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Aerodynamic coefficients of railway vehicles in cross-wind – introduction and preliminary research

Abstract: In recent years, dynamic development of high-speed railways is observed in Europe and in the world. Due to the train speeds increase, aerodynamics of railway vehicles becomes more and more important issue. In the paper, the cross-wind stability problem of a railway vehicle and the influence of the train speed on this phenomenon is discussed. As a derailment risk analysis requires to determine in total six cross-wind aerodynamic forces and moments acting on a given vehicle, a knowledge of six associated with them aerodynamic coefficients is a groundwork for train stability analysis. Two most common methods of analysis of air flow around trains are pointed out – wind tunnel testing and CFD method (Computational Fluid Dynamics method). Both methods are described in the paper, in reference to PN-EN 14067-6:2018-10 and TSI requirements, and later a CFD method is applied to examine a basic train model. The main aim of this preliminary research was to recognize CFD method as a tool for a further research on cross-wind-induced vibrations of a train - bridge system.

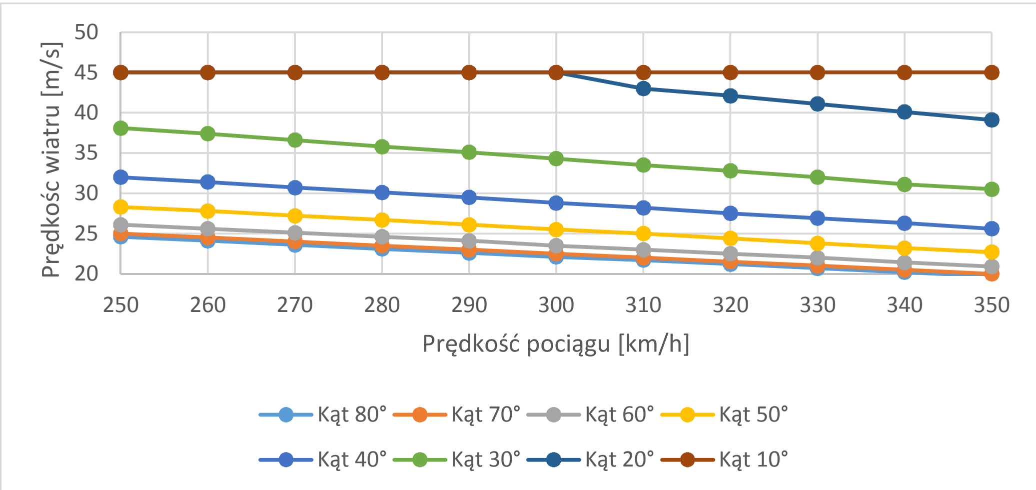
Keywords: Railway vehicles; Cross-wind stability; Aerodynamic coefficients; CFD analyses

Introduction

The dynamic development of high-speed rail has been observed in recent years in Europe and in the world. With increasing travel speeds, the aerodynamics of rail vehicles is becoming an increasingly important issue because the phenomena caused by airflow around a moving train have a dominant effect on its traction properties. The main problem considered widely in the literature for over 80 years are aerodynamic drag [2] - to achieve higher speeds, streamlined bow shapes are used and the weight of trains is reduced. The significant increase in speed of rail vehicles and the associated aerodynamic effects also have an impact on the surroundings. A train traveling at high speed causes large changes in air pressure on the side of the track, which threaten people on the platform and track workers [13]. In addition, high instantaneous pressures may cause fatigue failure of trackside infrastructure [2]. High shock pressure waves also arise when two trains pass by, posing a threat to their safety due to the high dynamic forces acting on the front of both trains. A similar phenomenon occurs when a train passes through a tunnel - especially when entering or leaving a tunnel. In many countries speed limits have been introduced in narrow tunnels [2] due to the high pressures at high train speeds. Another unfavorable phenomenon associated with aerodynamic influences is ballast tearing, which leads to damage to the rolling stock and track [13].

In the aspect of driving safety, however, it is essential to ensure the lateral stability of each vehicle in the train under cross-wind load (e.g. [5], [3]). In the history of today too, more than one rail disaster caused by transverse wind can be noted. An example is the derailment of the Inaho passenger express train in December 2005 in Japan [18] or a strong collision of the vehicle against a station platform in Moston, England, in 2015 [17], and many others. For this reason, more and more papers appear in the literature investigating the effect of side wind on trains traveling at high speeds.

