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WIND INDUCED CURRENTS IN AN INLET OF A SEMI-ENCLOSED BAY (KAŠTELA BAY, ADRIATIC SEA)

UTJECAJ VJETRA NA STRUJE U VRATIMA POLUZATVORENOG BAZENA (KAŠTELANSKI ZALJEV, JADRANSKO MORE)

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Set of current measurement data from the inlet of the Kaštela Bay (Adriatic Sea) and their relation with the wind are examined. Current response to the local wind forcing is described in terms of the linear dynamics. In one part of the inlet the surface inflowing current can be described in terms of the friction balance. At the opposite side of the inlet in the bottom layer, the current represents a compensatory flow to the wind induced surface currents.

The dependence of the wind induced flow pattern in the vertical cross section on the wind direction is also examined. During the wind episodes, the shear in the current field has a horizontal component (curl), while the northeast wind events induce water exchange pattern with the prevalence of the vertical shear.

INTRODUCTION

The Bay of Kaštela is relatively small bay of the total area of 61 km^2 and the volume of 1.4 km^3. The bay communicates with the open sea through a 1.8 km wide and relatively deep inlet (average depth is about 40 m). The fresh water inflow is rather poor (yearly mean of about 10 m^3/s) and probably the wind forcing is the most important mechanism generating the low-frequency current variations (Zore-Armanda, 1980., Gačić 1985 and Gačić *et al.*, 1987). In one of the previous studies (Gačić *et al.*, 1987) it was documented that up to 70% of the variance of current field variations at the synoptic time scales can be explained in terms of the local wind forcing.

The purpose of this work is:

- to try to explain in terms of the linear dynamics the current field response to the wind forcing in the inlet of the Kaštela Bay;

- to relate the water exchanges pattern in the inlet to the most frequent wind forcing.

EXPERIMENTAL DESIGN AND CURRENT DATA ANALYSIS

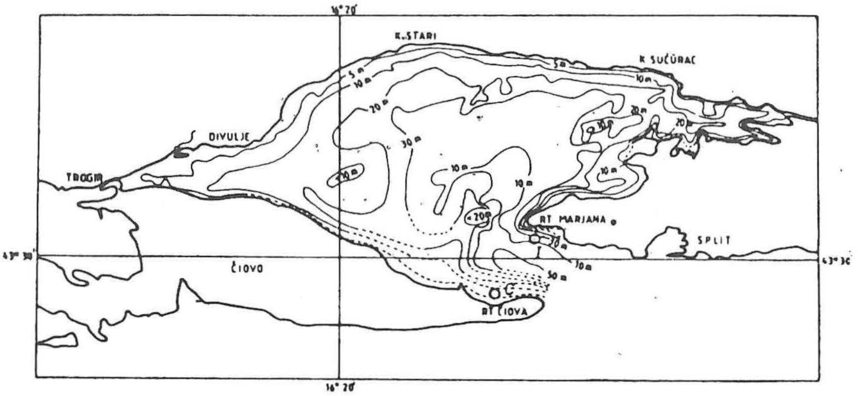

Fig. 1. The map of the Kaštela Bay. Current meter mooring are denoted by open circles and the meteorological station by a dot

Currents were measured in the inlet of the Kaštela Bay (Fig.1) at two stations for about two months in the period March - May 1989. "AAnderaa" current meters moored at two depths (5 and 30 m) of each station, were recording data with the sampling interval of 20 min. The current record at the depth of 30 m at the station I is shorter due to the malfunction of the current meter.

Hourly means of wind data for the same period were available from the meteorological station in the close vicinity (see Fig. 1). From the wind velocity data, vectors of wind stress were calculated assuming the constant drag coefficient (1.5×10^{-3}). Current and wind stress vectors were then decomposed into east and north components. The axis of the bay inlet is oriented east-west and, therefore, an east current component represents in- or out-flowing currents. Tidal (diurnal and semi-diurnal) and other daily oscillations were removed from both current and wind time-series by means of a digital low-pass filter 24m214 (Thompson, 1983). Comparison of wind and current low-pass time-series (Figs.2 and 3.) suggests that, in the surface layer of the station I, there is a high positive correlation between the east current and wind stress component.

