A COMPARATIVE WIND TUNNEL STUDY OF ENERGY HARVESTING FROM GALLOPING AND WAKE GALLOPING OF SQUARE PRISMS

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INTRODUCTION

We consider transverse galloping of square prisms flexibly mounted in a wind tunnel. Classical galloping occurring on a single flexible prism is a well known aeroelastic instability in which the external flow imposes an added negative damping to the structure [1]. Beyond a critical velocity, this negative added damping becomes larger than the structural damping so that transverse motion is triggered by any initial perturbation, leading to limit cycle oscillations (LCO).
When another prism is mounted upstream, depending on the relative distance between both prisms, the downstream prism is submitted to the wake of the upstream one. Such a stationary wake, *i.e.* the mean velocity deficit profile, can generate also unstable aeroelastic effects like added damping or added stiffness. This mechanism is traditionally called wake galloping.
In the last decade, the idea of using galloping oscillations in order to harvest energy from a flow has emerged [2-5]. However experiments remained relatively rare by comparison with analytical or numerical investigations.
In this paper we use square prisms, flexibly mounted in a wind tunnel and an energy harvester. The study is devoted to the comparison between a single prism, using classical galloping, and the same prism encountering wake galloping by means of another prism at rest and fixed upstream. It is an extension of a previous study [6] where the single prism was investigated.

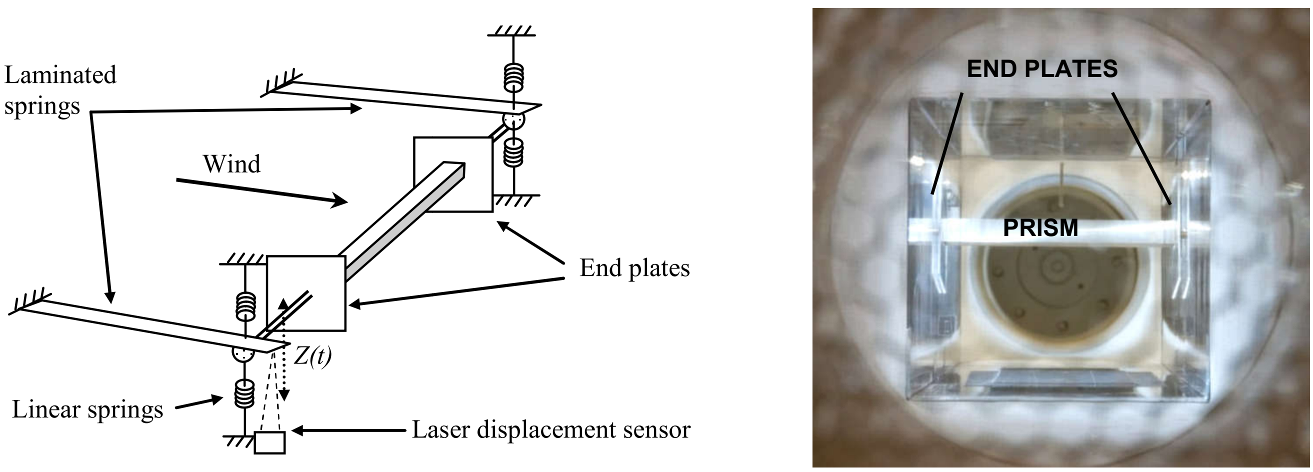


Figure 1. Experimental setup schematic for galloping (left) and picture taken through the inlet of the wind tunnel (right), single prism configuration

EXPERIMENTAL SETUP

Tests have been performed in an Eiffel open-loop wind tunnel with a square closed test section. The detailed description of experimental techniques can be found in [6] and only main points are recalled here with new information concerning the upstream prism.
The moving prism model almost span the width of the test section as shown figure 1. It is equipped with two end plates to keep the airflow as two-dimensional as possible. It is elastically supported in order to allow a one-degree-of-freedom transverse motion *Z(t)*. Structural parameters were identified under zero-wind velocity and presented in Table 1. f is the natural frequency of the prism motion, m the mass per unit length, and $S_c = 2m\eta/\rho D^2$ the Scruton number with η the structural reduced damping.