By the aerodynamic loss of transverse stability of a railway, a vehicle is meant the detachment of the vehicle wheels from the rail caused by destabilizing wind forces [13], also dependent on the speed of travel. According to the guidelines [13], [12], the wheel load reduction on the rail should not exceed 90% of the normal pressure derived from the weight of the vehicle. On this basis, the boundary (permissible) wind speed values are determined depending on the vehicle speed and its characteristic wind curves (CWC) [13], [12] are determined. They are compared with the characteristic reference wind curves (CRWC), with the CWC curves of the proposed rolling stock should be above the CRWC curves. Sample reference curves are shown in Figure **1**, depending on the angle of the side wind attack measured from the track axis.



1. CRWC curves depending on the angle of the cross-wind attack, with terrain configuration in the form of an embankment with a height of 6 m, [13]

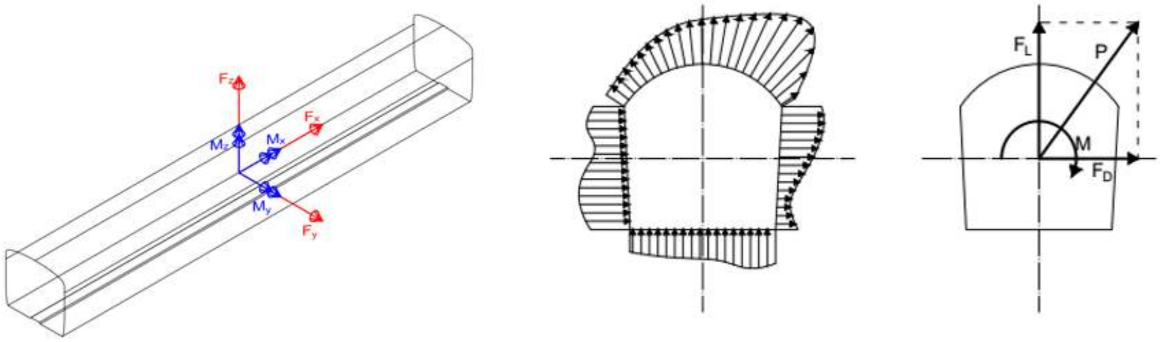
Aerodynamic forces and coefficients To determine the reduction of wheel pressure on a rail, destabilizing forces, i.e. aerodynamic forces acting on the vehicle, should be determined. In the general case, the vehicle is subjected to six aerodynamic forces (loads): three components of the overall force and three components of the overall moment, which are the result of bringing the pressure of the wind distributed on the surfaces of the vehicle to its center of gravity, as in Figure **2**. In computational practice, account is taken of the fact that the dominant influence on the stability of a railway vehicle is influenced by forces operating in a section perpendicular to the direction of travel and the problem is simplified by taking into account only three components of aerodynamic loads: lateral force F_D, lifting force F_L and deflecting moment M (otherwise the moment rotating) [5], [16], [11], [9], [19], [7], [20]. They are described by the following formulas known from the literature (e.g. [16], [21], [9])

$$F_D = \frac{\rho U^2}{2} A_{ref} C_D \quad (1)$$

$$F_L = \frac{\rho U^2}{2} A_{ref} C_L \quad (2)$$

$$M = \frac{\rho U^2}{2} A_{ref} b_{ref} C_M \quad (3)$$

where U is the wind speed, ρ is the air density. A_{ref} is the reference surface, which in the case of railway vehicles is most often taken as the windward side surface for all three forces, while b_{ref} is the reference length usually referred to as vehicle height (e.g. [5], [16], [11], [7], [20]). Exceptionally, Yongle Li in his works [9], [19] proposes that the bottom surface instead of the lateral surface should be used as the reference surface in calculating the lifting force and the deflecting moment, similarly to that used in bridge structures.