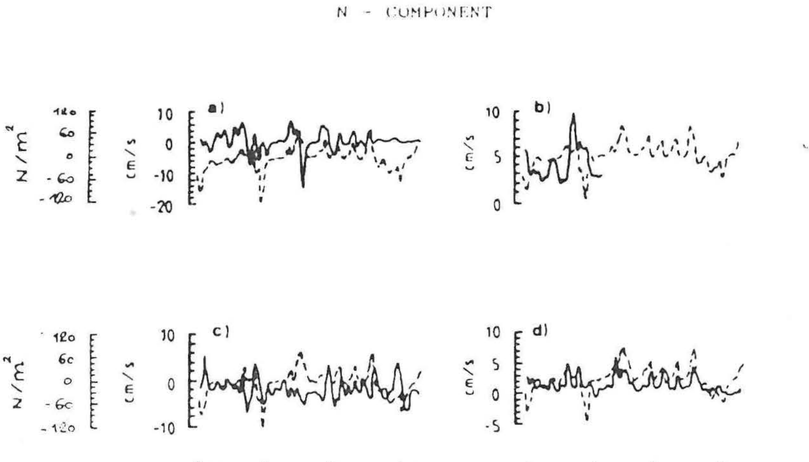

Fig. 2. Time series of low-pass north wind stress (dashed line) and current (solid line) component for station I at 5m (a), and 30m (b) and for station C at 5m (c) and 30m (d)

North current component has smaller variance mainly due to the orientation of the bay inlet (east - west). In the surface layer at the opposite side of the inlet (station C) the variability of the east current component appears completely independent on the wind

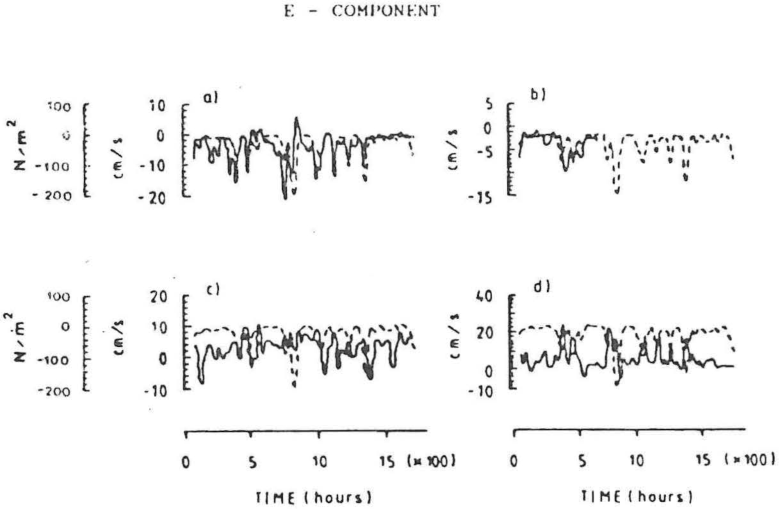

Fig. 3. Time series of low-pass east wind stress (dashed line) and current (solid line) component for station I t 5m (a), and 30m (b) and for station C at 5m (c) and 30m (d).

forcing. However, at the same station at depth of 30 m there is a high but negative correlation between the east wind and current component. The variance in the north component is reduced most at that depth.

Correlation coefficients between the east (u) and north (v) current and wind stress components (X and Y) are calculated for each measurement depth. Results are presented in the Table 1. Throughout the rest of the paper the x-axis will be oriented eastward and y-axis northward.

In the surface layer of the station I, statistically significant correlation coefficient is obtained only between the east components of wind stress and current. In addition, the Reynold stresses are negative (correlation coefficients between the east and north current components) for all measurement depths except for 30 m at the station C.

Correlation coefficients between wind and current components are all statistically insignificant in the surface layer of the station C. On the other hand, at the same station at 30 m depth, correlation coefficients between all combinations of current and wind components are statistically significant.

We sought for explanations of high correlation coefficients between winds and currents in terms of a linear dynamic balance. In the surface layer of the station I, the high positive correlation between the east current and wind stress components can be explained in terms of the frictional balance i.e. the balance between the surface and bottom stress term assuming that the bottom stress is linear or quadratic function of the current speed.

This balance is a good approximation of the equation of motion in the limit of very shallow water (Winant and Beardsley, 1979). Since, in our case the current field displays strong variability on the time scale of several days, one would expect that the time derivative term plays an important role and it has also been taken into consideration. Coriolis force term is neglected since the y current component is rather small due to the topographic constraints in the inlet.

