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Research paper

Research on the dynamics of lightweight shell and spatial structures with the aid of computational fluid dynamics and a shaking table

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Abstract: In determining the effects of actions when designing road structures, the influence of the loads caused by the buffeting of the passing vehicles (high-cycle forces) is neglected. Taking into account the fatigue load, they can have a very large impact on the assessment of the load capacity. The subject of analysis is the pressure and velocity distributions around a truck. At the current stage of the work, it can be concluded that the gusts of passing trucks affect the dynamics of the gantry structure and the elements suspended on it, such as platforms or boards. There is a strong suction force. It is possible to simplify the model in such a way that the board and the wind move with the speed of the vehicle while the truck remains stationary. Due to the lack of reliable guidelines for strength calculations of such structures, advanced Computational Fluid Dynamics (CFD) tools were used. This paper also presents a shaking table built by the authors for dynamic loading of structural models. It describes the construction of the shaking table and the kind of movement made by the table deck. It also shows a scheme of the table deck suspension on linear bearings, as well as a scheme of the table motion system.

Keywords: computational fluid dynamics, earthquake, light structures, paraseismic forces, shaking table

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1. Introduction

Examples of lightweight structures are road gantries or cantilever masts, and hyperboloid cooling towers. Defective, non-art constructions are often produced on the market. The reason is the lack of consistent design and construction guidelines for such structures, and hence the inability to safely design and verify them (see, e.g. [1, 2]). In determining the effects of actions, the influence of the loads caused by the buffeting of passing vehicles (high-cycle forces) is neglected. Taking into account the fatigue load, they can have a very large impact on the assessment of the load capacity. Guidelines are found in British Standard [3]. However, it only applies to road cantilever masts, excluding truss structures. There is also a design guide for such structures published by Austroads [4]. However, the problem of material fatigue is not fully described. According to the above standards, statistically 7 000 trucks pass under the structure in one direction in one day. Therefore, it is a high cycle load. Structures with large horizontal planes, e.g., platforms and those on which large boards are mounted, are particularly vulnerable. All this leads to the conclusion that it is necessary to systematise and supplement the knowledge on dynamic analyses of lightweight structures, including cooling towers and road structures. The research task includes the analysis of the wind load on road structures, including road gantries. The main goal is to analyse the load on the structure of passing vehicles. The structure suspended above the road is subject to high-cycle forces. The risk of material fatigue has been checked in the assessment of structural stress. The work is very time-consuming and is divided into stages. At the current stage of the work, this paper presents analyses based on which it was possible to conclude: 1) Does the gust from a passing truck affect the board suspended above it; 2) how can the model be simplified.

In the literature, work can be found on the flow of air around the vehicle itself [5, 6] as well as on the impact of gusts from passing vehicles on road structures [7, 8]. However, in their professional work in the design office, the authors faced much longer gantries and a different structure than in the literature. In addition, the intention is to reduce the computation time by converting the moving object from the truck to the board.

The air flow around the structures was analysed, for which the interference effect is extremely important. Due to the lack of reliable guidelines for strength calculations of such structures, advanced Computational Fluid Dynamics (CFD) tools are used.

Another way to test the structure is with a shaking table. The purpose of the experimental test on the shaking table is to check the dynamic response to vibrations coming from the ground of a 186-meter hyperboloid cooling tower. The essence of the study is to check the influence of the support of the cooling tower shell, once on the “vertical” columns and the second time on the "lattice" columns. For this, a shaking table was built, powered by a double-acting hydraulic cylinder. However, controlling the displacements over time was practically impossible, so the authors decided to build a shaking table driven by a synchronous three-phase AC motor. The electric motor will have a power of 1000 W. With experiments on a shaking table, it can be predicted which elements of the considered structure are susceptible to damage during earthquakes, and thus there is a chance to build safer constructions. Part of the information is presented in [9].

The results of tests carried out on a shaking table, during which the models of two towers were subjected to seismic excitation, are presented in [10]. The use of a shaking table as a gravity separator is shown in [11]. The results of the earthquake tests on a three-dimensional, full-size shaking table are shown in [12]. The subject of research are also wooden frame structures [13]. Methods of dynamic analysis of structures are also shown in [14].

