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Floating Offshore Wind Turbines Oscillations Damping

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Abstract. This article deals with the modelling and control of oscillations that appear on floating offshore wind turbines (FOWT). First, these offshore wind energy systems, located in deep waters, are described and the modeling approach is presented. Secondly, the traditional structural control strategies based on tuned mass-damper (TMD) systems for oscillations reduction are complemented with a passive mechanism called inerter in order to improve the performance of the structural controller. This work is based on a previous work by the authors in which the inerter was located in parallel to an existing TMD in the nacelle of the FOWT. In this work, the inerter is located between the tower and the barge and results are compared to those obtained previously showing better performance. The results here presented are promising in terms of oscillations damping, both in amplitude and frequency, and constitute preliminary results of the ongoing current research of the authors.

Keywords: Modelling, Control, Wind turbine, Floating Offshore wind turbines, marine energy, renewable energy.

1 Introduction

In recent years, there have been several technological advances in renewable energy systems. Although wind turbines do not have 100% efficiency, fossil fuel efficiency is as well below this figure. At the moment, wind energy is a mature technology but suitable locations for wind farms are by some setbacks such as the large amount of land they need and it is not rare to find residents complaining about their location. A suitable solution for these appearing problems are the Offshore Wind Turbines (OWT), which are located on the coast instead of on land. The most wide spread type of OWT are the fixed-bottom type. In general, the coast line has high energy winds, OWT are getting bigger and more power is generated achieving in this way lower damage to environment, but still there is great pressure to place these farms far from shore so as to not be so visible. Also, some coastal waters are relatively shallow and most of the greater potential wind energy resources are in waters exceeding the OWT depth.

Floating Offshore Wind Turbines (FOWT) seem to be a very good alternative in these cases. A floating wind turbine is an OWT mounted on a floating structure that allows the turbine to generate electricity in water depths where fixed foundation turbines are not feasible. FOWT are subjected to several adverse conditions: dynamic loads such as waves, strong winds and currents cause mechanical loads due to the coupled wind and waves. The FOWT cost is primarily associated with the floating foundation stabilization for unwanted oscillations, therefore, heavy loads and structure's fatigue reduction seems to be one of the main issues. All these may reduce the platform productivity, compromise safety, affect the utility of the structure and increase maintenance costs.

Most of the control carried out at the nacelle has the objective to maximize the energy production, and the type of control approach will depend (in between several other factors) of the wind turbine operating regimes and wind speed at any given time. The nacelle control is out of the scope of this research, but it is convenient to remark that maximum energy control can induce unstable barge pitch motions and that in addition to this, waves, winds, currents may introduce oscillations in the FOWT system. Therefore, the control objectives in OFWT must satisfy a compromise between optimal energy harvesting and structure's oscillation mitigation.

Structural control, refers to any device or material used in a WT structure to either enhance damping or to generate forces to control the structural response. It has been an active area of research for the past two decades in civil engineering applications. Developing structural control strategies and applying those to wind turbines is a relatively new field of research.

This article deals with the design of a particular type of passive structural control applied to a benchmark FOWT model. It is based on a previous work of the authors and represents an advancement in terms of FOWT oscillations damping by passive means. The work is divided as follows: in section 2, the authors describe the dynamical model used to carry out the work here presented, it consists on three rigid bodies that contain a TMD in the nacelle to control unwanted oscillations. Section 3 contains the details of the classical structural control and introduces the specifications and dynamical characteristics of a passive mechanical device to be added to the existing structural control TMD methodology. Section 4 shows the simulations results obtained and section 5 discusses the results and gives some insight on further research in this area.

2 FOWT Modelling

The wind turbine used for this analysis is the National Renewable Energy Laboratory (NREL) 5-MW wind turbine, a diagram of the system is shown in figure 1. This is a widely accepted benchmark model [1]. It is a simplified nonlinear model of a barge-type of FOWT. In this case, hydrodynamic and aerodynamic forces (wave and wind loads) are not considered. This barge-type wind turbine was treated as a multi-body dynamic system.