Regression estimates of the drag and linear friction coefficients are computed in two cases: assuming steady motion i.e. balance only between the surface stress and bottom friction term and, in other case, keeping the time derivative term. The x-component of the effective subsurface pressure gradient very likely does not play an important role due to the relatively small basin scale in the x direction (about five kilometers).
The acceleration term is calculated by finite central differences from the x-current component time series with the time step of seven hours. As a result, the friction coefficients of the linear and quadratic bottom friction are obtained for steady and unsteady case. The value of the drag coefficient computed from the equation of the motion keeping the acceleration term, is:

$$C_D = 1.924 \times 10^{-3}$$

while in the same case the linear friction coefficient has the value:

$$r = 4.450 \times 10^{-2} \text{ cm/s}$$

Assuming the steady state and computing again by regression estimates both drag and linear friction coefficients, we find them smaller by less than 10% than in the unsteady case. Therefore, the acceleration term can be neglected i.e. current field in the surface layer at the station I can be described by the frictional balance. Winant and Beardsley (1979) computed by the same method estimates of friction coefficients using current data from several shallow water experiments. They found rather large spread in the regression estimates of friction coefficients at similar depths but from different experiments varying by as much as the factor of 4. Our values of the drag and linear friction coefficients compare well with values computed from the data by Hunter *et al.* (1977) originating from the continental shelf off Chesapeake Bay. Agreement is good with data measured 19 and 31 m above bottom in the total water depth of 38 m.

Therefore, the data are very likely out of the bottom boundary layer what also applies to our data which are from the surface layer of the station I. In Fig. 4, time series of the surface and bottom quadratic friction terms are presented. At the same figure the acceleration term is also plotted. The acceleration term is generally smaller than the two frictional terms. The wind stress term is appreciably larger than the bottom stress only

Table 1. Correlation matrix for all stations

CORRELATION MATRIX - INSTITUTE 5 m

I_5	v	u	τ_v	τ_u
v	1.000			
u	-0.826	1.000		
τ_v	0.118	-0.388	1.000	
τ_u	-0.255	0.449	-0.653	1.000

N = 1286

CORRELATION MATRIX - INSTITUTE 30 m

I_{30}	v	u	τ_v	τ_u
v	1.000			
u	-0.923	1.000		
τ_v	-0.103	0.079	1.000	
τ_u	-0.334	0.462	-0.199	1.000

N = 593

CORRELATION MATRIX - ČIOVO 5 m

$Č_5$	v	u	τ_v	τ_u
v	1.000			
u	-0.828	1.000		
τ_v	-0.054	0.008	1.000	
τ_u	-0.000	-0.008	-0.633	1.000

N = 1643

CORRELATION MATRIX - ČIOVO 30 m

$Č_{30}$	v	u	τ_v	τ_u
v	1.000			
u	0.750	1.000		
τ_v	0.508	0.440	1.000	
τ_u	-0.727	-0.550	-0.633	1.000

N = 1501

during the strong wind episodes when probably some other terms in the equations of motion, may be even non-linear ones, become more important.

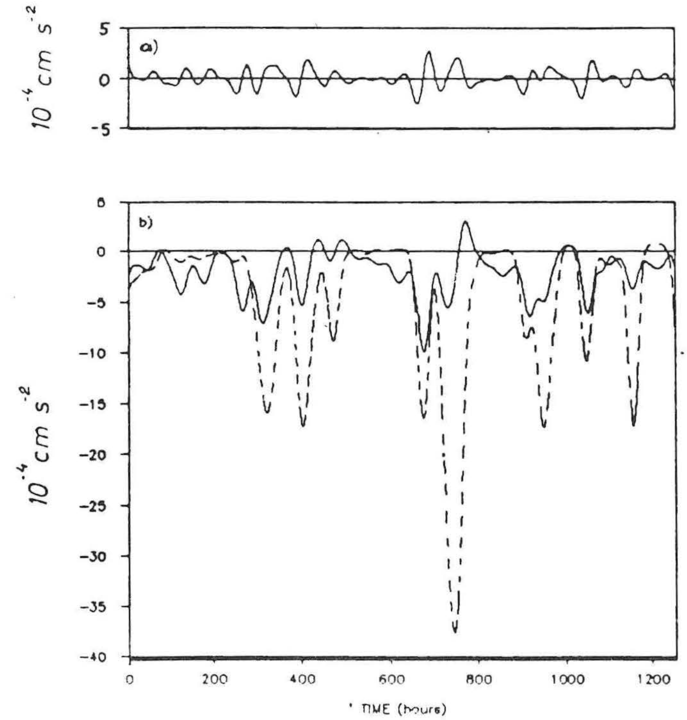

Fig. 4. Time-series of the time derivative of the east current component (a-solid line), quadratic bottom stress (b-solid line) and wind stress (b-dashed line) for the station I at the depth of 5 m.