2. Aerodynamic forces acting on the vehicle and simplification to the forces acting in cross-section

To determine the aerodynamic loads (1) - (3) it is necessary to determine the parameters C_D, C_L, C_M, called dimensionless aerodynamic coefficients that describe the airflow around the analyzed body (vehicle). These coefficients are specific to a vehicle with a given geometry, they are determined on the basis of tests, usually model tests in a wind tunnel. These tests are carried out at various terrain configurations, determining in each experiment the values of the aerodynamic forces F_i and moments M_i, with $i = x, y, z$ in the general case of six aerodynamic components (see Figure **2**). On this basis, aerodynamic coefficients are calculated according to the formulas

$$C_i = \frac{F_i}{0{,}5 \rho U^2 A_{ref}} \quad (4)$$

$$C_{m,i} = \frac{M_i}{0{,}5 \rho U^2 A_{ref} b_i} \quad (5)$$

directly related to the aerodynamic load definitions (1) - (3), which enables the determination of vehicle loads in many calculation scenarios.

Currently, due to the development of numerical methods, wind tunnel tests are increasingly replaced or supplemented with numerical tests using CFD (*Computational Fluid Dynamics)* methods. Then the forces and aerodynamic moments needed to calculate the aerodynamic coefficients (4) and (5) are determined not by measurement, but by numerical integration of the simulated distribution of air pressure on the body surface. Both approaches will be discussed in more detail below.

Model tests in aerodynamic tunnels

Aerodynamic tunnels allow testing the flow of body through the air with specified parameters, and their main advantage is the actual mapping of the flowing medium (air). The tunnel is a closed space in which continuous air movement is generated. Models of the examined objects are placed in it, observing the flow and measuring the forces acting on the model. Wind tunnel tests provide very high possibilities and in accordance with the recommendations of the TSI [13], it is assumed that they are the only sufficiently reliable source for determining the aerodynamic properties of the train. However, good preparation of tests brings many problems and the results depend on a large number of parameters. When scaling the model, in addition to assuming similarity criteria (Buckingham, 1914) [21], [10], [6] and selecting appropriate wind characteristics, one should also take into account the blocking factor determining what part of the free flow in the tunnel is blocked by the model placed in it [3]. Tests are usually carried out for low turbulence flow, but the flow roughness of the boundary layer is often an important element. In the research of aerodynamics of railway vehicles, the ground layer [5], [4] is particularly important, which is obtained by two methods - passive and active. The passive method involves the use of carpets or blocks that give the appropriate roughness to the substrate layer, while the active method is based on the use of additional wind sources, e.g. fans positioned perpendicularly to the flow direction [6].

An important parameter of any flow analysis is the Reynolds number representing the ratio of inertia forces to viscosity forces in the flow. In many works it has been shown [21], [10], [15] that aerodynamic coefficients depend on this parameter reaching high values in the laminar flow range, minimum values in the critical range and then, in the supercritical range, values rising slightly as the number increases Reynolds.

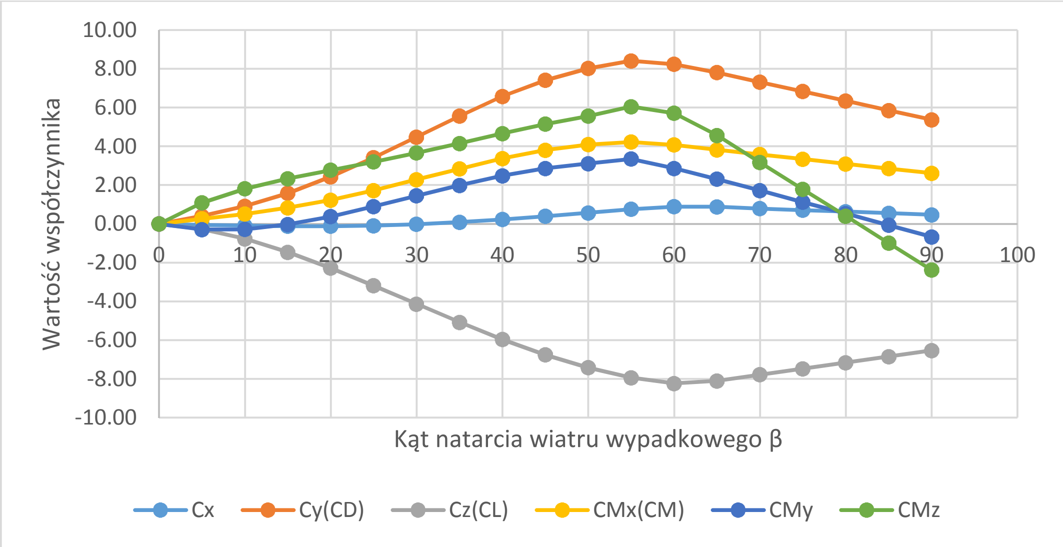
For testing the aerodynamic coefficients of railway vehicles in wind tunnels, the values of Reynolds number from the supercritical range are assumed so that their increase does not affect the obtained forces and moments [13], [16]. The most commonly used values are in the range $2 \times 10^5 \sim 1 \times 10^6$ [3]. The study considers various terrain configurations. Standard [12] and TSI [13] provide three basic configurations: flat terrain, single-track embankment with a height of 1 m and double-track embankment with a height of 6 m with the possibility of placing the vehicle on the windward and leeward side. Special configurations such as flyovers and long bridges require individual analysis [11], [9], [19], [7], [19].