In this model, the rigid bodies are the barge (platform), the tower, and the nacelle assembly with a tuned mass-damper system (TMD) composed by a mass, a spring and a damper. The rotor, generator, and gearbox dynamics were not considered in this analysis. For simplicity, the tower was treated as a linear rigid rotating

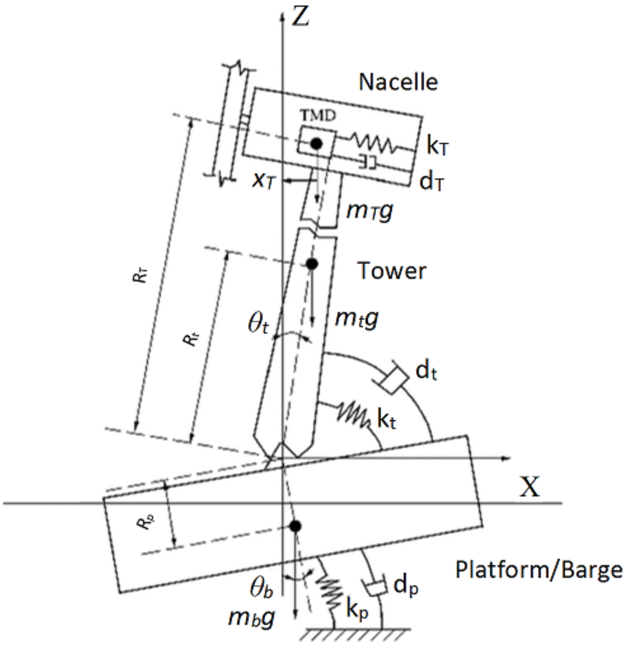

Fig. 1: Diagram of FOWT Model with a fore–aft TMD in the nacelle

beam hinged at the bottom of the tower [2]. The model does not include mooring lines as it has been found that these do not have a major impact in the tower oscillations or fatigue compared with the dynamics of the three degrees of freedom under study in here ([3], [4]).

The nonlinear dynamic equations of this system can be derived from first principles using a Lagrangian approach. Linearization by small angle approximations is then carried out because it is not usual for the barge pitch to exceed 10 degrees even in the heaviest wind and wave loadings ([2],[5]), the reader is referred to [6] for a complete derivation of the linearized equations of motion.

The linearized dynamics are represented by a set of three second order differential equations containing the corresponding terms for the restoring and damping sea hydrodynamic forces - these are modelled as rotational spring k_b and damper d_b attached to the barge. The tower flexibility and damping are represented by a rotational spring k_t and damper d_t respectively. A passive structural control system is implemented by means of a TMD located in the nacelle, it is assumed to move on a frictionless track along the fore-aft direction. The structural control spring k_T and damping d_T coefficients are assumed constant in the same way as in the limited degree of the free model represented by [6].

There will be three degrees of freedom under study: the barge pitch θ_b, the tower fore-aft angular displacement (bending) θ_t, and the TMD mass translation

x_T. Other DOF′s such as the rotor yaw motion or the generator rotation were not considered in this analysis.

Taking into account the above description, the linearized equations of motion are as follows:

$$\begin{aligned} I_t\ddot{\theta}_t = m_t g R_t \theta_t - k_t(\theta_t - \theta_b) - d_t(\dot{\theta}_t - \dot{\theta}_b) - m_T g(R_T\theta_t - x_T) \\ -k_T R_T(R_T\theta_t - x_T) - d_t R_T(R_T\dot{\theta}_t - \dot{x}_t) \end{aligned} \tag{1}$$

$$m_T\ddot{x_T} = k_T(R_T\theta_t - x_T) + d_T(R_T\dot{\theta}_t - \dot{x_T}) + m_T g\theta_t \tag{2}$$

$$I_b\ddot{\theta}_b = -d_b\dot{\theta}_b - kb\theta_b - m_b g R_b\theta_b + k_t(\theta_t - \theta_b) + d_t(\dot{\theta}_t - \dot{\theta}_b) \tag{3}$$

It is important to note:

- Most of the existing dynamical models in the civil engineering field use translational equations instead of rotational, but in the case of FOWT systems the moments induced by the gravity force need to be considered.

- Although usually FOWT barge oscillations do not exceed 10, still these are larger than those in buildings.

The main parameters for this model are as follows: barge an tower inertias I_b=$1.77\cdot 10^9\ kg\cdot m^2$, $I_t = 3.34\cdot 10^9\ kg\cdot m^2$, the masses of the three rigid bodies: $m_b = 5452000\ kg$, $m_t = 697460\ kg$ and $m_T = 4\cdot 10^4\ kg$. The tower flexibility and torsion properties are represented by a spring and damper of values $k_t = 1.25\cdot 10^{10}\ kg\cdot m^2/s^2$ and $d_t = 2.87\cdot 10^7\ kg\cdot m^2/s$. The barge flexibility and torsion are $k_b = 1.89\cdot 10^9\ kg\cdot m^2/s^2$, $d_b = 5.12\cdot 10^7\ kg\cdot m^2/s$. The barge center of mass is at $R_b = 0.281\ m$ and the tower center of mass is at $R_t = 64\ m$ from the bottom of the structure (axis origin $Z = 0\ m$). The TMD in the nacelle is at $R_T = 90.6\ m$ from the bottom. The TMD spring and damper coefficients are $k_T = 2.8805\cdot 10^4\ kg\cdot m^2/s^2$ and $d_T = 1.0183\cdot 10^4\ kg\cdot m^2/s$ respectively.