2. Research using Computational Fluid Dynamics (CFD)

2.1. Dynamic meshing

Simulating moving objects in numerical domains is a challenge for scientists and practising engineers. Some early aspects of the advanced zoning technique have been developed recently to overcome numerical problems related to continuous motion/generation of objects within a numerical domain [7, 15]. The building blocks for dynamic mesh capabilities within ANSYS FLUENT are three dynamic mesh schemes: smoothing, layering, and remeshing. Generally, the dynamic mesh technique simulates models that require a moving mesh area. The dynamic mesh technique consists of three steps: determining dynamic mesh methods, specifying specific modes with dynamic mesh options, and defining the dynamic mesh zone.

With respect to dynamic meshes, the integral form of the conservation equation for a general scalar, ϕ, on an arbitrary control volume, V, whose boundary is moving can be written as [16]:

$$\frac{\mathrm{d}}{\mathrm{d}t}\int\limits_{V} \rho\phi\,\mathrm{d}V + \int\limits_{\partial V} \rho\phi\left(\vec{u}-\vec{u}_g\right)\cdot \mathrm{d}\vec{A} = \int\limits_{\partial V} \Gamma\nabla\phi\cdot\mathrm{d}\vec{A} + \int\limits_{V} S_{\phi}\,\mathrm{d}V \tag{2.1}$$

where: ρ is the fluid density, $\vec{u}$ is the flow velocity vector, $\vec{u}_g$ is the mesh velocity of the moving mesh, Γ is the diffusion coefficient, S_{ϕ} is the source term of ϕ. Here, ∂V is used to represent the boundary of the control volume, V.

By using a first-order backward difference formula, the time derivative term in Eq. (2.1) can be written as:

$$\frac{\mathrm{d}}{\mathrm{d}t}\int\limits_{V} \rho\phi\,\mathrm{d}V = \frac{(\rho\phi V)^{n+1}-(\rho\phi V)^{n}}{\Delta}t \tag{2.2}$$

where: n and $n+1$ denote the respective quantity at the current and next time level, respectively. The $(n+1)^{\mathrm{th}}$ time level volume, V^{n+1}, is computed from:

$$V^{n+1} = V^{n} + \frac{\mathrm{d}V}{\mathrm{d}t}\Delta t \tag{2.3}$$

where: $\frac{\mathrm{d}V}{\mathrm{d}t}$ is the volume time derivative of the control volume. In order to satisfy the mesh conservation law, the volume time derivative of the control volume is computed from:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \int\limits_{\partial V} \vec{u}_g \cdot \mathrm{d}\vec{A} = \sum_{j}^{n_f} \vec{u}_{g,j} \cdot \vec{A}_j \tag{2.4}$$

where n_f is the number of faces on the control volume and $\vec{A}_j$ is the face area vector. The dot product $\vec{u}_{g,j} \cdot \vec{A}_j$ on each control volume face is calculated from:

$$\vec{u}_{g,j} \cdot \vec{A}_j = \frac{\delta V_j}{\Delta t} \tag{2.5}$$

where δV_j is the volume swept out by the control volume face j over the time step Δt.

By using a second-order backward difference formula, the time derivative in Equation (2.1) can be written as:

$$\frac{\mathrm{d}}{\mathrm{d}t} \int\limits_{V} \rho\phi \,\mathrm{d}V = \frac{3(\rho\phi V)^{n+1} - 4(\rho\phi V)^{n} + (\rho\phi V)^{n-1}}{2\Delta t} \tag{2.6}$$

where $n+1$, n and $n-1$ denote the respective quantities from successive time levels with $n+1$ denoting the current time level.

In the case of a second-order difference scheme the volume time derivative of the control volume is computed in the same manner as in the first-order scheme as shown in Eq. (2.4). For the second-order differencing scheme, the dot product $\vec{u}_{g,j} \cdot \vec{A}_j$ on each control volume face is calculated from:

$$\left(\vec{u}_{g,j} \cdot \vec{A}_j\right)^{n+1} = \frac{3}{2}\left(\vec{u}_{g,j} \cdot \vec{A}_j\right)^{n} - \frac{1}{2}\left(\vec{u}_{g,j} \cdot \vec{A}_j\right)^{n-1} = \frac{3}{2}\left(\frac{\delta V_j}{\delta t}\right)^{n} - \frac{1}{2}\left(\frac{\delta V_j}{\delta t}\right)^{n-1} \tag{2.7}$$

where $(\delta V_j)^n$ and $(\delta V_j)^{n-1}$ are the volumes swept out by control volume faces at the current and previous time levels over a time step.

