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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF WIND DRAG LOADS ON AN OFFSHORE STRUCTURE TRANSPORTED ON A BARGE TO AN OIL FIELD

EKSPERIMENTALNO I NUMERIČKO ISTRAŽIVANJE OPTEREĆENJA VETROM NA MORSKOJ KONSTRUKCIJI TRANSPORTOVANOJ NA BARŽI DO NAFTNOG IZVORA

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Keywords
- offshore structure
- oil field
- wind load, drag load, lift load
- subsonic wind tunnel
- towing power

Abstract

Environmental loads, such as wind, wave and current are random and are the main data players during an operation of sea transportation. The wind load, in particular and if not predicted, can cause a huge damage to the combined structure (barge and offshore structure). The purpose of this work is to investigate two folds. The first one is mainly to predict the wind drag loads on an offshore structure transported on a towed barge, if it is not self-propelled, to an exploration field and; the second, by adding the wave and current forces, to predict the tug towing capacity to prepare the required number of tugs for towing operation. In this case, the barge is not self-propelled. The wind drag force is measured experimentally and calculated numerically. The wind loads, lift and drag, can act on either direction depending on wind direction, i.e., longitudinally and transversally. In this study and for towing purposes, only the case of the headwind is studied. A model of a combined offshore structure transported on a barge is used inside a subsonic wind tunnel using different speeds model and a weather window of wind headings. Qualitatively and quantitatively measured and numerically calculated loads, in the transverse direction, enhance each other and the obtained experimental results are in good agreement with those provided by numerical calculation methods.

Ključne reči
- pomorske konstrukcije
- izvor nafte
- opterećenja vetra, otpora, uzgona
- podzvučni aerotunel
- snaga tegljača

Izvod

Spoljna opterećenja okoline, kao što su vetrovi, talasi, struje, su slučajna i igraju važnu ulogu u poduhvatima pomorskog transporta. Opterećenja od vetra mogu, posebno, i kada se ne mogu predvideti, izazvati ogromnu štetu na kombinovanim konstrukcijama (barža i pomorska konstrukcija). Cilj ovog rada ima dvojako istraživanje. Isprva se uglavnom procenjuju opterećenja otpora prema vetru na pomorskoj konstrukciji koja se transportuje baržom, vođena tegljačem ako nema sopstveni pogon, sve do izvora eksploatacije; i kao drugi tip istraživanja, dodavanjem talasa i opterećenja usled struja, kako bi se procenila snaga tegljenja radi pripreme potrebnog broja tegljača. U ovom slučaju, barža nema sopstveni pogon. Sila otpora vetru se određuje eksperimentalno i računski. Opterećenja od vetra, uzgon i otpor, mogu delovati u bilo kom pravcu, zavisno od pravca vetra, na pr., podužno i poprečno. U ovom radu, i za potrebe tegljenja, proučava se samo slučaj čeonog vetra. U podzvučnom aerotunelu, ispituje se model kombinovane pomorske konstrukcije koja se transportuje baržom, i to primenom modela različitih brzina i izvora vetra. Kvalitativno i kvantitativno izmerena i numerički sračunata opterećenja u poprečnom pravcu se pojačavaju, a dobijeni eksperimentalni rezultati se dobro slažu sa rezultatima dobijenim numeričkim proračunima.

INTRODUCTION

Offshore structures, in particular offshore oil exploitation, are subject to the mechanical action of waves, wind and currents. Since 1970, in connection with the development of offshore installations, numerous studies have been carried out in the field of the environment such as the forces exerted by wind. The Monin-Obukov /1/ similarity assumption is currently the most used for describing the vertical variation of wind speed as a function of altitude in the lower atmospheric boundary layer. This theory was completed by the works of Dryer /2/ and Paulson /3/, giving the expressions of the implicit functions according to the different classes of roughness.