Two other possible reasons could be responsible for these discrepancies; in the equations of motion representing the friction balance, current velocity is in fact vertically integrated one while in our case we were considering measured velocity at a given depth. In addition, the wind data for the surface stress calculations should originate from the height of 10 m above the sea level. However, in our case we have data recorded at an anemometer height of 135 m above the sea level. We decided to use these wind data without reducing them to the 10 m height since the reduction would probably be a source of some additional errors. Therefore, computed surface stress term is probably overestimated.

No linear dynamic balance can be assigned to the current field variations in the surface layer of the station C, since no statistically significant correlation coefficients

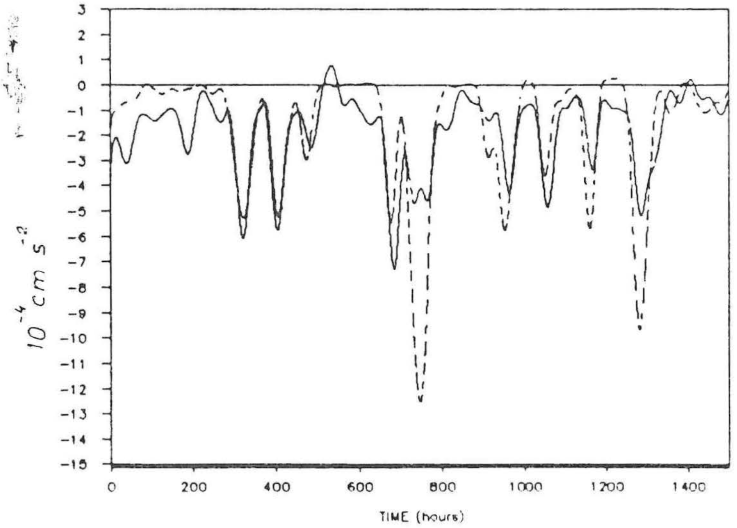

Fig. 5. Time-series of the Coriolis term (solid line) and the east wind stress term (dash line) for the station C at the depth of 30 m.

between different current and wind stress components are obtained. The lack of correlation will be explained later in terms of the flow pattern in the vertical transect across the bay inlet.

In the bottom layer of the station C, the high negative correlation between the east wind stress component and the north current component suggests an Ekman balance in the equation of motion along the east - west axis. Indeed, comparing the time-series of the wind stress and Coriolis term (Fig. 5) it appears that they are not only well correlated, but also most of the time, of the same order of magnitude. Their relation does not change to a larger extent by adding the acceleration term to the Coriolis force term (Fig. 6). On the other hand, a high correlation between east current component and the north wind stress component of a proper sign, does not lead to an Ekman balance along the y-axis since the Coriolis term is much larger than the wind stress term. By adding the bottom stress term the balance is not reached. Therefore, in the bottom layer of the station C, the low frequency variations of the inflowing (east) current component cannot be explained solely by the linear dynamic considerations. Probably, the condition of the zero mean flow through the bay inlet should additionally be taken into account.

In order to show the relationship between different current components at different stations and depths, linear correlations were computed (Table 2). High negative correlation coefficient is obtained between the east current component in the surface

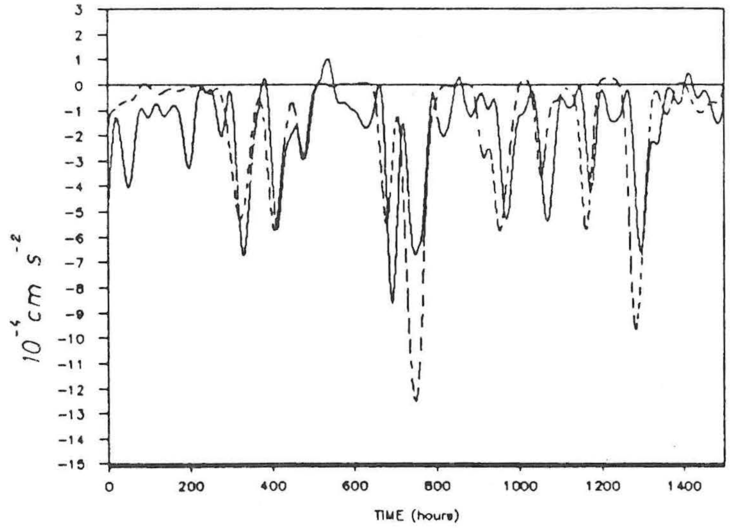

Fig. 6. Time-series of the expression "du/dt - fv" (solid line) and the east wind stress term (dashed line) for the station C at the depth of 30 m