The upstream prism, at rest, has a section identical to the moving one. It is fixed between wind tunnel walls. Preliminary tests were performed in order to find a relative position of prisms which was considered efficient. The resulting distance between prisms is presented in Figure 2 and Table 1. Only one position is presented in this study therefore it is not absolutely ensured that this position is optimal: however the preliminary tests were considered satisfactorily.

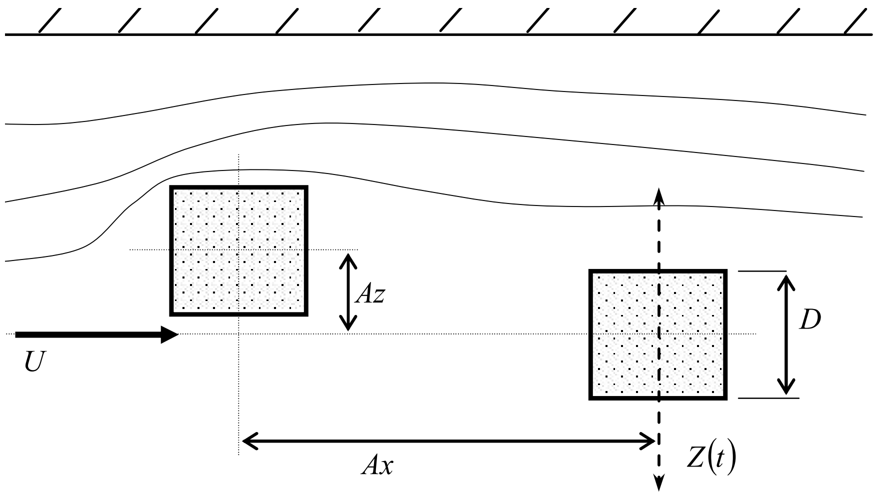


Figure 2. Geometric details of the studied prisms and notations.

TABLE 1 - Structural parameters of the prism

D (m)	Span (m)	*f* (Hz)	*m* (kg/m)	*Sc*	*Ax/D*	*Az/D*
0.0171	0.17	5.9	2.00	21.5	2.63	1.17

An energy converter consisting in a coil-core and magnets ensemble is used to produce electrical current which is dissipated in a calibrated variable load resistance *R* as shown Figure 3. A calibrated decade box is used for this resistance. The magnets are mounted on the moving prism while the coil-core is fixed. More detailed can be found in [6].

Apart the wind tunnel velocity *U* and standard environmental parameters, measurements are the prism oscillation amplitude *Z(t)* and the produced voltage *V(t)*. RMS values computed from these time histories are the final result. All tests and records are performed in stationary conditions after the transient regime that follows any change in a parameter of the system such as wind velocity or load resistance.

It is then possible to obtain the electrical power extracted from the flow, i.e. $P_e = {V_{RMS}}^2/R$. The power of the wind is determined by taking the surface swept by the prism during its motion, which gives $P_w = \frac{1}{2}\rho\, E\,(D + 2\, Z_{rms})U^3$ where E is the span of the prism.
Note that some authors take the surface of the prism only to compute this wind power: this may lead to very different results for the global efficiency of the system, defined as the ratio between both powers P_e/P_w.

