained results were not very satisfactory.

The Amesim™-based model has shown to be better suited to fit the experimental data because it allows to simulate the pressure–flow interactions between equivalent capacities of the brake pipe and the distributor.

Also internal friction/hysterersis phenomena have been introduced in distributor model in order to fit typical response delays clearly reported in the available experimental data.

6 FUTURE DEVELOPMENTS

The authors are working to improve reliability and performances of the tools developed for the simulation of the pneumatic railway brake.

Moreover, many improvements are possible in order to increase the number of potential application fields.

The first step will be the simulation of the interaction between the brake plant and the longitudinal train behaviour including its mechanical model.

For fast simulations, the mechanical model of the train has to be simplified using a lumped approach like E-train.

This simplified mono or bi-dimensional model can be developed using the Amesim™ or Matlab-Simulink™.

A more promising application, to which the authors are working, is the co-simulation with complete three-dimensional multi-body models generated with specific software like Msc Adams™ or Intec Simpack™ as discussed in the CIFI Congress of Pistoia [**9**, **10**].

In particular, full working models of the SAADKMS freight wagons have been developed and validated by some of the authors of this work in collaboration with Trenitalia SPA [**11**].

The three-dimensional multi-body models of the complete train composition may be very useful to understand how heavy longitudinal forces due to the application of the braking forces may influence safety and reliability under different operating conditions.

Since a large part of this work has been done this is a feasible subject for future publications.

Another interesting field of development will be the simulation of the interaction between mechatronic-pneumatic subsystems.

The Amesim™ supports both the simulation of mechatronics systems or the co-simulation with ‘state of the art tools’ like Matlab-Simulink™.

As a consequence, a feasible development is the simulation of electro-pneumatic braking systems and the prediction of interactions of the plant with additional mechatronic subsystems like WSP.

Some of the authors are still working in this field, developing models for the simulation of mechatronic device such as WSP [**12**], ATP-ATC on-board equipments [**13**], or SAFI/EBO subsystems [**14**] as a general subcomponent of modern electro-pneumatic braking system.

The development of open simulation tolls on the commercial software may be also interesting for real time applications for the virtual prototyping and testing.

Virtual prototyping and research activities concerning brake-related components often involve the development of virtual environments for the realization of ‘hardware/software in the loop’, testing devices [**12**].

Simulation libraries and models developed with commercial tools like Amesim™ are standard, fully accessible C-code programs that can be easily implemented for real time applications under some of the more diffused tools for HIL testing like dSPACE™, Mathworks xPC™, or Opal RT™.

Interest from final users, availability of data from experimental activities, further technology and research improvements, may decide what of these feasible future enhancements will be first reached.

7 CONCLUSIONS

Innovative methodologies and technologies can be applied to the simulation of railway brake equipment.

In this work, the authors show through a benchmark case study, how the use of numeric tools can lead to reliable simulations of the brake plant.

Robust tuning procedures, as the proposed one, can be used to reduce errors due to the uncertainties of parameters or to a partial lack of technical data.

However, it is important to understand that the development of a strategy for the application of simulation tools to the development of an industrial product involves the active cooperation between different subjects such as research institutions, developers, and final users.

Application of these concepts to the case of simulation of the railway braking plant needs a good management since costs of experimental, research, and development activities are quite high.

The development of open tools that can be modified and improved by a wide community of users may be a very interesting way to reduce costs and to accelerate technology and knowledge diffusion.

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