After choosing the test parameters, the standard [12] recommends comparative tests. For this one of three models is used: the ETR 500, TGV Duplex or ICE 3 train model, for which a multitude of tests allowed for precise determination of aerodynamic parameters. Sample results for the ICE 3 vehicle are shown in Figure 3. Note that the aerodynamic coefficient values given in the figure range from –10 to +10. In the literature (e.g. [5], [19]) the coefficients take values in the range from -2.5 to +2.5. The reason for this discrepancy is the use in the standard [12] of a standardized reference surface, which is 10 m^2 irrespective of the type of vehicle. After scaling to the actual reference surface, the values of the coefficients coincide with the literature.

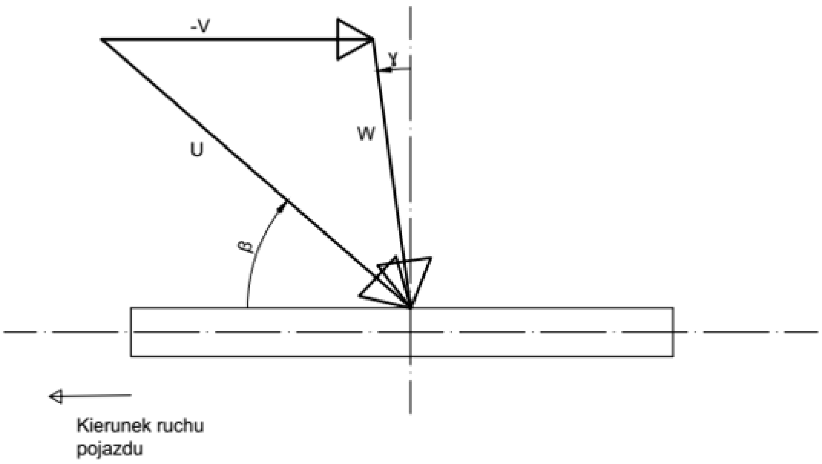
The aerodynamic coefficients in Figure **3** depend on the angle of the so-called attack resultant wind, the speed of which is the result of the assembly of the lateral wind speed vectors and the airflow speed caused by train running, as shown in Figure **4**. The resultant velocity relative to a moving vehicle is given by the formula

$$U = \sqrt{(V + W\sin(\gamma))^2 + (W\cos(\gamma))^2} = \sqrt{V^2 + 2VW\sin(\gamma) + W^2} \qquad (6)$$

where γ is natural wind angle, W and V represent the natural wind speed and vehicle speed, respectively.



3. Aerodynamic coefficients of the ICE 3 vehicle obtained in the wind tunnel for the 1:15 scale model and windward embankment settings [11]



4. Wind speed vector assembly

Model tests conducted in wind tunnels take into account the movement of a railway vehicle in two ways: tests are carried out on a fixed model, set at an appropriate angle relative to the airflow generated at the resultant speed, or (very rarely) tests are carried out on a mobile model [5], [3], [1]. Baker et al. in [1] they presented an example comparison of the results from both tests, using the example of the Pendolino 390 train model, made on a 1:25 scale. The stationary test (on a fixed model) was carried out in accordance with the approach currently adopted, i.e. the vehicle model was set at an angle reflecting the angle of attack of the resultant wind. Whereas tests on the mobile model were carried out in a 150-meter tunnel in which a passing wind was affected by the passing vehicle. Bocciolone and colleagues conducted similar studies [5], expanding their scope - in addition to the impact of vehicle movement, the impact of turbulence and various terrain configurations were also analyzed. In both the cited works, it was found that the way the vehicle motion was taken into account in the wind tunnel has a negligible impact on the test results because the aerodynamic coefficients obtained for the stationary and movable model are very similar. However, this problem requires further research, because in both cases only the flat terrain configuration was used for comparative tests.

