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Short note

Drag coefficients and Strouhal numbers of a port crane boom girder section

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Abstract

This work reports the drag coefficients (C_d) for three wind directions measured in low turbulence flow and in turbulent flow with characteristics of the atmospheric boundary layer wind, and the Strouhal numbers (*St*) of an approximately trapezoidal flanged section, used in the boom girder of a 100 m high port crane. These experimental results were obtained at the Boundary Layer Wind Tunnel of the Dept. Aeronautica at the Universidad Nacional de La Plata, in the range of Reynolds numbers between 30,000 and 180,000. The drag coefficients in the three studied directions showed a reduction for turbulent flow. Further measurements were carried out for the model with an inclination of 80° relative to the flow direction, the position of the crane boom when out of service, giving practically the same drag coefficients.

Keywords: Bluff bodies; Drag coefficient; Strouhal number; Turbulence

1. Introduction

One of the hazards of port crane operation is the effect of wind on the crane structure. Static and dynamic wind loads are important design considerations, both in terms of the structure and mechanisms to withstand the wind loads and for the

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crane operator to be able to take whatever precautions may be necessary. Container crane accidents have been caused by the effect of strong gusts of wind (such as microbursts) during normal operation. The approximately two-dimensional (2-D) geometry and the low natural frequencies of the long crane booms cause that even light winds may be able to generate dangerous dynamic loads through vortex shedding mechanisms.

The fact that turbulence influences the wind loads on bodies has been widely reported [1–3]. Therefore, drag coefficients obtained in wind tunnel tests under ideal conditions are not always representative of the real wind loads on a structure.

The aim of this work is simply to report the drag coefficients and Strouhal numbers of a characteristic section of a port crane boom girder in smooth flow and in flow with turbulence intensity and spectral characteristics representative of atmospheric wind.

2. Methodology

The experiments were carried out at the Boundary Layer and Environmental Fluid Dynamics Laboratory (LACLYFA) at the Faculty of Engineering at the Universidad Nacional de La Plata, Argentina. The wind tunnel, equipped with an electronic speed control, which allows speeds up to 20 m/s, is described in Boldes et al. [4]. It is a closed section tunnel with a test section 1.40 m wide, 1 m high and 7.2 m long, powered by a 50 HP DC electric motor with an axial flow, adjustable pitch blade propeller. The natural turbulence intensity of the wind tunnel in the range of velocities for these experiments was below 2%. The conditions for the measurements in atmospheric turbulence were generated by means of an array of vertically distributed equally spaced horizontal airfoils at the entrance of the test section, which induce different vertical deflections of the flow. Each airfoil could be individually rotated 360° around its longitudinal axis. Additionally, upstream of the section model, the flow was processed by an arrangement of triangular spires.

A model of the boom section, of 0.194 m width, 0.091 m depth and 0.7 m height, was mounted vertically in the test section, on an aerodynamic balance (load cell and V-Shay 2310 bridge) placed under the tunnel floor. No corrections were made for blockage ratio, which was less than 10%. The model scale was 1:20. The balance was calibrated with an accuracy of ± 0.01 N. A flat plate was placed slightly above the top of the models, without touching them, in order to reduce any 3-D effects.

Fig. 1 shows the cross section, which is trapezoidal with flanges at the top, at the floor and on the sides, as shown; the model dimensions and the different studied wind directions.

Fig. 2 sketches the crane boom girder for which this section is proposed. In its operating condition the boom is horizontal, and wind direction 3 is perpendicular to its axis. The out-of-service position is close to vertical (80° to the ground). In this condition, wind directions 1, 2 and 3 must be considered. For generality, and for comparison with other shapes, we studied first the 2-D characteristics of the section with a model mounted vertically on the wind tunnel floor. Then, we measured the

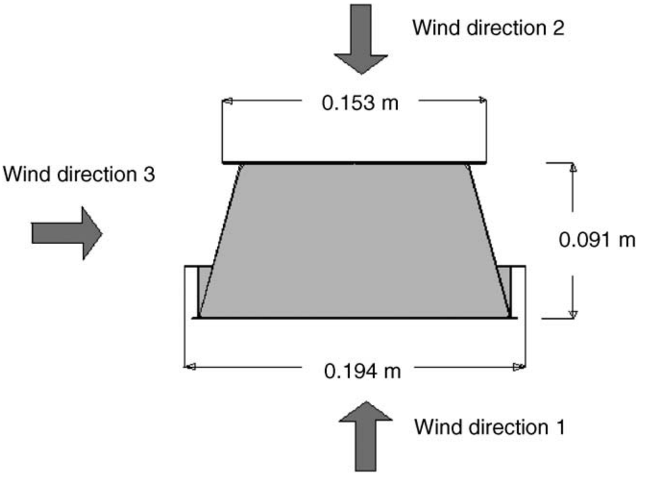


Fig. 1. Model cross section, and wind directions.