2.2. Numerical models

For the calculations a typical 3.40 m high truck is considered passing over a 3.20 m high board (see Figure 1).

The dimensions of the board were selected from the data contained on the website of the road construction manufacturer. This is a simplified model. In fact, the board is suspended on a road gantry structure. However, because a gantry is a bar structure and a board is large, the influence of gusts from the truck passing at a speed of 25 m/s (90 km/h) on a large board is decisive in this stage of analysis. In future considerations, a dynamic analysis of the entire gantry will be carried out. The safe height of the board suspension is assumed to be 6.10 m. In preliminary research, rectangular and planar (2D) computational domains

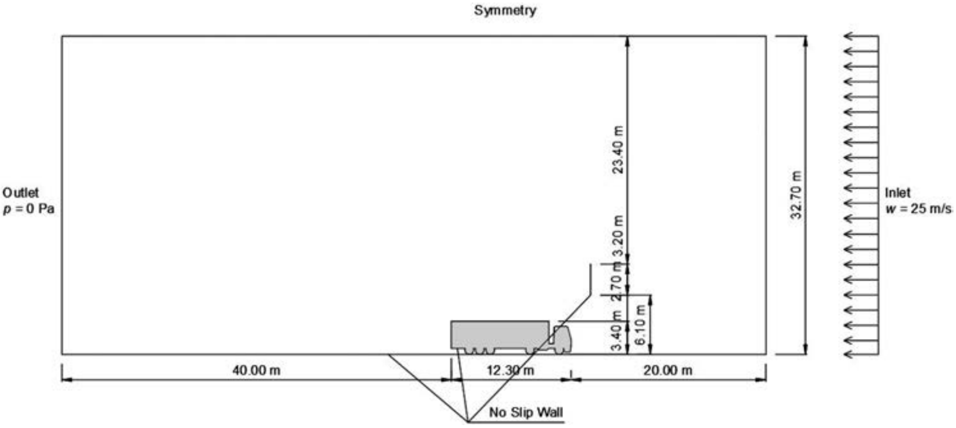

Fig. 1. Dimensions and boundary conditions of a model of air flow around a truck and a board

were prepared in the ANSYS Workbench. Also, to speed up the calculations, it is assumed that the truck is stationary and the board is a moving object.

Air with a velocity of 25 m/s enters the rectangular domain through a front surface (inlet) and flows out through the back surface (outlet), where the pressure is equal to that of the atmosphere. Air velocity is constant because it reflects the moving truck. The truck model is stationary. The board moves at the speed of the truck, which is 25 m/s. Symmetry, which is essentially a wall with slip condition, is chosen for the top to reduce computational time. The bottom surface of the domain, the truck, and the board are declared as No Slip Walls. An important issue is the selection of an appropriate size of a domain while simultaneously keeping in mind that the calculations are complex and require considerable computing power. The dimensions of the computational model are chosen so that the inlet, outlet, and symmetry boundaries are far enough from the truck and board surfaces to avoid any boundary effects, according to [16–20]. The fluid is modelled as an incompressible Newtonian fluid.

Finally, the following computational methods (options) are selected (among others): pressure-based solver, coupled scheme, and transient flow. A time-step size equal to 0.005 s is applied.

The shear-stress (SST) $k-\omega$ turbulence model is chosen. This model is more accurate and reliable for a wider class of flows (e.g., adverse pressure gradient flows, airfoils, transonic shock waves), according to [16] and earlier works by the authors [21, 22]. It blends the robust and accurate formulation of the k–ω model in the near-wall region with the freestream independence of the k–ε in the far field.

Figure 2 shows the FVM mesh of the numerical model.