3 Structural control design

In the last years there have been several efforts tackling different control approaches with the objective of reducing oscillations and loads on floating offshore wind turbines ([7], [8], [9], [10], [11], [12]). These methods, are not based in structural control ideas, instead, the proposed control ideas were based on performing pitch agle control on the blades at the rotor level.These methods, although effective are known to pose two major problems: They demand a high level of blade pitch actuator usage (blade roots may suffer fatigue loads) and some of these control desings may not be viable due to unacceptably large absolute loads. In fact, for some FOWT, even larger load and motion reductions are needed, therefore, alternative control methodologies like structural control approaches (usually known for their civil engineering applications) are suggested (see [13] and references within).

3.1 TMD

Vibration reduction can be achieved in various ways, depending on the problem; the most common are stiffening, damping and isolation. Stiffening methods consist on a shift of the structure's resonance frequency beyond the frequency band of excitation. Damping methods provide a reduction of resonance peaks by dissipating the vibration energy and isolation prevents the propagation of disturbances to sensitive parts of the structure. One of the classical methods for reducing vibrations in mechanical systems are the passive TMD (Tuned Mass-Damper), this is a combination of a spring, damper and mass, that translate longitudinally and reduce structural vibrations. The spring force is proportional to the relative displacement of its two ends, and the damper force is proportional to the relative velocity of its two ends or attachment points. In order to successfully achieve significant damping of the system's oscillations, the TMD should be adequately tuned: this is, to find the adequate parameters, or optimal, such that the tower's oscillations are reduced. TMD methods became popular in the $60'$s-$70's$ in buildings, bridges, towers and industrial infrastructures to control the oscillations produced by the wind. When these passive TMD methods are applied to FOWT, very often do not achieve complete tower oscillations produced by waves and wind.

3.2 Inerter

This subsection presents the basic properties of an Inerter, this is a mechanical passive device designed by [14]. Since its introduction (firstly known as J-Damper) within the context of racing vehicles [15] it has become very popular and has been quickly adopted in the civil engineering community ([16]-[18]) and control systems engineers within the field of oscillation damping for vehicles such as racing motorbikes ([19]-[21]) or trains [22], just to cite a few.

An ideal Inerter is defined to be a mechanical one-port device such that the equal and opposite force applied at the nodes is proportional to the relative acceleration between the nodes, i.e., it is a physical device such that the relative acceleration between its endpoints is proportional to the applied force:

$$F = b(\ddot{x}_1 - \ddot{x}_2) \tag{4}$$

The constant b is known as inertance and its units are kilograms. The ideal inerter can be approximated in the same sense that real springs, dampers, inductors, etc. approximate their mathematical ideals.

3.3 Inerter between the Tower and the Barge

The control designed in this work is based on a previous work of the authors [24] which consisted in designing a passive network combining parallel spring, damper and inerter, in the nacelle (TMDI). Results showed the benefit of including such a passive device in the nacelle since the tower and barge platform oscillations were damped at a faster rate than the case of the baseline TMD. In here, a different configuration is proposed: an inerter will be fitted between the tower and barge instead. Figure 2 shows the diagram of the model to be used in this work, when an inerter is fitted between the tower and the barge platform.