CFD numerical tests

Research in aerodynamic tunnels are expensive and time-consuming - they require, among others preparation and construction of the vehicle model and appropriate terrain configuration. For this reason, at the initial stage of analysis, numerical methods are currently used, based on CFD (*Computational Fluid Dynamics*) analyzes.

CFD analyzes rely on numerical flow simulation, carried out under the assumption of a Newtonian fluid model that maps the behaviour of many fluids and gases relatively well, including water and air [10]. The basis of these methods is Navier-Stokes equations describing fluid flow. Their analytical solution is only possible in the simplest cases, hence in CFD analyzes the flow space and the flowing body are discretized using the finite element method (FEM) and the finite volume method (MOS). With turbulent flow, there is a need to map the smallest vortices, due to which the density of the finite element mesh is of the order $R_e^{9/4}$ [3]. Therefore, if we consider the fact that the Reynolds number R_e ranges from 10^6 for wind tunnels to 10^7 for realistic simulations, we obtain an impossible task [3], [10]. For this reason, wind engineering uses methods averaging Navier-Stokes equations, among which can be distinguished methods averaging over time - RANS (*Reynolds Averaged Navier-Stokes*) or averaging flow field in space - LES (*Large Eddy Simulation*).

In engineering, the RANS methods are most often used because they have the lowest computational demand. As a result, we obtain averaged flow over time, which is often sufficient. However, when vortex detachments appear, the RANS method significantly loses accuracy. As shown in many works, among others in [3], [10], [8], the basic RANS model (model k-ε) incorrectly maps turbulence on the upper windward edge. However, other RANS models such as k-ω or RSM (Reynolds Stress Model) allow good results to be obtained at a low cost.

In the event that the use of RANS models does not allow to obtain satisfactory results, the LES model is used, which gives much more accurate results, but its use leads to very large calculation costs. This method simulates vortices about the mesh size, while smaller vortices are represented by additional, non-existent, viscous force. However, direct integration in the space of Navier-Stokes equations even averaged ones, and the requirement of a much denser grid than in the case of RANS methods means that the calculation time increases significantly [19].

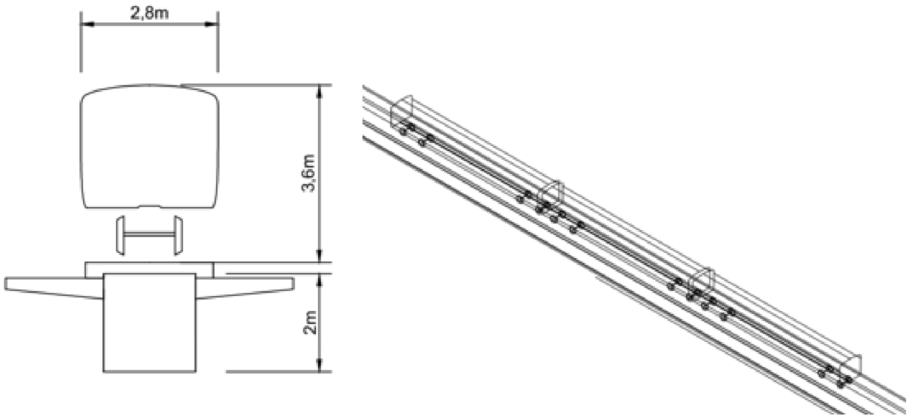
As in wind tunnel research, CFD analysis also requires consideration and preparation of many important parameters, not just the choice of method. As mentioned earlier, the key is to adopt an appropriately compacted FEM mesh. In addition, the correct size of the flow space should be assumed so that the planes that restrict it do not affect body flow. The fact that the streamlined space can be defined as any large is one of the advantages of CFD analysis over wind tunnels. The standard [12] recommends that in the case of CFD tests, comparative analyses should be performed on one of the reference models. It is assumed that the analysis parameters are correct if the results obtained differ by no more than 3% of the results contained in this document. This standard also provides guidelines on the adoption of basic parameters of the analysis.