The results of the drag coefficient in previous works by the authors lead to the conclusion that, for calculations and analyses, a structural grid should be chosen if possible. In these analyses an unstructured quadrilateral mesh is used. Models have significantly lower computational requirements (and coarse mesh) when using wall functions. The mesh is

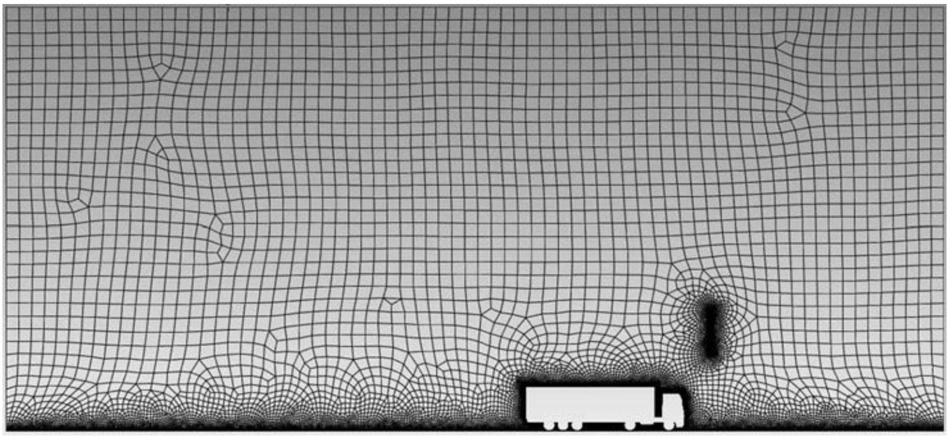

Fig. 2. FVM mesh of a model of air flow around a truck and a board

adopted according to [16, 23–25]. In the references mentioned, among others, possible to use ranges of values $y+$ corresponding to each zone of the viscosity-affected region are included. In this paper, the height of the first mesh element is set to 0.01 m. The density of the mesh around the truck was twice the density and had no effect on the results of pressure and wind velocity. The mesh on the bottom surface of the computational domain is also condensed.

The dynamic mesh model in ANSYS FLUENT can be used to model flows where the shape of the domain changes with time due to motion on the domain boundaries. It is used to move a board toward the truck. It is a rigid body whose direction and velocity of movement are compiled in Fluent using User-Defined Functions (UDFs), written in the C++ programming language. Smoothing, Layering, and Remeshing Mesh Methods, as well as Mesh Adaption are also set.

Behind the truck is the region where the air recirculates. A similar flow visualisation was determined experimentally and described in [5]. Furthermore, a very good agreement is observed between the results of the pressure distribution around the truck surface in [6] and in this paper.

Following the adoption of all previous rules, the problem is converged. Residuals are reduced by three orders of magnitude. The net mass imbalance is less than 0.2% of the net flux through the domain. This means that when the present models are used, reliable results are obtained.

2.3. Results

The subject of analysis are pressure and velocity distributions around a truck and the effect of gusts from a passing truck on a board suspended above it. Due to the fact that these are preliminary studies and the model should be spatial, only qualitative results are presented.

Figure 3 illustrates the pressure changes around a model without and with a board. The effect of gusts on the board is visible. This makes it clear that the impact of passing vehicles should be taken into account in future dynamic analyses of the gantry structure.

