Surface pressure measurements on train for an on board cross-wind speed detection device

Cheli F., Mariano L., Rocchi D., Tomasini G.

Abstract

The paper presents the results of a research activity aimed to study the possibility to evaluate the cross wind velocity acting on a running train though surface pressure measurements. A complete design of the system is carried out using a neural network approach and wind tunnel test results. It will be demonstrated that the estimation of the magnitude and the direction of the wind speed can be solved by using only two suitably chosen pressure taps. Three train models, having different geometries and surface roughness, are tested in order to highlight some general features for the identification of the most suitable pressure taps for the considered application.

Keywords. Railway vehicle, Neural Network, surface pressure measurements, wind tunnel test, surface roughness, FADS.

1 Introduction

The aim of the research is to develop a measuring device to estimate the cross-wind direction and speed on an operating train using measurements performed by pressure taps located on the train surface.

Work’s field of interest concerns the methodologies to reduce the overturning risk of railway vehicles subjected to cross-wind. In fact, combined to Characteristic Wind Curves (CWCs, [1]) referred to the train in which the device is installed, the knowledge of wind data permits to establish in real-time the train speed limit that has to be observed to avoid overturning.

Currently, in some high-speed railway lines as the Rome-Naples in Italy ([1]) and the TGV Méditerranée in France ([2]), the wind direction and speed estimation is provided by using discrete measurements performed by anemometrical stations installed along the railway lines. These measurements are then transmitted to the line manager which, independently from the train types that will pass through the line, will impose the speed limits according to a wind forecast model that translates the single point wind data to what is expected on different positions along the line. The measuring device, studied in this work, could replace this modus operandi and allows a measurement of the wind acting on the train, directly in the point of interest, resulting in a more accurate and quick estimation of the wind variation on site. Furthermore, it will be possible to develop speed limits strategies according to the CWCs of the train in which the system is installed directly on board.

The system is based on the contemporary measurement of the pressure in different points on the train surface and on a combination of these signals to estimate the wind speed magnitude and direction. A similar technology is adopted in aerospace field and it is known as flush air data sensing system (FADSs, [3-7]). Its application to the train field is presented in detail in [8] and requires wind tunnel tests, to investigate the surface pressure distribution variation with angle of attack, and an algorithm to select the number and the position of pressure taps to correlate pressure data of selected taps to the magnitude and direction of cross wind.

In this paper, a FADS system will be developed for two railway vehicles, characterized by different surface geometries, in order to verify that the set up methodology is applicable and effectively independent from the geometrical characteristics of the train. Wind tunnel tests on a 1:15 train scaled models have been performed in different conditions to set-up and to calibrate the cross-wind detection device. The pressure distribution on the surface of the train leading cars close to the vehicle head has been measured for different incoming wind directions and Reynolds numbers. Moreover, different surface finishing have been analysed for one of the two train models in order to study the effect of surface roughness.
The obtained wind tunnel database has been used both to identify the more suitable pressure taps for the implemented algorithm and to calibrate the system for both the trains. From the comparison between the two solutions, some guidelines in the measuring system set up are proposed.

2 Analysis of the problem

A train that is moving with a speed $V$ in a cross wind condition when the air is blowing at a speed $U$ from the $\gamma_w$ direction, experiences a relative wind speed $V_{\text{rel}}$ with an angle of attack $\beta_w$ as reported in Figure 1.

![Figure 1. Triangle of velocity for a moving train under cross-wind conditions.](image)

The parameters that have to be estimated by the measuring system are the angle of attack $\beta_w$ and the relative velocity $V_{\text{rel}}$. These parameters are related to the surface pressure distribution through a vector of functions $f$, according to the following relation:

$$p = f(V_{\text{rel}}, \beta_w)$$  \hspace{1cm} (2.1)

where $p$ is the vector containing the pressure data measured by all the considered pressure taps. The function $f$ is known in discrete points; in fact, during each $i$-th wind tunnel test, for each simulated couple of values ($V_{\text{rel},i}$ and $\beta_{w,i}$), a pressure distribution $p_i$ is measured.