The same studies by Guesdon et al. /4/ for the behaviour of flows dealing with a complex aerodynamic obstacle with pressure faces, depressed zones, more or less stationary local detachments, etc. Structures subject to even steady wind can be subjected to dynamic stresses that put them in a state of forced oscillations, according to Von Karman /5/. In 1993 Agustin /6/ shows an interest in steel offshore structures that are transported to the exploration site. The transport of a hydrodynamic structure has been traditionally solved in a marine oil project leading the determination of the performed offshore-barge movement, and the dynamics of the rigid structure with applied forces. The finding of Olagnon et al. /7/ is operational in the maritime and offshore operations; the studies are based on elements of towed structures with the securing system (fixing the cargo of a ship) on the barge which is solicited by a strong wind. A review carried out for the calculation of wind loads on ships and coastal structures presented by Haddara et al. /8/. A comparative study is performed experimentally and numerically, where forward force, lateral force, and yaw moment are calculated. The difference between the obtained estimates is compared with the methods and experimental results of Blendermann /9/. The work of Turblen /10/ is based on numerical modelling of wind and the study of its action on constructions. The two-dimensional analysis developed has made it possible to identify the main mechanisms that occur when the wind crosses transversely a slender structure that is not profiled. Jouëtte et al. /11/ compare the free-standing steady-surface dragging coefficients around the ship, obtained experimentally and by a numerical approach of the Navier-stokes type, which consists in assimilating the wind to an incompressible fluid flow governed by the atmospheric boundary layer, and to represent turbulence using a first-order model of the k-epsilon type. De la Foye /12/ determines forces exerted on the envelope of a structure using wind tunnel measurements, the forces generated by wind on models, or he solves numerically calculations with the help of CFD codes (Computational Fluid Dynamics) based on the resolution of Navier-Stokes equations. Denoel /13/ investigates the effects of nonlinear characteristics of aerodynamic loading of a structure, whose numerical and analytical results are close for turbulent wind analysis. Facchinetti et al. /14/ research is based on vortex-induced vibrations which constitute a phenomenon of fluid-structure mechanical interaction. For the exploitation of offshore oil fields, very slender structures are used, subjected to strong winds and currents (Blevins /15/). Rouault et al. /16/ studied the dynamic behaviour of anchored Floating Production Storage and Offloading (FPSO) structures due to wind forces, for the exploitation of offshore oil fields. The aerodynamic coefficients are provided using stationary flow wind tunnel tests with numerical simulations by solving the Navier-Stokes equations. The studies of Turk et al. /17/ are based on the calculation of stationary wind loads on ships and offshore structures, expressed in forward force, lateral force and yaw movement, with angles of incidence from 0° to 180°. Kasbadji et al /18/ modelled the vertical profile of the wind in a semi-arid zone according to the thermal stability of the atmosphere. Violette /19/ shows an interest in offshore structures that vibrate under the effect of sea currents. These vibrations are induced by the periodic detachment of vortices in the wake of the structure called vortex induced vibrations. An experimental wind tunnel synthesis carried out by Tran /20/, on the determination of the forces caused by the wind on lattice structures. An experimental programme is carried out on angles at the wind tunnel in order to determine the parameters and aerodynamic coefficients which influence these coefficients according to the angle of incidence of the wind. In the same year, Derbal et al. /21/ works on the field of fluid-structure interaction, in particular the aerodynamic forces (average and fluctuating) due to the wind speed on the numerical simulation of random effects of the turbulent wind on a structure.

To define the forces of wind on a structure, a study is carried out with the aim of numerically modelling atmospheric turbulence, in order to study the aerodynamic action of the wind as a function of the angle of incidence on the offshore oil structure transported on a barge in a wind tunnel. The analysis developed is based on aerodynamic disturbances generated with a wind speed field characterised by a transverse incident profile on the structure. The lift and drag forces are generated on rigid sectional models of constant section made in a subsonic wind tunnel. Results of experimental tests are compared to the results obtained with numerical resolution using Computational Fluid Dynamics (CFD) code which is a viable alternative for the modelling of airflow on the platform.