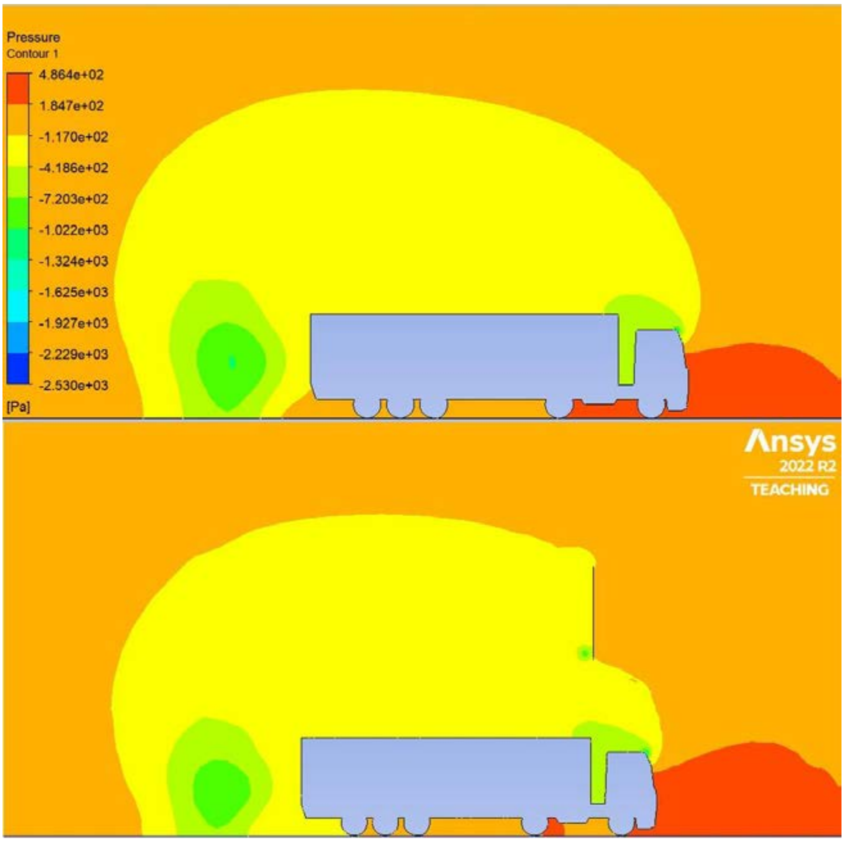

Fig. 3. Pressure distributions around a model without and with a board

Figures 4 and 5 show the pressure and velocity distributions around a model with three board positions. A path of disturbed flow is created behind a windward part of an object. Pressure and velocity distributions are almost constant over time. Vortices are formed above a truck. The flow behind a leeward part of an object is unsteady, swirling, asymmetric, chaotic, and random. The pressure and velocity distributions change over time.

Figure 6 shows the pressure distribution in the vertical section through the model, i.e., the line between the ground and the upper surface of the board in its second position (Fig. 4). In this area, there is a negative pressure of more than –500 Pa.

The next step will be full dynamic analysis in the ANSYS package, using the two-way fluid-structure interaction (2-way FSI) and a spatial model. Wind loads, sign loads and self-weight of the structure have been taken into consideration to determine stresses