layer of the station I and in the bottom layer (30 m) of the station C. This correlation coefficient is even higher than the coefficient between currents at different depths of the same station. This suggests that the east current component or the inflowing current at 30 m of the station C represents to a large extent, a compensatory flow to the surface flow at the station I. This is probably related to the condition that the transport through the bay inlet in each moment should be zero on the time scale of these low frequency current variations.

Table 2. Correlation coefficients between currents for different stations

CORRELATION COEFFICIENTS	MEANS
EC5, EC30 = -0.345	
EC5, EI5 = 0.152	N - N-COMPONENT
EC30, EI5 = -0.714	E - E-COMPONENT
NC30, EI5 = -0.612	5 - 5 METER DEPTH
NI30, EC5 = 0.361	30 - 30 METER DEPTH
EI30, EC5 = -0.361	C - ČIOVO
EI5, EI30 = 0.623	I - INSTITUT

Statistically significant correlation coefficient is also obtained between the north current component at 30 m depth of the station C and the east component at 5 m depth of station I. This high correlation is the consequence of the fact that both north current component at 30 m depth of the station C and the east component at 5 m depth of the station I, are related to the same wind stress component; former via a friction balance and latter via an Ekman balance:

Station I (5 m): $x = \rho r\, u_{I5}$

$$\Rightarrow u_{I5}\ \alpha\ v_{C30}$$

Station C (30 m): $-fv_{C30} = x/\rho h$

The letter r stands for the linear friction coefficient, f is a Coriolis parameter, while h is a watter depth. Subscripts c30 and I5 denote 30 m level at the station C and 5 m level at the station I, respectively.

Wind and current time-series were sub-sampled by centring the filter at noon of each day. The typical pattern of the wind generated water exchange through the bay inlet is then obtained by selecting current data for all synoptic situations with the northeast (bora) and southeast (jugo - sirocco) winds for the filtered wind speeds exceeding the value of 5 m/s. The two winds are considered the most frequent winds in the area during the winter (Makjanić, 1978). Five situations with the southeast and two situations with the northeast wind were identified. Distribution of the east current component in the vertical cross - section of the inlet are presented schematically (Fig. 7a-g) taking into account the measured data at the current meter depth. Certainly, these are only rough approximations of the wind forced water exchange pattern in the inlet of the Kaštela Bay. For a more reliable schemes a better horizontal and vertical resolution is needed i.e. more current meters and moorings should be used (at least three mooring along the transect with three current meters each).

In all the cases with the southeast wind the inflow appears along the northern shore of the inlet (station I), while the outflow is mainly present in the bottom layer along the southern shore (station C). From the schematic presentation of the distribution of the in- and outflow, one can also see that the line of the zero flow lies rather close to the depth of the surface current meter at the station C. This can, therefore, explain weak low-frequency current variations and their poor correlation with the wind forcing observed at that level.

During the northeast wind episodes, the outflow prevails over the entire surface layer of the vertical cross section in the inlet. The compensatory inflow appears in the bottom layer. Unfortunately, only two situations with the northeast wind were