EXPERIMENTAL STUDY

During the realisation of this work, experiments are carried out on a prototype of an offshore structure fixed on a barge, Fig. 1a. The study is carried out on the transverse face (a square plate) whose dimensions of the section are shown in Fig. 1b. Dimensions are calculated using a similarity law. It is assumed that the viscosity of the air remains unchanged throughout the duration of this experimental work. Pressure and temperature are measured by a barometer and thermometer.

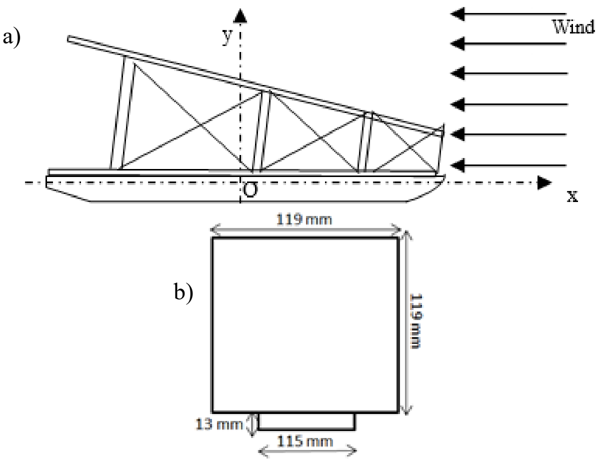

Figure 1. a) Offshore structure transported on a barge; b) transversal view of the offshore structure and barge.

By using the notations of Fig. 1a, the two-dimensional loads, acting on the combined structure reference, consist of two forces: drag force F_x; lift force F_y.

Study on a rigid model

Wind tunnel experimentation is based on classic principles of similarity, which can be given by:
- geometric and cinematic similarity,
- turbulent wind simulation.

Four different speeds are used in order to perform the measurements, i.e., v_1 = 5 m/s, v_2 = 10 m/s, v_3 = 15 m/s, v_4 = 20 m/s, to establish a series of calculations of various coefficients characterising the profile studied for the coefficient of drag and lift (the lift force in the vertical plane is not represented on result curves of this work).

Experiments are accomplished through the use of sophisticated experimental equipment including a TE44 subsonic wind tunnel and a TE81 scale equipped with software, the DATASLIM, designed to measure both magnitudes: drag, lift Fig. 2 a, b.

Figure 2. a), b) Transverse plate in the wind tunnel.

Drag force calibration

As given in Fig. 3, the drag force is calibrated with 10 kg until the monitor indicates the value of 98.2 N.

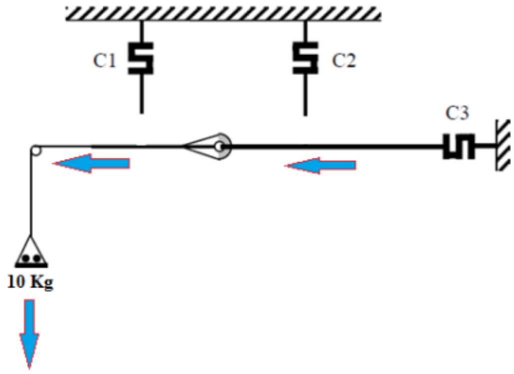

Figure 3. Schematic of horizontal calibration (drag force).

In Fig. 3, C1, C2 and C3 represent the load cells in order to measure the loads. The cells used for drag measurement are known as the TML Tokyo Sokki TCLZ-10KA with a sensitivity of 1.5 mV/V for maximum loads of 10 kg.