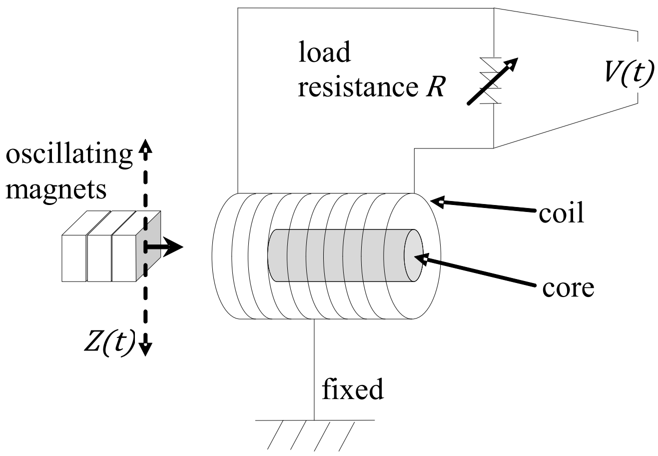


Figure 3. Principle of the electric energy harvesting device

RESULTS

We first make tests with the energy harvest not activated by setting the load resistance to infinite. The comparison between the LCO amplitude of the two kinds of galloping is presented Figure 4 versus reduced velocity.

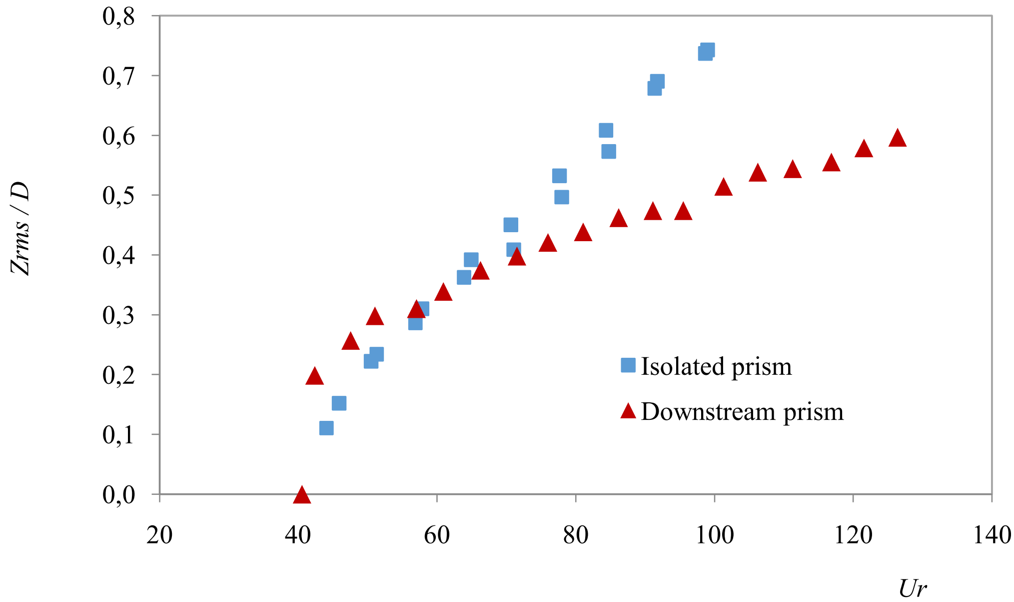
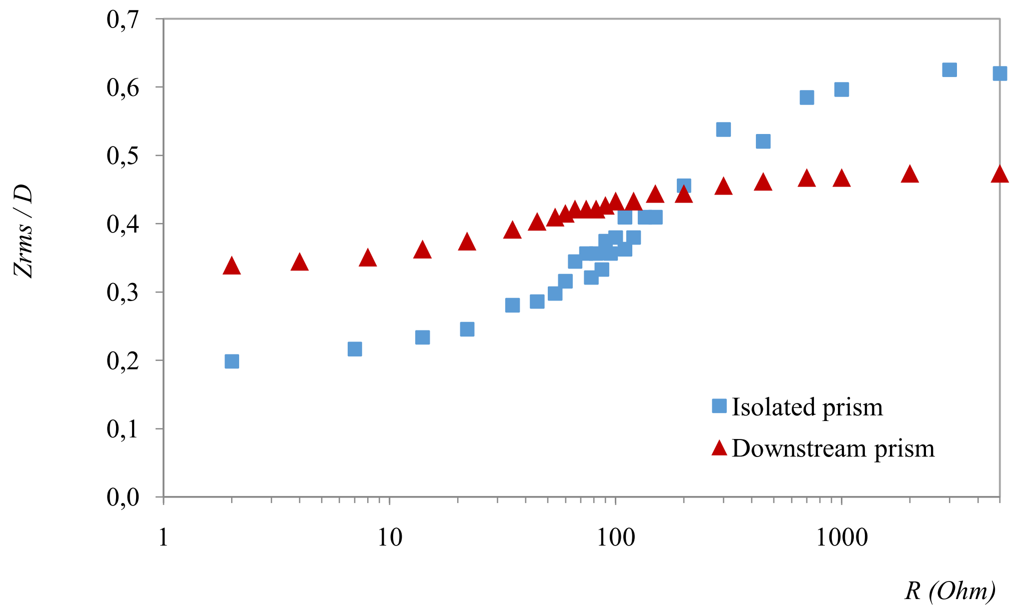