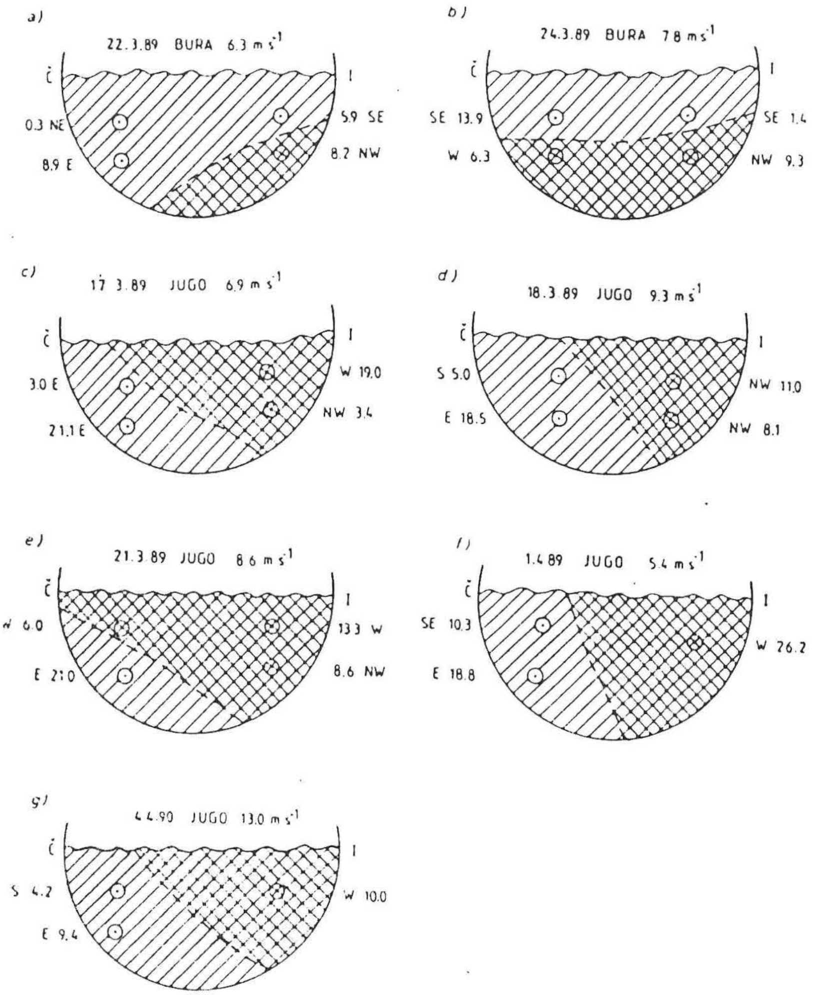

Fig. 7. Schematic presentation of the east (inflowing) current component in the vertical cross-section of the inlet of the Kaštela Bay. Numerical values of the low-pass current and wind velocities are also given

available and the obtained scheme is not as representative as it is the case with the southeast wind.

Therefore, during the northeast wind episodes the shear in the current field is prevalently vertical. On the other hand, during the southeast wind events it has an appreciable horizontal component, i.e. there is also a curl in the current field. However, during both wind episodes in the central part of the inlet, the distribution of the inflowing current component along a single vertical line displays a structure similar to the first baroclinic mode with one zero-crossing. Above the zero-crossing the outflowing current dominates during the northeast wind episodes, while during the southeast wind inflowing current appears. This wind forced current structure along the vertical axis was documented in some previous studies (Gačić, 1983; Gačić *et al.*, 1987).

CONCLUSIONS

The analysis of current data in the inlet of Bay of Kaštela has shown that the response to the wind forcing can be successfully described in terms of the linear dynamics. The surface inflowing current in northern part of the inlet can be represented by the friction balance i.e. the current response to the wind forcing can be described as a series of steady states in which the bottom friction balances the wind stress. On the opposite side of the inlet, the inflowing current in the bottom layer represents a compensatory flow to the surface wind induced flow to satisfy the boundary condition of the zero transport through the bay inlet.

The analysis of the wind induced flow pattern in the vertical cross section of the inlet shows that this pattern depends on the wind direction. During the southeast wind episodes, the shear in the current field has appreciable horizontal component, while during the northeast wind events, the vertical shear prevails.

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UTJECAJ VJETRA NA STRUJE U VRATIMA POLUZATVORENOG BAZENA (KAŠTELANSKI ZALJEV, JADRANSKO MORE)

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KRATKI SADRŽAJ

Analizirani su rezultati mjerenja struja u vratima Kaštelanskog zaljeva te njihova zavisnost o lokalnom vjetru. Promjene u strujnom polju su objašnjene linearnom dinamičkom ravnotežom. Uz sjevernu obalu vrata u površinskom sloju strujanje se u prvoj aproksimaciji može opisati ravnotežom člana tangencijalne napetosti vjetra i člana pridnenog trenja. S druge strane vrata u pridnenom sloju strujanje predstavlja

kompenzaciju površinskom ulaznom strujanju izazvanom vjetrom.

Analizirana je raspodjela ulaznog strujanja u poprečnom vertikalnom presjeku u zavisnosti o smjeru vjetra. U situacijama sa jugoistočnim vjetrom smicanje u strujnom polju ima i horizontalnu komponentu tj. vrtložnost je različita od nule. Sjeveroistočni vjetar međutim izaziva strujanje u vratima zaljeva kod kojega je smicanje pretežno vertikalno.