Although the current regulations do not allow for full proof of aerodynamic stability of a railway vehicle solely with the use of CFD [13], [12], numerical methods together with the development of computing power of modern computers allow obtaining results which are more and more accurate. As Sima and others showed in the work [14] that is part of the AEROTRAIN project, the results obtained by numerical methods can already match the results of wind tunnel tests. For this reason, nowadays, when conducting complex analyses (e.g. coupled vibrations of a bridge - train - wind systems) CFD methods are increasingly used to obtain aerodynamic coefficients.

Own research

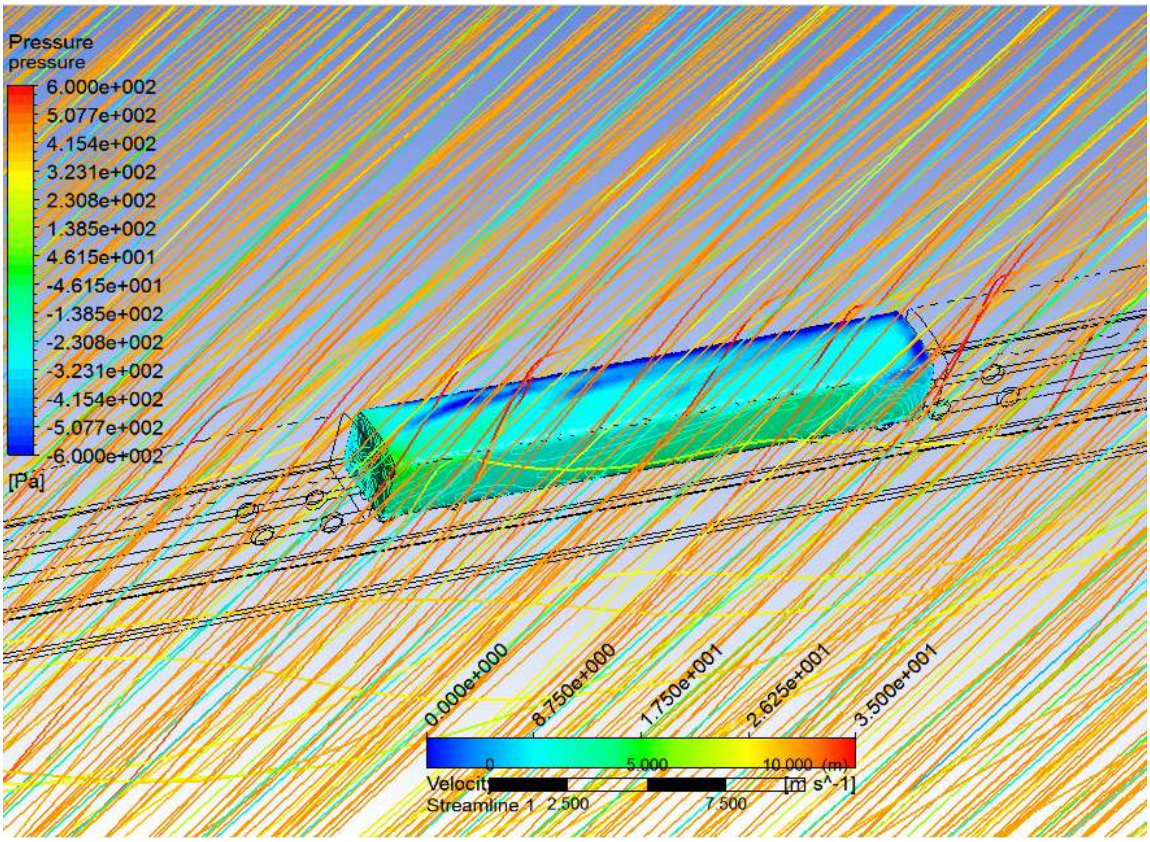
The aim of the authors of this study was to identify the CFD method as a tool for determining the aerodynamic coefficients of a railway vehicle. In further studies, it is planned to develop a method of dynamic analysis of the train - bridge system exposed to cross-wind, including the analysis of aerodynamic stability of a train moving on a bridge.

In the conducted preliminary tests, as in [16], a simplified, rectangular block of the vehicle shown in Figure **5** was analyzed. As a terrain configuration, a single-track beam bridge with a girder height of 2 m was adopted. For the study, it was assumed that the train consists of three identical vehicles (wagons), each 19.5 m long. Aerodynamic coefficients were determined for the middle vehicle, the presence of the neighboring ones was to ensure proper flow representation. The RSM (*Reynolds Stress Model)* method from the RANS group was used in the calculations. This method is based on the closure of the Navier-Stokes system of equations using direct transport of individual components of the Reynolds stress tensor [10]. The projected side surface of the windward wall of the wagon was taken as the reference field value.