Experimental set up

The experiment is conducted by starting to calibrate the balance for lift and drag, then fixing the combined structure on the barge where the balance must face the wind flow in the wind tunnel. The fixation of the structure in the barge is performed in such a way that the combined offshore/barge must be in the centre of the wind tunnel. The following step is to start the wind tunnel, Fig. 4b, and give the value of Δh in mmH_2O that is calculated before starting the tests from the selected speed. The azimuthal angle is varied from -45° to +45° with a step of 5° and the adjustment of the speed must take place after each change of angle of incidence. At the end, the values of lift forces (AFT and FORE) and drag (DRAG) are read on the monitor screen, Fig. 4b.

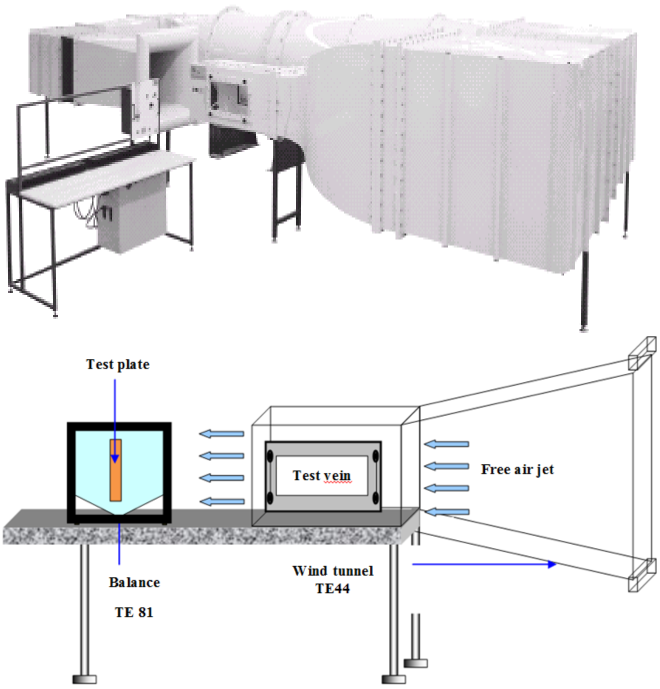

Figure 4. a) Subsonic wind tunnel TE44; b) free jet scheme of the flow.

NUMERICAL SIMULATION

The numerical approach of the problem is complementary to the experimental approach, carried out to deepen and verify our hypotheses and our knowledge on the behaviour of wind on the structure in towing conditions. A number of simulations of the airflow around generic models are made to examine the effect of wind on the offshore structure on the barge.

Wake wind

The generation of wind field is considered as an input of the numerical simulation model, carried out using CFD codes which offer the possibility of simulating unsteady wind fields around any obstacle. Thus the study of the atmospheric wind tunnel is configured with a similar domain (45 mm wide and high, and 1200 mm long), Fig. 2. The CFX meshing software makes it possible to realise the geometry of the offshore structure on a barge, whose final construction of the geometry has defined the domains of computation which are made in a 2D problem and volumes in a 3D problem, as given in Figs. 5 a, b. Initial generation is made by tetra unstructured mesh that generates numerical errors (false diffusion) that can be larger, then with a hexa structured mesh, or refined near the offshore barge structure to capture at best the strong gradients present in its boundary layer.

Mesh validation

Numerical tests have generated mesh grids for element numbers 839394 and 60532 nodes.

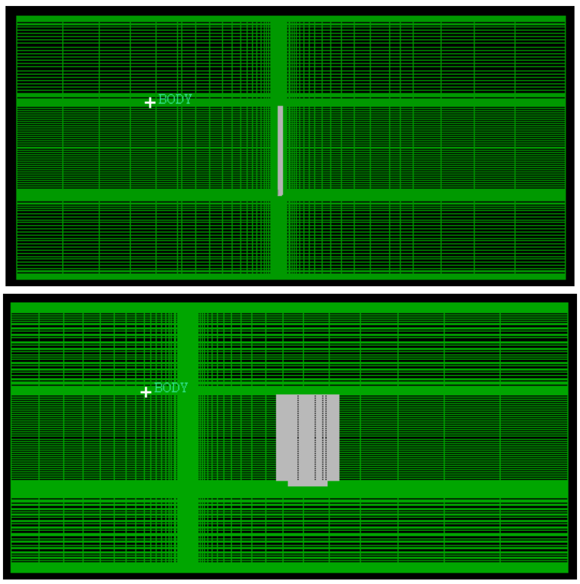

Figure 5. Mesh offshore structure barge transverse face with: a) 0° incidence; b) 45° incidence.