The analytical problem can be therefore expressed as in Eq. 2.2:

$$\begin{bmatrix} V_{\text{rel}} \\ \beta_w \end{bmatrix} = f^{-1}(p) = \begin{bmatrix} f_{\text{rel}}^{-1}(p) \\ f_{\beta}^{-1}(p) \end{bmatrix}$$  \hspace{1cm} (2.2)

The parameters $V_{\text{rel}}$ and $\beta_w$ are estimated by solving Eq. 2.2 using the available wind tunnel surface pressure measurements $p$ to extrapolate the continuous form of $f^{-1}$ with a Neural Network technique [3-8].

The multi-layer perceptron ([9]) has been adopted as neural network architecture for the algorithm set up. It is characterized by different transfer functions: hyperbolic tangents for the neurons of the hidden layer, whose non-linearity is useful to reproduce the non-linearity of $f^{-1}$; linear transfer function just for the single neuron of the output layer.

A supervised learning training has been adopted to re-build the continuous functions $f^{-1}$. The Bayesians regularization algorithm ([9]) has been used to train the neural network. This method has shown to be the most suitable for the present application, to avoid overfitting problem ([9], [8]). Moreover, if a set of just two pressure taps is considered, the two functions $f^{-1}$ of the vector are 2-variables functions and they can be easily plotted through surfaces, allowing a direct verification of the overfitting absence.

3 Experimental set-up

The experimental tests on two train models (ETR500 and CAF trains) have been performed in the wind tunnel of Politecnico di Milano using a 1:15 geometrical scale (Figure 2). All the tests were performed on still train models positioned on a Single Track Ballast and Rail scenario (STBR, [10]) embedded on a turning table allowing for changing the angle of attack.

Different incoming wind directions, as well as different Reynolds numbers have been simulated for both the considered trains in order to build the experimental database that will be used to train the neural network. Moreover, in order to verify the effect of a different surface roughness, two different surface finishing have been realized for the ETR500 train model: the first model nominally smooth, the
second with an increased surface roughness. The rough model has been obtained by a special painting and the level of surface roughness (sand grain) is equal to three tenths of mm. The models have been realized in carbon fiber and instrumented for the pressure measurement: 64 taps for the CAF train and 96 for the ETR500 train have been positioned on the model surface, especially on the head and on the connection surfaces between side and upper part of the carbody, where the higher pressure gradients are expected. The surface pressure measurements have been performed through high-resolution 2.5 PSI multi-channel pressure scanners (PSI Initium with ESP-DTC scanners), set directly inside the model. This type of scanners is thermally compensated and, consequently, no calibration procedure is needed before the acquisition. The sampling frequency was equal to 200 Hz and a low pass filter was implemented to compensate any noise corruption, with a cut-off frequency of 1.5 Hz for the average values estimation. As presented in Figure 2, for both the models, pressure taps are arranged in a symmetrical scheme, on different vertical sections: for the first three sections, the position of pressure taps is reported in the same figure.

![Vehicle scale models on Single Track Ballast & Rail scenario](image1)

*Figure 2. Vehicle scale models on Single Track Ballast & Rail scenario: CAF train (a) and ETR500 (b).*

![Leading car: position of the considered pressure taps](image2)

*Figure 3. Leading car: position of the considered pressure taps. CAF train (a) and ETR500 train (b).*

For the CAF train, the pressure taps adopted for FADS system set up belong to the sections A and D (Figure 3-a) while for the ETR500 train the chosen taps belong to sections 11 and 13 (Figure 3-b). Wind speed has been measured by a pitot tube, connected to low pressure micromanometers (Furness FC0510, range 200-2000Pa, accuracy 0.025% FSD). Tests have been performed for angles of attack ranging between $\pm 30^\circ$ and wind speed ranging between 10 and 50 m/s.
4 Calibration algorithm setting up

In order to set up the calibration algorithm two steps are needed:

- to chose the number and the position of the pressure taps to be adopted for the evaluation of the wind velocity vector;
- to define the most suitable neural networks for the considered applications.