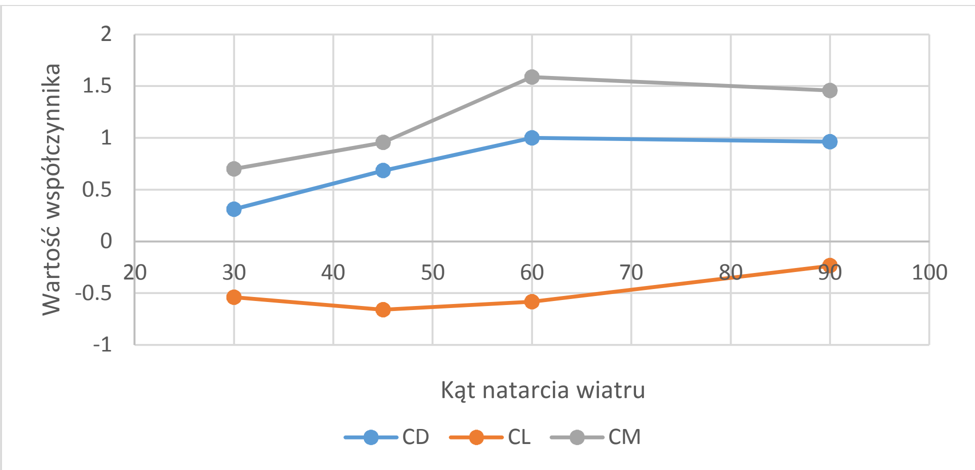
5. Model accepted for own research

The calculations were made in the CFD ANSYS programming environment. First, verification tests were carried out for wind speeds of 20 m/s and 30 m/s, showing the invariability of aerodynamic coefficients, characteristic for the Reynolds number from the supercritical range. The size of the flow around was adopted in accordance with the guidelines of the standard [12]. Sample calculation results are shown in Figure **6**. Next, four angles of the accidental wind attack on the vehicle were considered and the values of aerodynamic coefficients were presented in Figure **7**. These results were read after convergence at several hundred iterations, however, they may be subject to error due to the adopted size finite element approx. 0.2 m.



6. Sample CFD test results for 30˚ rake angle - wind speed lines and pressure distribution on the body surface

The approximate shape of the dependence of aerodynamic coefficients on the angle of attack of the resultant wind, schematically shown in Figure **7**, is similar to the shape of the curves known from the literature and those presented in Figure **3**. In addition, the obtained values of the coefficients fall within the range known from many studies, e.g. 16] or [5], which means that the first results of using the proprietary CFD calculation procedure are promising, although the computational effort turned out to be relatively large - the time of one series of calculations was about four hours. In order for the developed procedure to be considered reliable, comparative analyses should be carried out on one of the reference models according to the standard in the next stage of work [11].



7. Aerodynamic coefficients depending on the angle of attack of the resultant wind

Concluions

Nowadays, the norms allow determining the aerodynamic coefficients of railway vehicles only in wind tunnels, as it is still the most accurate method. However, it requires access to a wind tunnel, a lot of work, appropriate equipment and many tests to obtain reliable results, in particular when various land configurations are being considered. The alternative is numerical methods, which together with the dynamic increase in computing power of modern computers give at once greater possibilities and increasingly better results. The work describes both groups of methods for determining aerodynamic coefficients - based on model tests in wind tunnels and numerical tests using CFD simulations, in relation to railway vehicles, PN-EN 14067-6: 2018-10 standard and TSI requirements.

The paper presents the results of initial own research carried out numerically using the author's calculation procedure implemented in the CFD module of the ANSYS programming environment. The determined values of aerodynamic coefficients of an exemplary hypothetical railway vehicle allow to initially assess the procedure as correct. In the next stage of the study, in order to confirm the reliability of the developed calculation procedure, comparative analyses will be performed on one of the reference models, according to the standard [12]. The developed procedure will be used in the future to determine the aerodynamic coefficients of the train - bridge system, for the needs of dynamic analyzes of such a system subjected to side wind, including the analysis of the aerodynamic stability of a train moving on a bridge.

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