RESULTS

Figures 6 a-d show that as soon as the flow comes in contact with the combined offshore barge structure (transverse view) with 0° incidence and depending on different speeds v_1 = 5 m/s, v_2 = 10 m/s, v_3 = 15 m/s, v_4 = 20 m/s, a detachment of flow, generated at the ends (edges) of the structure, and in the vicinity of the walls. The high speed can undergo very strong disturbances until a reversal of direction in the form of vortices, an exhaust of vortices stronger at the rear of the structure placed in a flow. The magnitude of resulting drag forces of wind velocities v_1 and v_4 are as follows: F_1 = 0.91 N, F_4 = 14.6 N for an angle of incidence 0°. The forces are maximal for an impact undergone by the contact of the fluid (wind) and the combined offshore barge structure that create a zone of high pressure with significant friction force for a totality of the structural surface and a zone of depression created behind the structure, creating two swirls which are summed up with recirculation of flow.

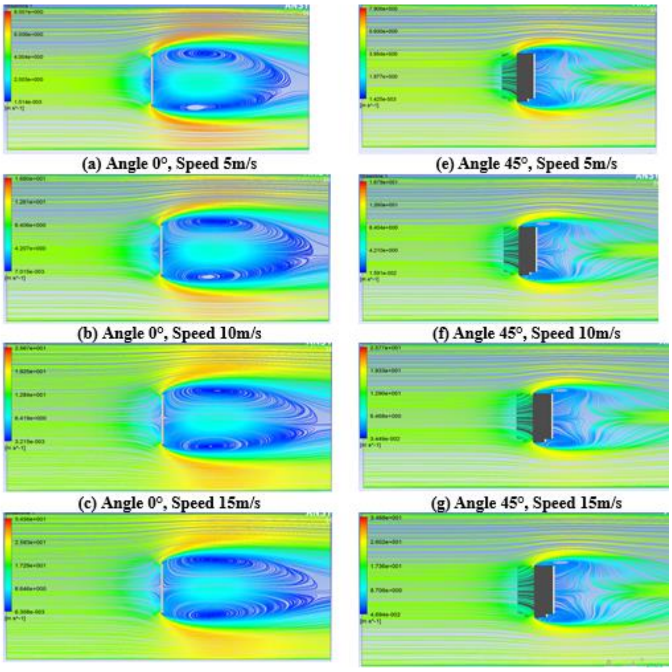

Figure 6. Presentation of flow velocity distribution as a function of the 0° and 45° angles of incidence.

For an angle of incidence 45°, Figs. 6e-h show a less important perturbation due to the contact of flow with the offshore barge structure which varies according to different speeds v_1 = 5 m/s, v_2 = 10 m/s, v_3 = 15 m/s, v_4 = 20 m/s, and which generate a detachment of flow created near the ends of the edges of the structure with lower loads than at velocities of the 0° angle of incidence. For this incidence, the magnitudes of resulting drag forces of wind speeds v_1 and v_4 are as follows: F_1 = 0.479 N, F_4 = 7.549 N. An obvious reduction in the values of forces and a form of the vortex flow created behind the structure of a reduced or reduced-form recirculation zone is due to the inclination of the structure and contact of the fluid (wind) with the combined surface of the offshore barge considered as a surface smaller than the surface perpendicular to the wind flow.