The choice of the pressure taps is a crucial point in the design of FADSs. As a general rule the pressure taps, used by the algorithm, must have the following characteristics:

- high sensitivity to the variation of both the angle of attack $\beta_w$ and the relative wind speed $V_{rel}$;
- substantial independence of the pressure coefficient from Reynolds number in the range of interest;
- surjective relation between the pressure values measured $p_i$ and the estimated variables $V_{rel}$ and $\beta_w$.

While the sensitivity of pressure measurements to the variations $V_{rel}$ and $\beta_w$ is mandatory since it affects the accuracy of the estimations, the verification of the pressure coefficients independence from the Reynolds number is necessary to make predictions on the pressure data in full scale.

4.1 Selection of the pressure taps

From a preliminary analysis ([8]), it has been shown that a very good estimation of both the parameters, $V_{rel}$ and $\beta_w$, can be reached using only a couple of symmetric pressure taps. This leads to a calibration algorithm simple and fast, with the advantage that the graph showing the Pressure Variation Domain (PVD)\(^1\) can be easily plotted through a bi-dimensional representation. Moreover, to increase the robustness of the estimation, the final system could use more than one couple of pressure taps, to obtain redundant estimations of the measurements.

By the analysis of the PVD, it is possible to evaluate the sensitivity of the couple of pressure taps under consideration, both to $V_{rel}$ and $\beta_w$ variation. Furthermore, it is possible to verify that, a given vector of pressure values $p_i$ (bi-dimensional for a couple of taps) corresponds to just one couple of $V_{rel}$ and $\beta_w$ values. This means that functions $f_{rel}^{-1}$ and $f_{\beta_w}^{-1}$ are defined (surjective property).

To better investigate the dependence of these properties from the tap positions and from the train geometry, in the following, four couples of pressure taps, having similar positions on the two trains, will be analysed. Moreover, some of the taps chosen for the ETR500 smooth model will be analysed also for the ETR500 rough model in order to verify the effect of surface roughness on the pressure taps characteristics.

The four considered couples of pressure taps are one on the first section of the two trains (couple I, AA01-AA04 for the CAF train and 1111-1123 for the ETR500 train) while the other three are on an intermediate section of the nose, section DD for the CAF and 13 for the ETR500. In particular, on this section, it has been considered a couple on the upper part of the section (couple II, DD04-DD05 for the CAF and 1301-1329 for the ETR500), a couple on the section sides (couple III, DD02-DD07 for the CAF and 1311-1323 for the ETR500) and a couple on the upper corners (couple IV, DD03-DD06 for the CAF and 1303-1327 for the ETR500).

CAF model vs ETR500 smooth model

For a couple of symmetric taps with respect to the longitudinal plane, the corresponding PVD should be, in theory, symmetric with the same sensitiveness to the angles of attack with opposite sign. In Figure 4, Figure 5 and Figure 6 it is possible to observe the PVD for the couples I, II and III of the two considered trains. The pressure values measured during tests with the same angle $\beta_w$ are aligned on the same line while pressure values measured during tests with the same wind speed $V_{rel}$ have similar distance from the origin on which all the lines converge, corresponding to zero wind speed.

The sensitivity of the considered couple to variations of the angle of attack is a function of the angular distance among the different lines of the PVD while the sensitivity to the wind speed depends on the distance among the symbols belonging to the same line.