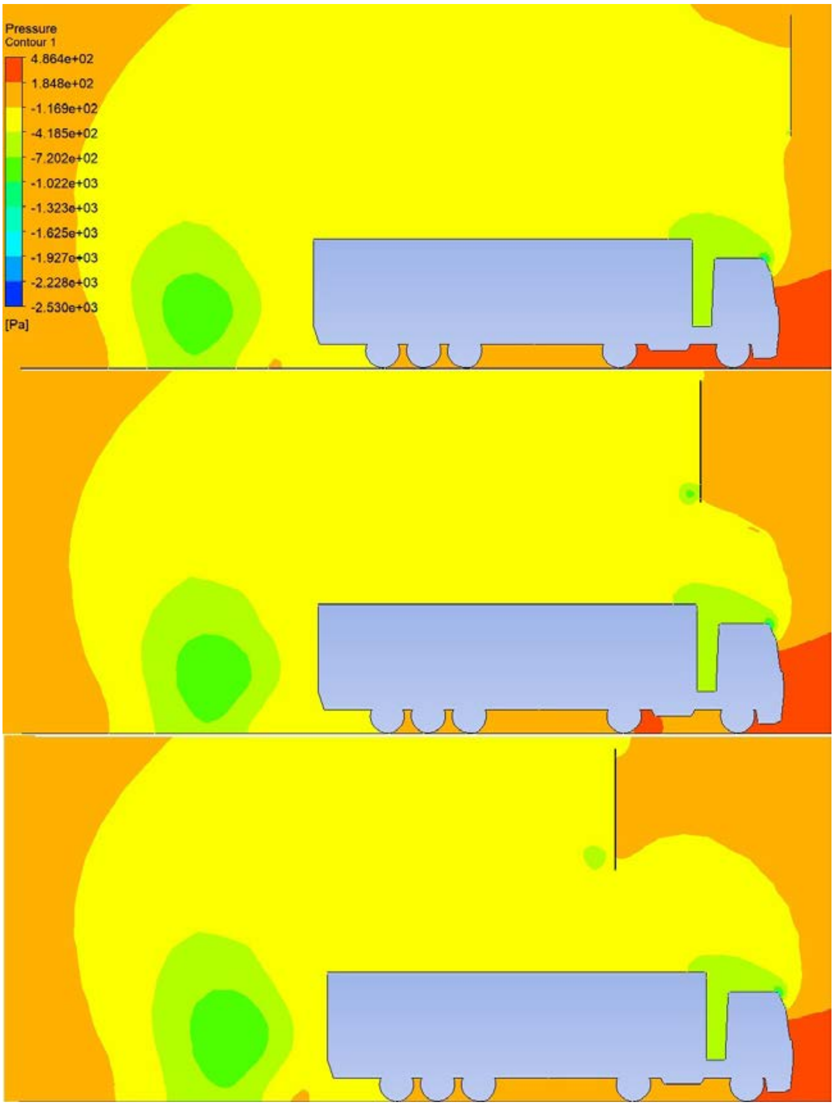

Fig. 4. Pressure distributions around a model with a board

and deflections generated in the structure. The frequency-domain-damped spectral eigen element approach, which has already been developed for vibrational analysis, benefits from the speed and accuracy of the fast Fourier transform (FFT) and fractional derivative damping models. In addition to the ultimate static/dynamic forces considered for the design of highway structures, other dynamic effects, such as fatigue, must be considered. In the future, field tests of the actual structure located on the highway are also planned.

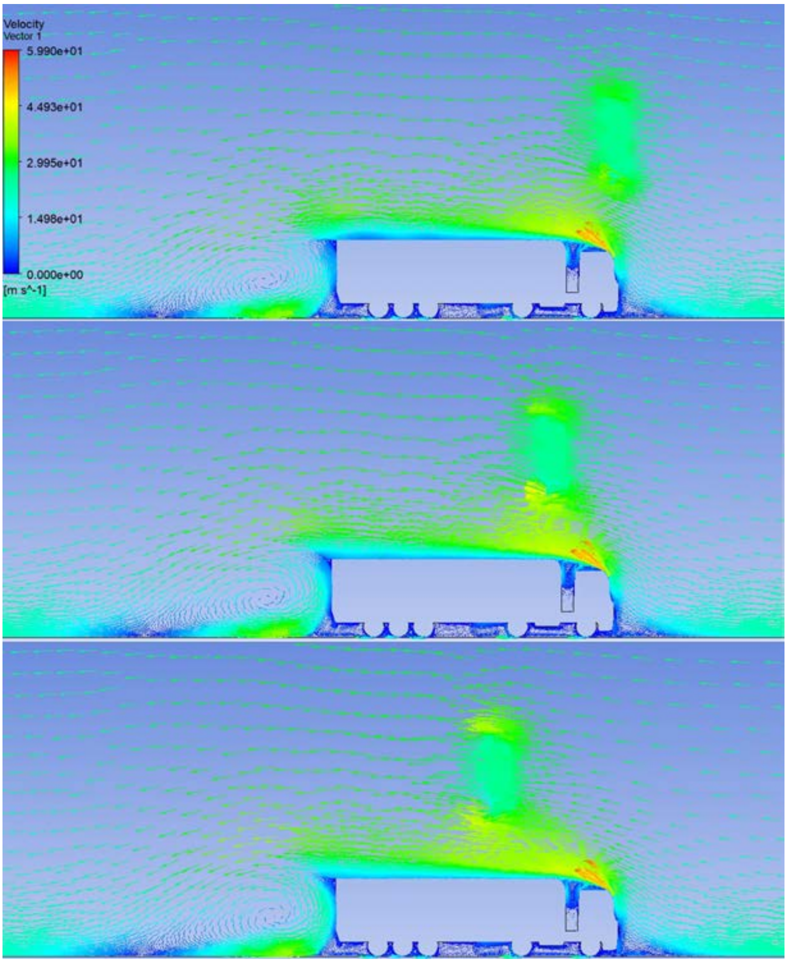

Fig. 5. Velocity distributions around a model with a board

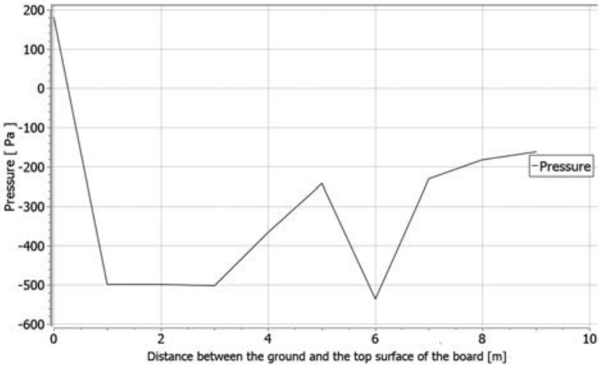

Fig. 6. Dependence of pressure on the distance between the ground and the top surface of the board