Validation

Wind tunnel tests evaluate the values of drag forces (F_{exp}) that are validated against the results obtained with a numerical simulation (F_{num}). A comparison is made between the drag forces of the two angles of incidence 0° and 45° for speeds v_1, v_2, v_3, v_4. Figure 7 shows two symmetrical curves of drag forces for wind speed 5 m/s with maximal values for 0° angle of incidence: F_{exp} = 0.767 N and F_{num} = 0.910 N and minimal values with respect to two angles of incidence -45° and 45°: F_{exp} = 0.456 N and F_{num} = 0.479 N (angle -45°) and F_{exp} = 0.575 N and F_{num} = 0.479 N (45° angle).

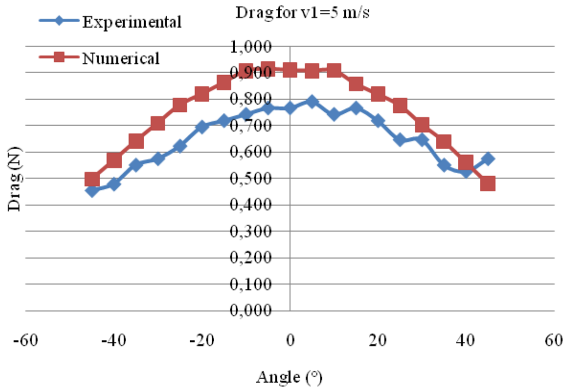

Figure 7. Presentation of experimental and numerical drag forces for angles of incidence and speed v_1 = 5 m/s.

Figure 8 shows two experimental drag forces vs. numerical results for a wind speed of 10 m/s with maximal values over the 0° angle of incidence: F_{exp} = 2.829 N and F_{num} = 3.636 N and minimal values for the two angles of incidence -45° and 45°: F_{exp} = 1.918 N and F_{num} = 1.964 N (-45°) and F_{exp} = 1.702 N and F_{num} = 1.913 N (45°).

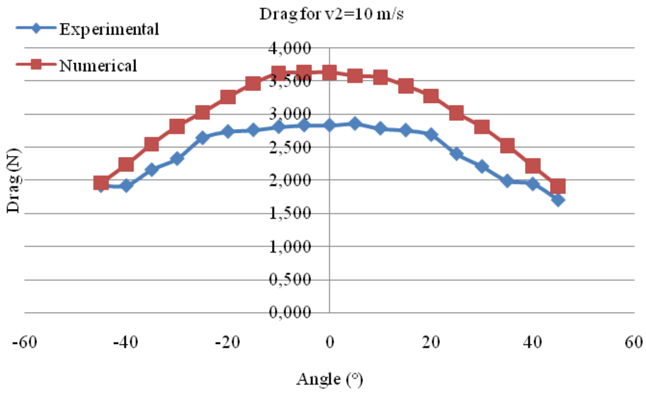

Figure 8. Presentation of experimental and numerical drag forces for angles of incidence and speed v_2 = 10 m/s.

Figure 9 shows two experimental drag forces vs. numerical results for wind speed of 15 m/s with maximal values over 0° incidence angle: F_{exp} = 7.144 N and F_{num} = 8.172N and for minimal values relative to two angles at incidence, -45° and 45°: F_{exp} = 4.411 N and F_{num} = 4.383 N (-45°) and F_{exp} = 4.988 N and F_{num} = 4.264 N (45°).

Figure 10 shows two experimental drag forces vs. numerical results for wind speed of 20 m/s with maximal values for 0° angle of incidence: F_{exp} = 12.802 N and F_{num} = 14.589 N and for minimal values relative to two angles of incidence, -45° and 45°: F_{exp} = 7.6 N and F_{num} = 7.749 N (-45°) and F_{exp} = 8.487 N and F_{num} = 7.549 N (45°).