Figure 4 shows a comparison of the PVD for the couple I of the two trains: it possible to observe that in both cases the PVD is wide and both the couples show a good sensitivity to both angle of attack and speed. In particular, the couple AA01-AA04, positioned on the upper part of the section, has a wider PVD but it shows different sensitivity varying the angle of attack, lower at low angles ($0^\circ$-$10^\circ$) and better at higher angles ($10^\circ$-$30^\circ$). On the contrary, the couple 1111-1123, positioned on the side

\(^1\) The Pressure Variation Domain is a plot where the pressure values measured by the two pressure taps are reported on the axes.
of the first section, is characterized by a PVD less wide but more homogeneous (same sensitivity at all angles of attack). This is mainly due to the different position of the couples on the section: in the upper part, the couple of CAF train, and on the side, the couple of ETR500. Figure 5 and Figure 6 show the PVD of the two couples positioned on the intermediate section of the two trains. It is possible to observe that, for both the trains, the couple II, set in the upper part of the section, shows a wider PVD compared to the couple III, positioned on the side. Moreover, while for the CAF, the couple II (DD04-DD05) is characterised not only by a wide domain but also by a good sensitivity at low angles, for the ETR500 train, the corresponding couple II (1301-1329) shows a poor sensitivity to the variation of $\beta_w$ at low angles of attack. In fact, the functions $f^{\beta_w}_{I}$ and $f^{\beta_w}_{II}$ exist (because it is possible to distinguish among all the lines), but the lines referred to the tests with angles of attack smaller than 10° are very close one each another and small errors in the pressure measurements can lead to large errors in the estimation of the angle of attack. As a consequence, for the ETR500, the couple III, although characterized by a more narrow domain (Figure 6-b), is preferable with respect to the couple II, thanks to its more homogeneous distribution of the lines over all the PVD.

![Figure 4. Couple I, Pressure Variation Domain. Taps AA01 and AA04 (a) for the CAF train, Taps 1111 and 1123 (b) for the ETR500 train.](image)

![Figure 5. Couple II, Pressure Variation Domain. Taps DD04 and DD05 (a) for the CAF train, Taps 1301 and 1329 (b) for the ETR500 train.](image)

All the taps of the considered couples are characterised by PVD with separated lines; this means that the surjective relation between the pressure values and the variables $V_{rel}$ and $\beta_w$ is verified. For some couples, this property is not satisfied: Figure 7 shows a case where the functions $f^{\beta_w}_{I}$ and $f^{\beta_w}_{II}$ do not exist. In fact, it is possible to see that, at high angles of attack for the CAF train (Figure 7-a) and at all angles for the ETR500 train (Figure 7-b), for the same combination of pressures, measured by the two taps, there are different combinations of $V_{rel}$ and $\beta_w$. Also in this case this is due to the position of the taps that, for both the trains, are in correspondence of the corners (sharp changes of curvature). As it
will be shown in the following, in this zone, the pressure coefficients are significantly depending on the Re number.

Figure 6. Couple II, Pressure Variation Domain. Taps DD02 (a) and DD07 (b) for the CAF train, Taps 1423 (c) and 1411 (d) for the ETR500 train.

Figure 7. Couple II, Pressure Variation Domain. Taps DD03 and DD06 (a) for the CAF train, Taps 1303 and 1327 (b) for the ETR500 train.

For the same couples over analysed, Figure 8, Figure 9, Figure 10 and Figure 11 show the diagrams of the pressure coefficients variation with the angle of attack for different Reynolds numbers. It is possible to observe that the first three couples are not significantly sensitive to the Reynolds number and a light dependency is shown at high angles of attack, on the downwind taps. On the contrary, the couple IV, set in correspondence of the upper corners, shows an important Reynolds effect especially on the CAF train.

The first couple of both the trains (Figure 8) is characterized by parabolic trends that reach their maximum at different angles of attack: about 10°-15° for the windward tap (AA01 for the CAF train and 1111 for the ETR500 train) and -10° for the leeward tap (AA04 for the CAF train and 1123 for the ETR500 train).