Figure 4. LCO amplitude at $R = \infty$ (energy harvest not activated) versus reduced velocity

Both oscillations start beyond $Ur = 40$ and amplitude grows with reduced velocity. At high values the wake galloping response is lower than for the single prism: it is an effect of the upstream prism wake that limit the LCO amplitude due to the velocity deficit region reached by the moving prism.

Effect of the load resistance

The effect of the load resistance is studied by varying the resistance value thanks to the decade box. The reduced velocity is fixed first at a relative high value, *Ur* = 89, which showed previously different LCO amplitudes. The series of tests start with high load resistance which is decreased. Each records is about one minute long in stationary conditions.



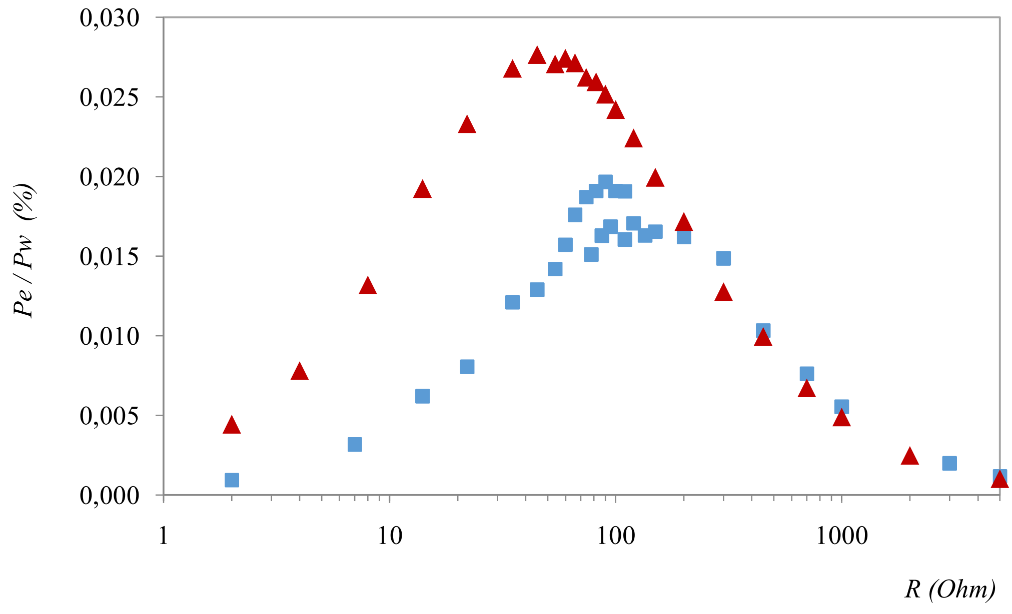


Figure 5. LCO amplitude (top) and efficiency (bottom) at *Ur*=89 versus load resistance

Results are presented in Figure 5 and show that wake galloping, although generating lower Limit Cycle Oscillation (LCO) amplitudes at the beginning, is more robust than standard galloping for energy harvesting. This is due to the LCO amplitude that remains higher when energy is harvested.
Moreover the optimal load resistance, at which the efficiency is the highest, is slightly different in both cases. It is lower in the wake galloping case, passing from 90 Ω for single prism to 58 Ω for the wake galloping case.