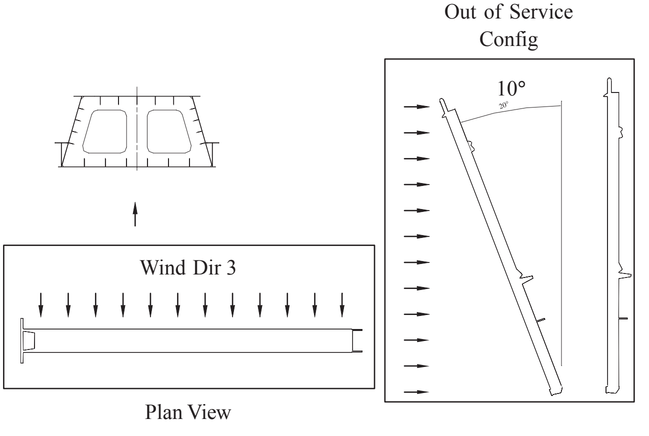


Fig. 2. Sketch of the boom girder.

drag coefficients of the section for wind directions 1 and 2, with a second model inclined 80°, as shown in Fig. 3. The aerodynamic drag for direction 3 should not be affected for this inclination, which implies a rotation in the plane normal to the wind.

The mean velocity was measured with a portable hot wire anemometer Dantec Flowmaster. Instantaneous velocities were acquired at a sample rate of 600 Hz with a two-channel hot wire anemometer Dantec 90C10, with an X film probe, and data were postprocessed in order to obtain values of turbulence intensity and velocity spectra, for the characterization of the incident turbulence, and for the determination of the frequency of vortex shedding in the wake of the model.

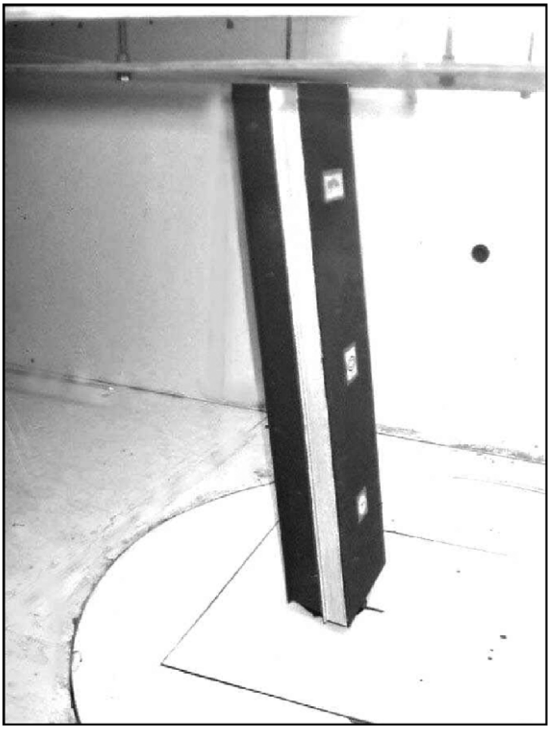


Fig. 3. Model with 80° inclination, in the wind tunnel. The upper flat plate forces the flow to be 2-D.

Through trial and error, we were able to reproduce the desired characteristics of the turbulence (intensity and spectrum) at the model mid height, and for an average Reynolds number of the tested range. By means of variable opening of vanes in the entrance of the test section, an approximately homogeneous mean velocity profile was achieved, in spite of the perturbations due to the triangular spires.

For the measurements in turbulent flow, the modeled wind was representative of flow over open terrain, with a roughness height z_0 between 0.001 and 0.005 m, at target heights between 40 and 100 m. The turbulence intensity for the longitudinal velocity component, Iu, at a height z is given by ([5])

$$\mathrm{Iu} = \frac{1}{\ln(z/z_0)}.$$

For these heights, this expression gives

$$0.09\ (9\%) < \mathrm{Iu} < 0.11\ (11\%).$$

The turbulence intensity obtained with the spires and airfoils was $\mathrm{Iu} = 10\%$, considered representative of the desired conditions.