3. Research using a shaking table

3.1. Commencement to shaking table

Earthquakes, paraseismic impacts, as well as strong gusts of wind induce vibration in structures. How the structure will vibrate depends, generally speaking, on the characteristics of the acting force, on the stiffness of the structure, and on the distribution of mass in space. On the other hand, the distribution of mass and stiffness depend on the materials of which the structure is built, on the geometry of the structure, on the bearing capacity of the foundations, and on the ground conditions.

3.2. Shaking table

To understand and see the dynamic response of the structure to seismic and paraseismic forces, it is good to test the model on a shaking table. Testing on a shaking table is one of the basic ways to simulate ground movements. For example, the Large High Performance Outdoor Shake Table, the largest in the United States, has dimensions of 7.6 by 12.2 m, and the maximum acceleration that can be obtained on it is 4.2 g. This table is used to study large-scale models and has 6 degrees of freedom. Thanks to the use of the above equipment, engineers are able to design structures that are highly resistant to earthquakes and paraseismic impacts. Describing the shaking table, four main components can be mentioned.

3.3. The shaking table foundation

The foundation of the shaking table must be designed and made so that no vibrations are induced on it. It is a good solution to fix the shaking table to a reinforced concrete element, such as a reinforced concrete slab or block.

3.4. Deck of the shaking table

The table deck must withstand the horizontal and vertical forces acting on it during the test, and at the same time it should be as light as possible so that it requires as little force as possible to set it in motion. Decks made of aluminium are popular, due to the fact that it is a relatively solid material, it is less dense than steel, and at the same time it is cheap.

The shaking table deck in the table designed and built by the authors is made of a steel plate and has dimensions of 600 by 400 by 3 mm.

3.5. Suspension of the deck of the shaking table

In the case of the table, the way the deck moves is ensured by the linear bearings mounted on the linear guides, as it is shown in the scheme below. This type of shifting is simple in construction and makes it possible to test large masses. The use of this type of support for the deck does not generate any vertical motion component.

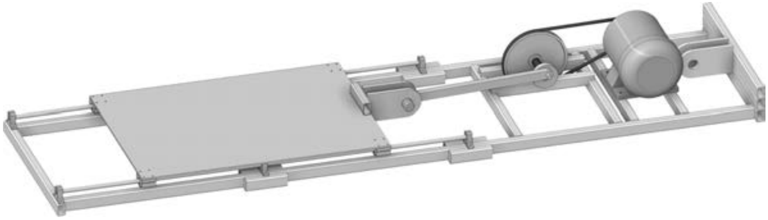

Fig. 7. Suspension of the table deck on linear guides

3.6. Table motion system

The table top is driven by a 1 kW three-phase asynchronous electric motor, which rotates at a maximum velocity of 1400 rpm. The electrical current to the motor is supplied by the inverter, which controls the rotational velocity of the motor shaft. The inverter is an analogue controlled variant of SIEMENS SINAMICS G110, which uses the voltage/frequency control method to rotate the shaft of the motor at the certain velocity. The scheme below shows the table motion system.