Note that the better result obtained with the wake galloping case is partially due to the energy conversion setup used in this study, see [6], which optimal efficiency is around 35 Ω: energy conversion is then better because the wake galloping case has its optimal resistance closer to that of the conversion setup.

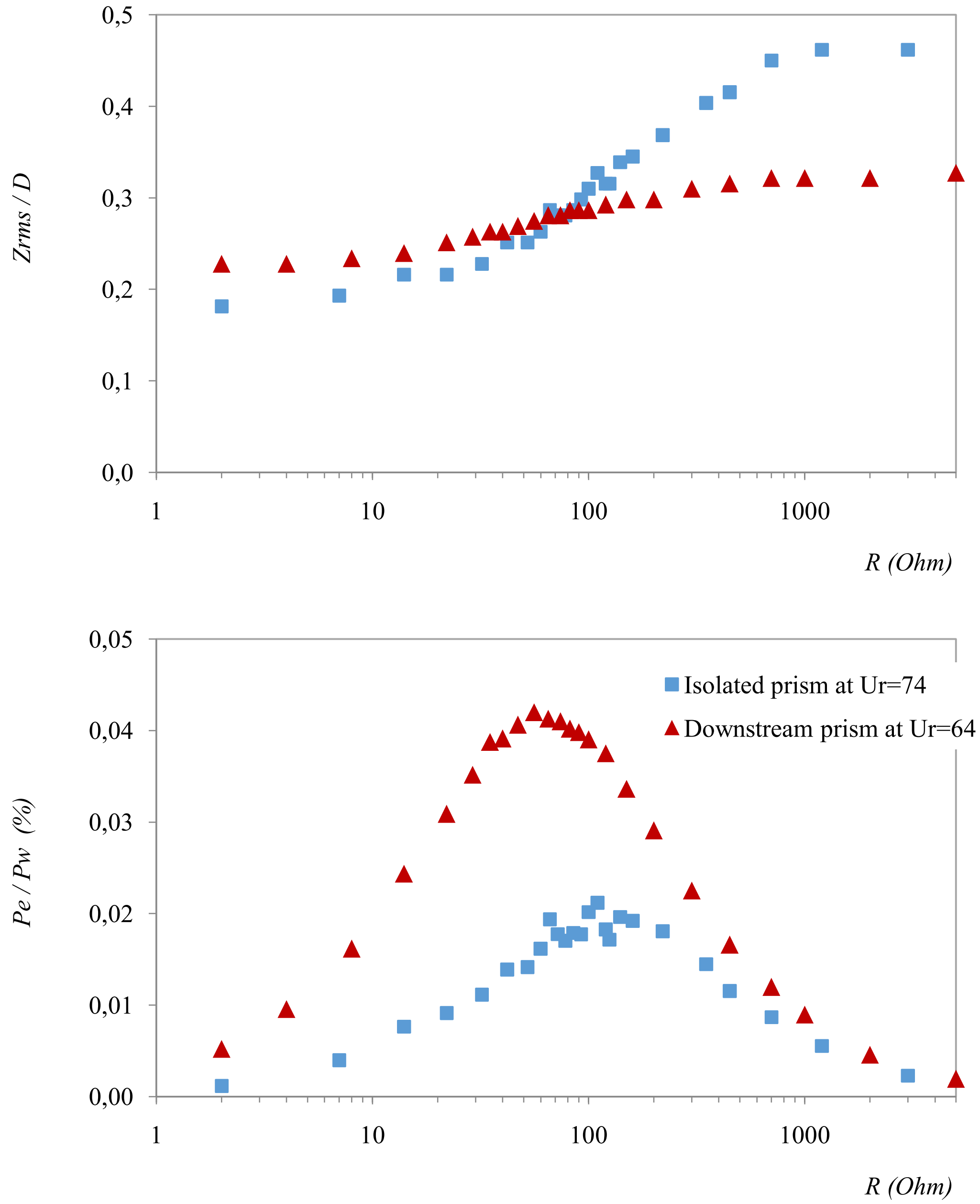


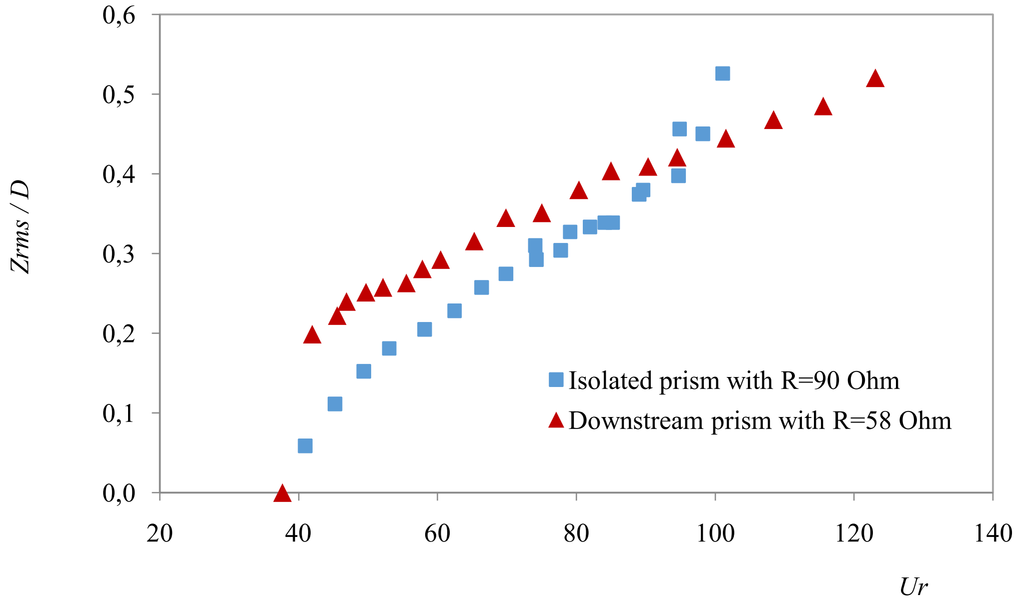
Figure 6. LCO amplitude (top) and efficiency (bottom) at small reduced velocity versus load resistance

The robustness of the wake galloping is also put into evidence at lower reduced velocity as shown in Figure 6. In these tests the LCO amplitude for the downstream prism remains almost constant, but not very high, when energy is harvested. However this leads to better efficiencies than at high reduced velocity.

Remember also that the wind power is computed here including the surface swept by the moving prism: yet the downstream prism is found more efficient than the isolated prism, although its LCO amplitudes are larger for small velocities. This better efficiency is obtained not only by its capability of remaining the motion amplitude but also from the aeroelastic behaviour of the setup.

Effect of the reduced velocity at optimal load resistance

In this series of measurements the load resistance is fixed at its optimal value found previously, *i.e.* at R=90 Ω for the single prism and R=58 Ω for the downstream prism. The wind velocity is the variable parameter.
The results are shown in Figure 7 where we observe a very different behaviour for the two kinds of galloping. For the single prism the efficiency first increases with the velocity and reaches a plateau around *Ur* = 70 and remains almost constant beyond that value. We cannot really define an optimal value.