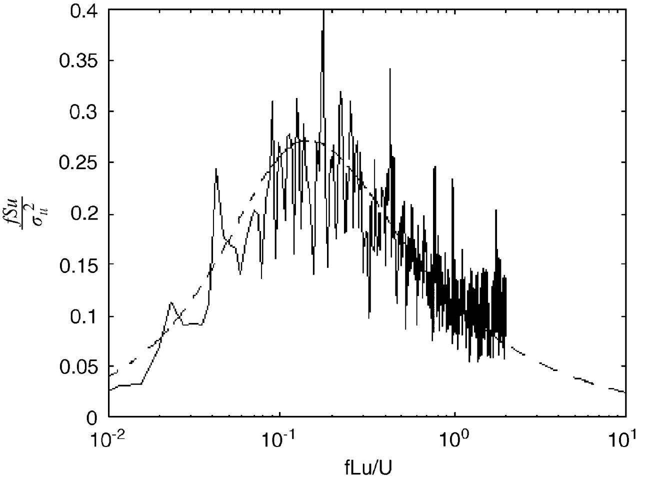


Fig. 4. Normalized spectrum of longitudinal velocity fluctuations (continuous)—Von Karman–Harris spectrum (dashed). $U = 10\,\mathrm{m/s}$.

The integral time scale was approximated with the time lag $\tau_{1/e}$, for the $1/e$ value of the autocorrelation function [6]. The integral length scale for the longitudinal fluctuations, Lu was estimated from the integral time scale, T_u, using frozen flow theory, as $\mathrm{Lu} = UT_{\mathrm{u}}$, giving values close to 0.08 m.

Normalized spectra were computed for the longitudinal fluctuation u'. As shown in Fig. 4, spectra were in very good agreement with Von Karman–Harris' analytical approximation [5]

$$\frac{f\,\mathrm{Su}}{\sigma_{\mathrm{u}}^2} = \frac{4(f\,\mathrm{Lu}/U)}{[1 + 70.8(f\,\mathrm{Lu}/U)^2]^{5/6}},$$

f being the frequency in Hz, Su the spectral power density of the longitudinal fluctuations u', σ_{u} the longitudinal fluctuations rms value, Lu the longitudinal turbulence length scale and U the mean velocity.

The drag coefficients were then measured for wind directions 1 and 2, with the second model inclined 80° with respect to the wind direction, the angle of the crane boom when out of service.

In order to determine the different Strouhal numbers, instantaneous velocity data were acquired in the shear layer in the wake of the section, as sketched in Fig. 5, and the vortex shedding frequency was deduced from the marked spectral peaks of the velocity fluctuations. Due to the wider spreading of the spectra in turbulent flow, Strouhal numbers were only computed for low turbulence flow (indicated in the results as "smooth flow").

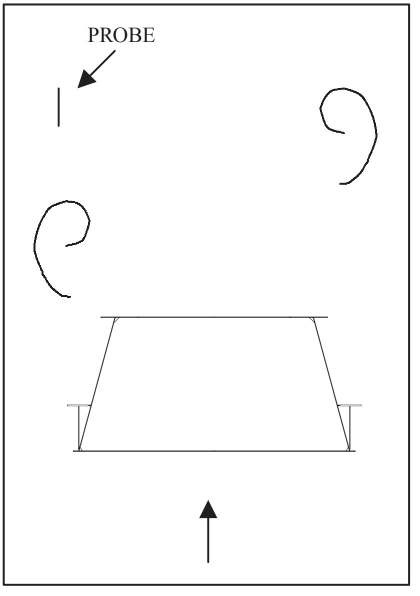


Fig. 5. Location of the anemometric probe for the determination of *St*.

3. Results

Table 1 summarizes the computed mean drag coefficients and Strouhal numbers. The balance registered only the mean drag force. Numbers in brackets indicate the minimum and maximum values and the standard deviation of the mean drag coefficient for each wind direction over the range of Reynolds numbers covered in our experiments. C_d for the inclined model showed a very slight reduction.

Both the Reynolds ($Re = LU/\nu$, with ν the kinematic viscosity) and the Strouhal ($St = f_\mathrm{s}L/U$) numbers are computed with L being the projected width of the section (0.194 m for wind directions 1 and 2, and 0.091 m for wind direction 3) and U the mean velocity. The vortex shedding frequency, f_s, is identified from the normalized frequency at the peak in the spectrum of the velocity fluctuations.