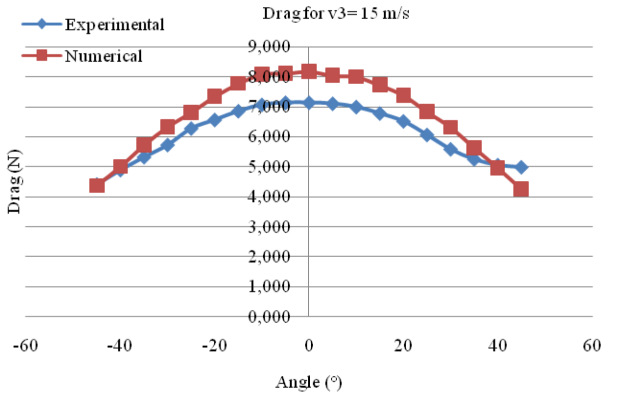

Figure 9. Presentation of experimental and numerical drag forces for angles of incidence and speed v_3 = 15 m/s.

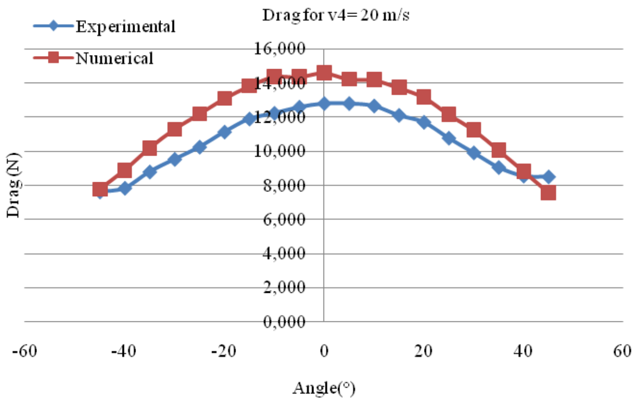

Figure 10. Presentation of experimental and numerical drag forces for angles of incidence and speed v_4 = 20 m/s.

One can observe a perfect symmetry of the curves of drag forces for four previous Figs. 7, 8, 9, 10, varying according to the angles of incidence (-45°, 45°) and for speeds v_1, v_2, v_3, v_4. This symmetry may translate the effect of inclination of combined offshore barge to wind speed conditions.

Figure 11 shows an analogy made after a validation carried out between the wind tunnel tests that generate wind-induced aerodynamic drag forces on the structure of an offshore structure transported on a barge and a numerical simulation, realising two close curves summarising the two drag forces as a function of angles of incidence within the range of (-45°, 45°) and velocities (v_1, v_2, v_3, v_4).

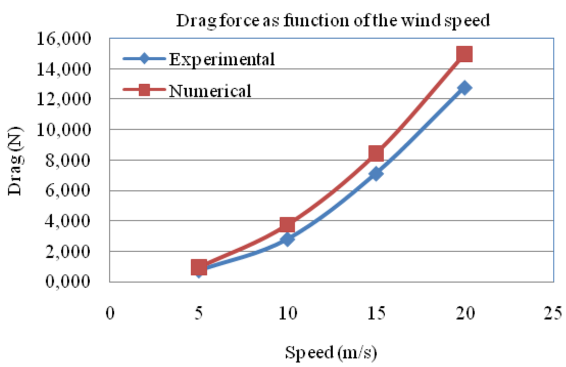

Figure 11. Validation of experimental and numerical results.

Figure 12 shows the measured drag forces for different wind speeds (v_1, v_2, v_3, v_4) vs. the different angles of incidence. From these results and if the barge is not self-propelled one can easily predict the number of tugs which can be used to tow the combined structure on the offshore barge to an oil field.

It has to be mentioned that the error is inevitable during any measurement tests. Therefore, extra care is taken to minimise the effect of any possible error and many measurements during the tests, that have not been used because a number of errors take place during experimental work. The wrong readings are disposed of.