The same parabolic trend is shown by the taps of couple II (Figure 9) but, while for the CAF train (Figure 9-a) the maximum values of the two taps are well separated as in the previous case, for the ETR500 (Figure 9-b), the two maximum values are both close to 0°. This different trend leads to different sensitivity of the couple to the angle of attack, especially at low angles, as already observed from the analysis of the PVD (Figure 5): therefore, it is possible to conclude that well separated maximum values of the parabolic polar diagram lead to an higher sensitivity of the couple to the angle of attack. On the contrary, when the maximum values are nearer, the sensitivity to the angle of attack is reduced.

The third couple examined of both the trains, with the taps set on the section side, is characterized by almost linear trends: the consequent PVD, as already seen in Figure 6, is characterized by an angular
amplitude lower than that described by the couples I and II having parabolic diagrams, which are therefore preferable.

(a)  Figure 8. Couple I: effect of Reynolds number. Taps AA01-AA04 (a) for the CAF train, Taps 1111-1123 (b) for the ETR500 train.

(b)  Figure 9. Couple II: effect of Reynolds number. Taps DD04-DD05 (a) for the CAF train, Taps 1301-1329 (b) for the ETR500 train.

(a)  Figure 10. Couple III: effect of Reynolds number. Taps DD02-DD07 (a) for the CAF train, Taps 1323-1311 (b) for the ETR500 train.
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Figure 11. Couple IV: effect of Reynolds number. Taps DD03-DD06 (a) for the CAF train, Taps 1303-1327 (b) for the ETR500 train.

Smooth model vs rough model

Figure 12 shows, for the couples II and III, the PVD obtained for positive angles of attack with the rough model of the ETR500 train while Figure 13 presents, for the same couples, the corresponding trends with the angle of attack, for different Reynolds numbers.

From the pressure variation domains (Figure 13), it is possible to note that both the graphs are very similar to what was found with the smooth model (Figure 5-b, Figure 6-b).

Figure 12. ETR500 train, rough model, PVD. Couple II (a) (taps 1301-1329) and couple III (b) (1311-1323).

Figure 13. ETR500 train, rough model, pressure coefficients for different Re numbers. Couple II (a) (taps 1301-1329) and
couples III (b) (1311-1323).
About the pressure coefficients diagrams, it is clear that the general observations related to the couple position, reported in the previous section for the smooth model, are valid also for the rough model: moving from couple 1301-1329 (on the top of the section, Figure 13-a) to couple 1311-1323 (on the section sides, Figure 13-b), the corresponding dependency on the angle of attack changes from parabolic to linear trend. Also the sensitivity to the Re number is very similar: the pressure coefficients of the windward taps (1301 and 1311) show to be insensitive to Re effects while the corresponding coefficients of the leeward taps (1329 and 1323) present a little dependency. However, differences arise between smooth and rough model, at high angles of attack (higher than 20°), for the couple III, set on the section side. The nose of the vehicle has therefore the advantage to be very sensitive to angles of attack variations (and, as a consequence, suitable for the considered application) thanks to the high pressure gradients but it is also the zone where the large train geometrical curvature produces the largest flow deflections, resulting to be very sensitive to the surface finishing of the model. A different slope or a different trend of the pressure values vs the angle of attack would require a different calibration of the measuring system. Therefore, a calibration performed relying on wind tunnel database should not be suitable for full scale data. It is worth, considering that the roughness of the rough model is intentionally much larger than that is actually present in full scale, in order to better highlight the sensitivity of the procedure to this effect. In conclusion, it is possible to assert that the couples of pressure taps selected from the tests carried out on the smooth model are suitable also for the real train but a validation with field tests data is needed for the setting up of the algorithm.