The drag coefficients for wind directions 1 and 3, and the Strouhal numbers for all wind directions compare well with those of other sharp-edged sections shown in Table 2.

Fig. 6 shows the experimental results. The drag force D was measured, and the drag coefficients $C_\mathrm{d} = D/(\frac{1}{2}\rho U^2 LH)$ are presented as a function of the Reynolds number based on the mean velocity U and the projected width of the section in the direction of the wind, L. H is the height of the model and ρ the air density.

Whereas the drag coefficients for low turbulence flow are practically constant through the range of tested Reynolds numbers, for turbulent flow all show a small decreasing trend for larger values of Re. The drag coefficients obtained in smooth flow are higher, and could therefore be used in a conservative design.

Table 1
Drag coefficients C_d and strouhal numbers St of the section

	C_d	(Min.–Max, Std. dev.)
Model perpendicular to the wind		
Wind direction 1	1.87 (smooth)	(1.84–1.91, 0.027)
	1.71 (turbulent)	(1.61–1.79, 0.065)
Wind direction 2:	1.28 (smooth)	(1.26–1.30, 0.012)
	1.05 (turbulent)	(0.95–1.13, 0.054)
Wind direction 3:	1.57 (smooth)	(1.52–1.61, 0.027)
	1.31 (turbulent)	(1.26–1.43, 0.090)
Strouhal number:	0.14 (Wind direction 1)	
	0.175 (Wind direction 2)	
	0.07 (Wind direction 3)	
Model inclined at 80° *(out-of-service position):*		
Wind direction 1:	1.88 (smooth)	(1.83–1.92, 0.023)
	1.61 (turbulent)	(1.57–1.64, 0.028)
Wind direction 2:	1.24 (smooth)	(1.18–1.27, 0.029)
	1.07 (turbulent)	(1.02–1.12, 0.043)

Table 2
Cd and Strouhal number of other sharp-edged shapes, from Refs. [5] and [7]

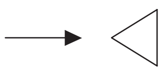
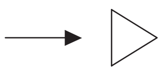
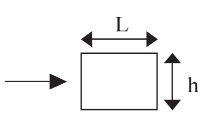
Cross-section		C_d	St
		1.2	N/A
		2	0.14
		2	0.145
	**L/h** 0.5	2	0.06
	2	1.5	N/A

Fig. 7 illustrates two spectra obtained for wind direction 3, at different Reynolds numbers, in the shear layer of the near wake of the section. The frequency in the abscissae has been made non-dimensional as fL/U, in order to identify the Strouhal