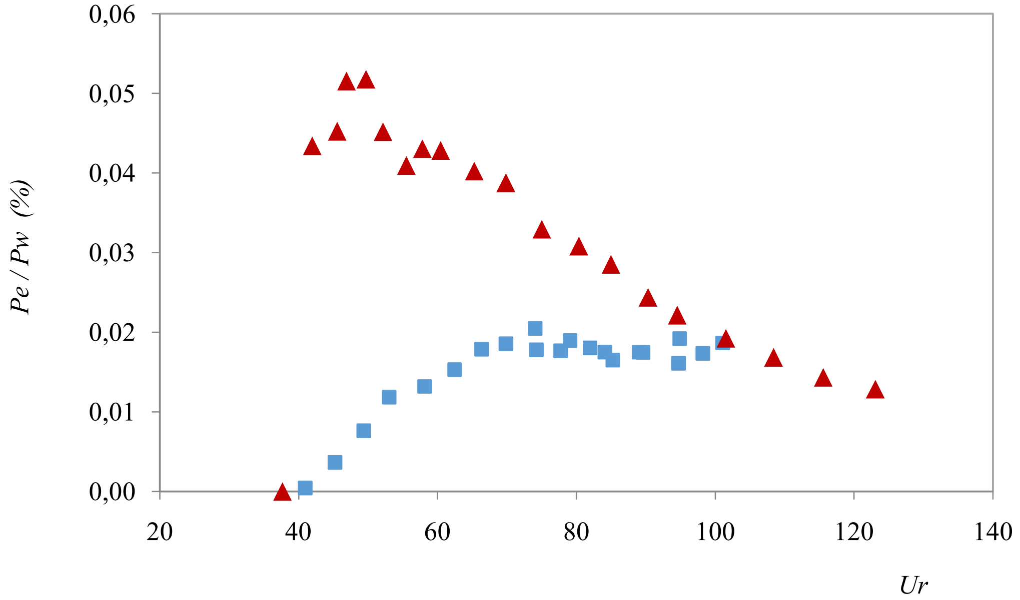


Figure 7. LCO amplitude (top) and efficiency (bottom) around best load resistance versus reduced velocity

But for the wake galloping case, the efficiency increases very rapidly with the velocity, starting at the critical value *Ur* = 41 and reaching a maximum around *Ur* = 50. Beyond that value, the efficiency decreases progressively. In this case, there is clearly an optimal reduced velocity that maximizes the efficiency: this optimal velocity is surprisingly relatively small, about 1.25 times larger than the critical velocity.

CONCLUSION

A comparison of harvesting energy with classical galloping of a square prism and wake galloping of the same prism has been performed by experiments in a wind tunnel. Results show that the behaviour is different and particularly an optimal reduced velocity exists for the wake galloping case, while this seems not the case for the classical galloping.

In the next step, the comparison of the wake galloping case should be pursued by including the single prism inclined by 10° from the wind flow, as presented in a previous study [6], because the behaviours of these two kinds of galloping look similar, possibly because of the asymmetry of the flow.

REFERENCES

[1] Blevins, R. D., 2001. Flow-Induced Vibrations. Reprint of the 1990 second edition, Krieger Publishing Company, Malabar, Florida.

[2] Barrero-Gil, A., Alonso, G., Sanz-Andres, A., 2010.Energy harvesting from transverse galloping. *J. Sound and Vibration* 329, 2873-2883.

[3] Ewere, F., Wang, G., Cain, B., 2014. Experimental investigation of galloping piezoelectric energy harvesters with square bluff bodies. *Smart Materials and Structures*, 23, 104012.

[4] Vicente-Ludlam, D., Barrero-Gil, A., Velazquez, A., 2014. Optimal electromagnetic energy extraction from transverse galloping. *J. Fluids and Struct.* 51, 281-291.

[5] Kiwata, T., Nakajima, A., Mizukami, S., Ueno, T., Kono, T., 2016. Effect of Angle of Attack on Vibration Characteristics of a Cantilevered Prism for Energy Harvest. *First International Symposium on Flutter and its Application*, Tokyo, 15-17 May, Paper ISFA-5R02.

[6] Hémon P., Amandolese X., Andrianne T. 2017. Energy harvesting from galloping of prisms: A wind tunnel experiment. *J. Fluids and Struct.* vol. 70, 390-402.