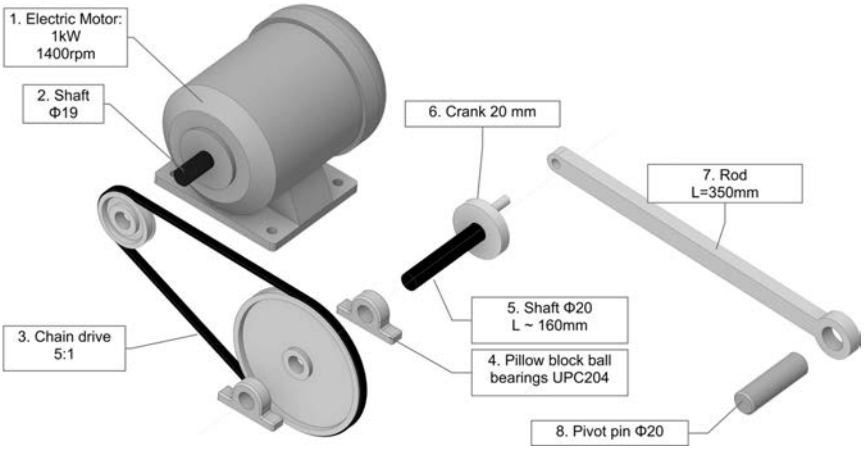

Fig. 8. Table motion system scheme

The table deck performs reciprocating motion which is forced by the construction of the table motion system. The amplitude is 40 mm and the maximum frequency of the reciprocating motion is 4.5 Hz.

4. Conclusions

The subject of the first analysis is pressure and velocity distributions around a truck and the effect of gusts from a passing truck on a board suspended above it. At the current stage of the work, it can be concluded that it is possible to simplify the model in such a way that the board and wind move while the truck remains stationary. The pressure and velocity results in this case are similar to those reported in the literature.

The second conclusion is that the gusts of passing trucks affect the dynamics of the gantry structure and the elements suspended on it, such as platforms or boards. A path of disturbed flow is created behind a windward part of an object. Pressure and velocity distributions are almost constant over time. Vortices are formed above a truck. The flow behind a leeward part of an object is unsteady, swirling, asymmetric, chaotic, and random. The pressure and velocity distributions change rapidly over time.

However, due to the fact that these are preliminary studies and the model should be spatial, only qualitative results are presented. Two-way (strong) coupling between the structure and the flow, in which the flow depends on the changing shape of the structure, along with the formation of a mesh that follows the objects, should be used in modelling the vehicle and the vibrating structure of the gantry. The structure suspended above the road is subject to high-cycle forces. The risk of material fatigue should be checked in the assessment of structural stress. In the future, field tests of the actual structure located on the highway are also planned. The combination of snow and ice loads on the road gantries should also be taken into account. Regarding the conditions in Poland, the analyzes in [26] will be helpful.

Another way to test the structure is with a shaking table, driven by a synchronous three-phase AC motor. The paper describes the construction of the shaking table and the kind of movement that is made by the table deck. It also shows a scheme of the table deck suspension on linear bearings, as well as a scheme of the table motion system. The electric motor will have a power of 1000 W. With experiments on a shaking table, it can be predicted which elements of the considered structure are susceptible to damage during earthquakes, and thus there is a chance to build safer constructions.

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Badania dynamiki lekkich konstrukcji powłokowych i przestrzennych przy zastosowaniu obliczeniowej mechaniki płynów oraz stołu wstrząsowego

Słowa kluczowe: lekkie konstrukcje, obliczeniowa mechanika płynów, siły parasejsmiczne, trzęsienie ziemi, stół wstrząsowy

Streszczenie:

Przy określaniu skutków oddziaływań przy projektowaniu obiektów drogowych pomija się wpływ obciążeń wywołanych podmuchami od przejeżdżających pojazdów (siły wysokocyklowe). Biorąc pod uwagę również obciążenie zmęczeniowe, mogą one mieć bardzo duży wpływ na ocenę nośności konstrukcji. Przedmiotem analizy są rozkłady ciśnień i prędkości wokół samochodu ciężarowego. Na obecnym etapie prac można stwierdzić, że podmuchy od przejeżdżających ciężarówek wpływają na dynamikę konstrukcji bramownicy i zawieszonych na niej elementów, takich jak pomosty czy tablice. Istnieje duża siła ssąca. Możliwe jest uproszczenie modelu w taki sposób, aby tablica i wiatr poruszały się z prędkością pojazdu, podczas gdy ciężarówka pozostaje nieruchoma. Ze względu na brak rzetelnych wytycznych do obliczeń wytrzymałościowych takich konstrukcji, zastosowano zaawansowane narzędzia obliczeniowej mechaniki płynów (CFD). W artykule przedstawiono również zbudowany przez autorów stół wstrząsowy do dynamicznego obciążania modeli konstrukcyjnych. Opisano w nim konstrukcję stołu oraz rodzaj ruchu, jaki wykonuje płyta stołu. Przedstawiono również schemat zawieszenia płyty stołu na liniowych łożyskach oraz schemat układu ruchu stołu.

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