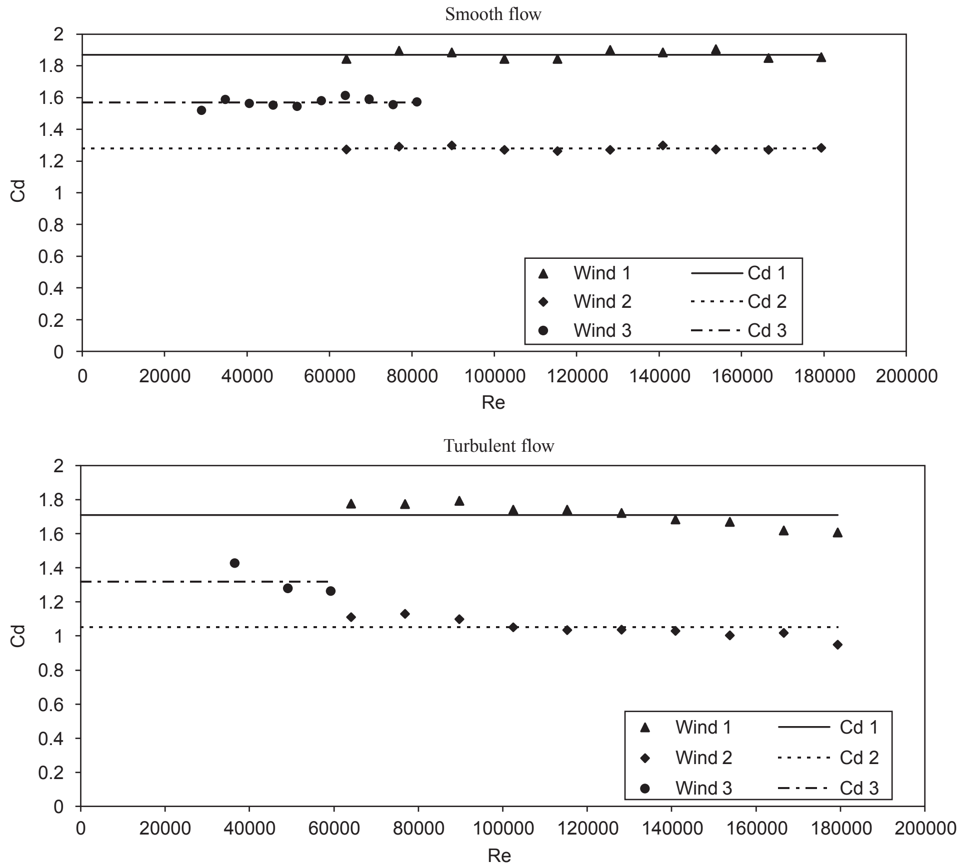


Fig. 6. Drag coefficients for wind directions 1, 2 and 3. The horizontal lines represent the mean values over all the tested *Re*.

number at the spectral peak. In all tested cases, the spectral peaks were easily identified and their non-dimensional frequencies did not depend on the Reynolds number.

4. Conclusions

Aerodynamic drag coefficients for smooth and turbulent flow and Strouhal numbers of a flanged trapezoidal section used in a port crane boom girder are reported in this work. For smooth flow, the drag coefficients and Strouhal numbers compare acceptably with reported values for other sharp-edged sections.

For turbulent flow, the drag coefficients showed a reduction between 4% and 11%, compared with those measured in smooth flow and also a small decreasing

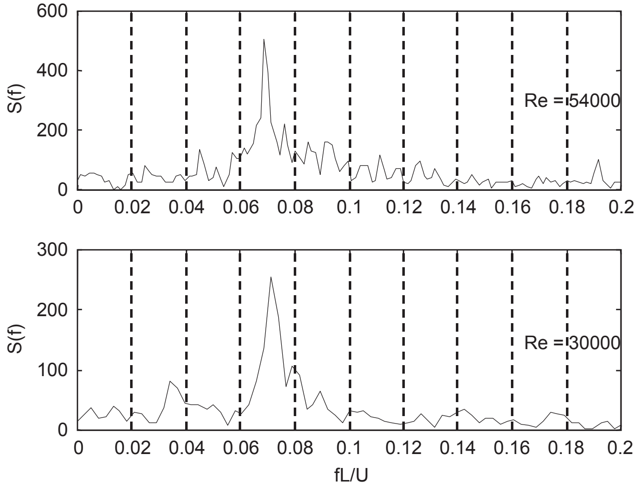


Fig. 7. Example of spectra in the model wake, wind direction 3.

trend with Reynolds number. Further work is needed in order to investigate the possible reasons for this behavior, testing this and different sections with turbulence of different intensities and scales.

For sharp-edged bluff bodies, separation of flow occurs at the sharp edges and corners for practically all values of *Re* of interest in wind engineering, in wind tunnel or full-scale problems. This leads to the fact that the dependence of pressure coefficients and consequently of drag coefficients on Reynolds number for sharp-edged bluff bodies (but not for rounded edges) is often negligible, at least in smooth flows [5,7]. The same happens for the non-dimensional vortex shedding frequency for sharp-edged sections. Our results confirm this independence. On the other hand, in turbulent flows, some characteristics, as the turbulence small scales, can affect the pressure distributions and, in consequence, the resultant aerodynamic forces [8,9].

Pressure and force coefficients in turbulent flows show a larger scatter than in smooth flows, depending on the characteristics of the incident turbulence, making difficult the choice of the suitable coefficient for a given problem. Furthermore, while an approximately homogeneous turbulent flow can be reasonable for computing the forces on the boom in its horizontal operating condition, a realistic analysis of the wind loads in the quasi-vertical out-of-service position requires the simulation of the atmospheric boundary layer on a model of the whole crane structure, and not only the characteristics of the ABL at a certain height. In this context, and in a design stage, the use of conservative values seems reasonable. The C_ds obtained with smooth flow are at most 20% higher than those measured with turbulent flow, and this is much less than the safety factors usually employed for design.

Acknowledgments

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