Results
The available data from wind tunnel tests have been divided into two sets: 70% of data is used for neural network training (“training set”) while the remaining 30% is used for validation (“test set”). The training is considered to have good generalization properties when the errors made on the “training set” have the same order of magnitude of what is obtained with the “test set”. In order to cover the whole domain of interest, tests for the “training set” have been selected uniformly for the first 50% and randomly for the remaining 20%.
As an example, Figure 14 and Figure 15 show respectively, for the couple II of the CAF train (taps DD04-DD05) and for the couple III of the ETR500 train (taps 1311-1323), the functions $f_{\beta}^{-1}$ and $f_{\beta}^{-1}$ obtained from the trained neural networks. The optimal number of layers and neurons, giving both good response accuracy and no overfitting phenomena, have been found for both the functions. The absence of overfitting phenomena can be verified directly by observing $f_{\beta}^{-1}$ and $f_{\beta}^{-1}$ trends. Outside the training range, the pvd functions have been forced to a constant value to make easier the representation. In particular, neural network for $f_{\beta}^{-1}$ function uses 3 hidden layers with 3 neurons each for couple DD04-DD05 (CAF train) and 2 hidden layers with 5 neurons each for the couple 1311-1323 (ETR500 train). Neural networks for $f_{\beta}^{-1}$ uses 3 hidden layers with 4 neurons each for couple DD04-DD05 and 3 hidden layers, the first with 5 neurons, the others with 3 neurons each, for the couple 1311-1323.

Figure 14. Couple II of the CAF train smooth model (taps DD04-DD05): estimation surface $f_{\beta}^{-1}$ for $\beta_w$ (a) and $f_{\beta}^{-1}$ for $\beta_w$ (b).
In Figure 16 and Figure 17 $V_{rel}$ and $\beta_w$ estimation errors are reported respectively for the couple II of CAF train and for the couple III of the ETR500 train. It is possible to observe that in each case, the training errors have the same order of magnitude than the test errors: this means that the trained neural networks have good generalization capability. For both the considered couples, the absolute value of the maximum estimation error an is lower than 1 m/s for $V_{rel}$ and lower than 0.8 deg for $\beta_w$.

5 Conclusions and future work

Experimental data have been used to train multilayer perceptron neural networks with good generalization capabilities and no overfitting problems. The properties of several couples of taps on both the trains have been studied in terms of sensitivity to wind speed and angle, verification of surjective property and dependency on Reynolds number in order to highlight some general trends useful for the identification of the couples most suitable for the considered application, also taking into account the effects of the surface roughness. From the comparison between the experience gained in the design of a FADS system for the evaluation of the cross wind velocity from surface pressure measurements on two trains some common features may be observed as useful guidelines for future applications:

- a) It is preferable to measure the surface pressure on points close to the vehicle head that lead to a larger sensitivity to the angle of attack changes.
- b) The trend of the pressure values measured on the vehicle head surface with the wind angle of attack has peculiar features depending on the position on the vehicle, in particular points on the lateral surface show almost linear trends while points close to the vehicle roof show a parabolic trend.
- c) Combinations of pressure taps with parabolic trends gives a more wide sensitivity to angle of attack. Surjective property may be not satisfied if the vertexes of the two parabolic trends are coincident.
- d) The high sensitivity of the head pressure distribution to the angle of attack is related to strong flow deflection driven by the large geometrical curvature of that part of the train. Therefore the surface finishing may play a rule in the measuring system calibration. The error in the estimation of the magnitude and angle of the cross wind velocity using the algorithm trained with smooth model data with the input pressure distribution measured on an extremely rougher model remains in a acceptable range.
- e) The estimation errors obtained with the set up neural networks were of the same order of magnitude for both the trains, lower than 1 m/s in absolute value for $V_{rel}$ and lower than 1° for $\beta_w$.

A validation using full scale pressure data is under studying. The geometric simplicity of the identified functions should allow reaching accurate results, using neural networks with few layers and neurons, resulting in a fast real time application on board.
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Figure 16. Couple II of CAF train (taps DD04-DD05): $V_{rel}$ (a) and $\beta_w$ (b) estimation error.

Figure 17. Couple III of ETR500 train, smooth model (taps 1311-1323): $V_{rel}$ (a) and $\beta_w$ (b) estimation error.

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