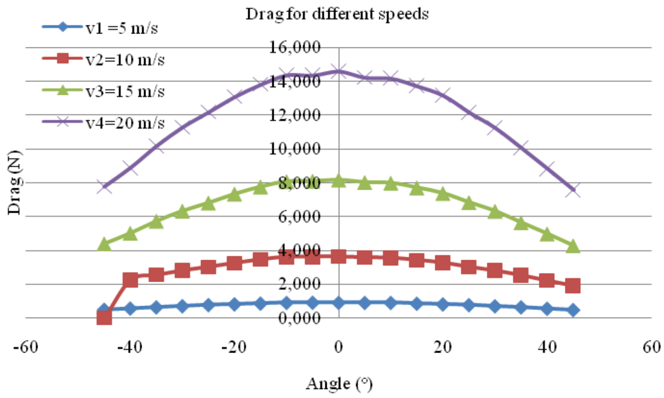

Figure 12. Measured drag forces for different speeds and wind angle incidences.

The following results, Fig. 13, show that drag estimation coefficient is predicted using the previous drag forces measured for different speed and wind angle incidences. This coefficient is deducted from drag force ratios, i.e., the drag force for v_2 is divided by drag force v_1 giving a straight line crossing the vertical axes at the value of 4 and the drag force for v_4 is divided by drag force v_1 giving a straight line crossing the vertical axes at 16. Other results can be interpolated or extrapolated in order to predict tug towing power.

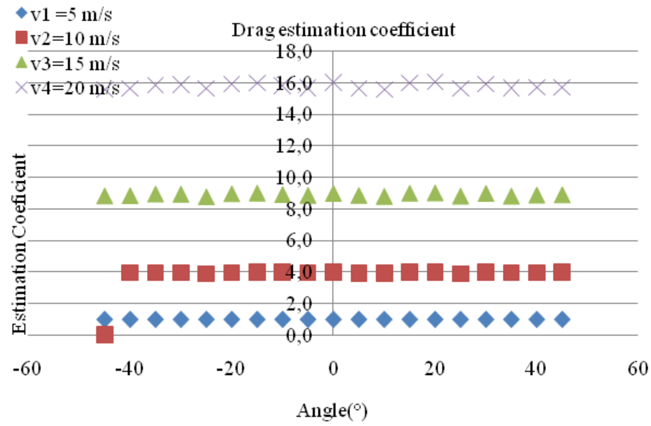

Figure 13. Drag estimation coefficient.

CONCLUSION

In this work, atmospheric turbulence is modelled numerically to study aerodynamic actions of the wind as a function of the angle of incidence on an offshore oil tanker transported on a barge in a wind tunnel. The developed analysis is based on aerodynamic disturbances generated with a wind speed field characterised by a transverse incident profile on the structure. The loads are generated on rigid sectional models of constant section made in the wind tunnel. A symmetry of resulting curves of drag forces made between the positive and negative part of the angle of incidence, which varies from -45° to 45° with respect to the 0° incidence in function of different speeds v_1, v_2, v_3, v_4, and which shows a significant increase in drag forces at maximal velocity v_4 = 20 m/s of 0° incidence, and which decreases with respect to the inclination of angles smaller or greater than 0°. Results of experimental tests are compared to the results obtained with numerical resolution using CFD codes for modelling of the air flow on the platform. The surface of the offshore barge encountered by a flow assisted the birth of secondary flows that led to the creation of vortices of a recirculation zone and a detachment of a turbulent flow of the edges of the offshore barge structure whose turbulent nature of the considered flow is important with high speeds for a 0° angle of incidence, and decreases with respect to angles greater than or less than the 0° angle. The decrease in resulting forces remains proportional with the angle of incidence. The validity of the results corresponds to the comparison of the two experimental and numerical results that imply a coherence and analogy relative to forces of drag caused by wind at different speeds.

Results of the presented investigation can be useful for the prediction of tug towing power for non-self propelled barges.

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