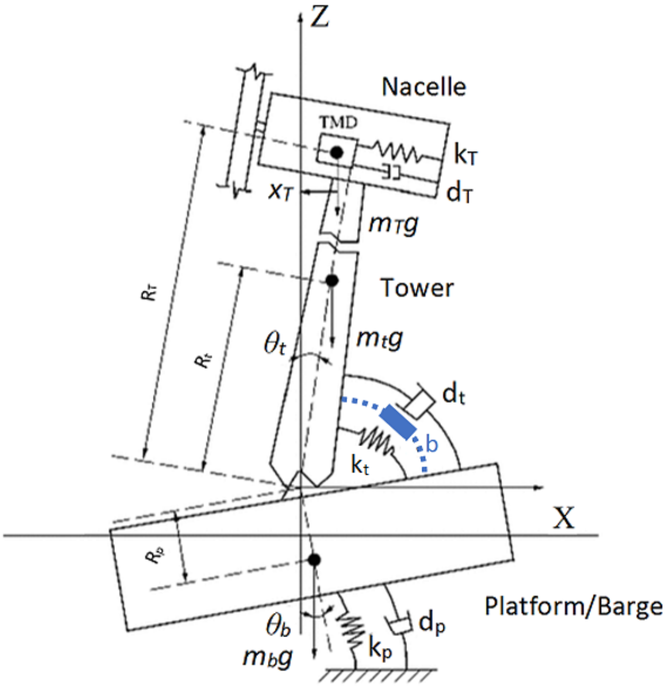

Fig. 2: Modified diagram of FOWT model with an inerter between the tower and the barge (platform).

The corresponding equations of motion should then be modified to account for the inerter force existing between the tower and barge (proportional to the relative acceleration between both rigid bodies).

$$F = b(\ddot{\theta}_b - \ddot{\theta}_t) \tag{5}$$

Therefore, equations (1) and (3) become now:

$$\begin{gathered} I_t\ddot{\theta}_t = m_t g R_t \theta_t - k_t(\theta_t - \theta_b) - d_t(\dot{\theta}_t - \dot{\theta}_b) - m_T g(R_T\theta_t - x_T) \\ -k_T R_T(R_T\theta_t - x_T) - d_t R_T(R_T\dot{\theta}_t - \dot{x}_t) + b(\ddot{\theta}_b - \ddot{\theta}_t) \end{gathered} \tag{6}$$

$$I_b\ddot{\theta}_b = -d_b\dot{\theta}_b - k_b\theta_b - m_b g R_b \theta_b + k_t(\theta_t - \theta_b) + d_t(\dot{\theta}_t - \dot{\theta}_b) - b(\ddot{\theta}_b - \ddot{\theta}_t) \tag{7}$$

4 Simulations and results

4.1 Model validation

Once the dynamical model was written in the form (1)-(3), these equations were programmed in Matlab and compared to the previously existing benchmark model [1] for validation. Simulations were done for the same initial conditions and system′s parameters. Figure 3 shows the barge angular displacement, tower traslational displacement (in mm) and the TMD traslational displacement. The results show that

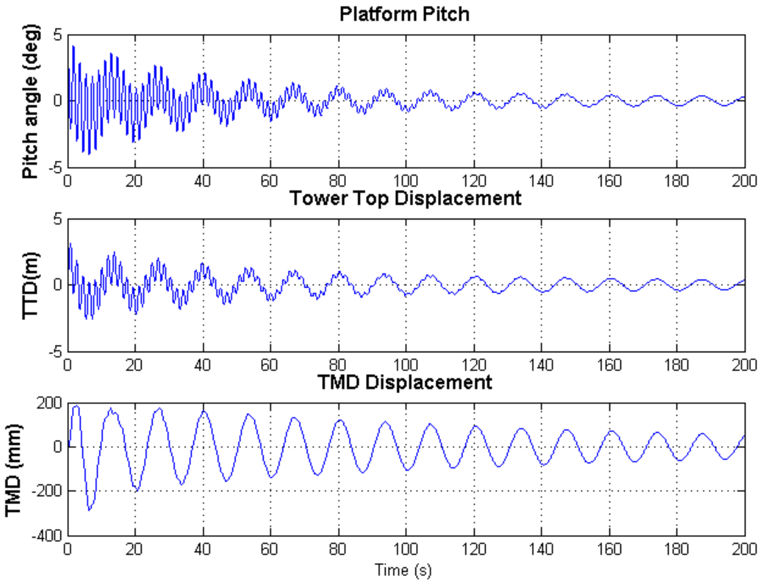

Fig. 3: Response of the system's dynamics with TMD as structural control.

the model implemented in Matlab is in agreement with the benchmark model, and therefore it is correct. This now can be used to introduce some changes accor4ding to equations (6)-(7) and proceed with further simulations.

4.2 Structural control simulations

Once the model has been validated, first, the force of an inerter is included in parallel to the existing TMD control devices. Simulations are carried out in Matlab for the choice of initial conditions in order to show the improved performance of the modified passive network.

Figure 4 shows the response of each of the three rigid bodies when the structural control consists of a TMDI, this is: a combination of a parallel spring, damper and inerter in the nacelle. Similarly to [23] and [24]) the value of the inertance ($b = 10000$ kg) has been chosen according to a reduction of amplitude requirement only, being possible to adopt more sophisticated methods for optimization of this value.

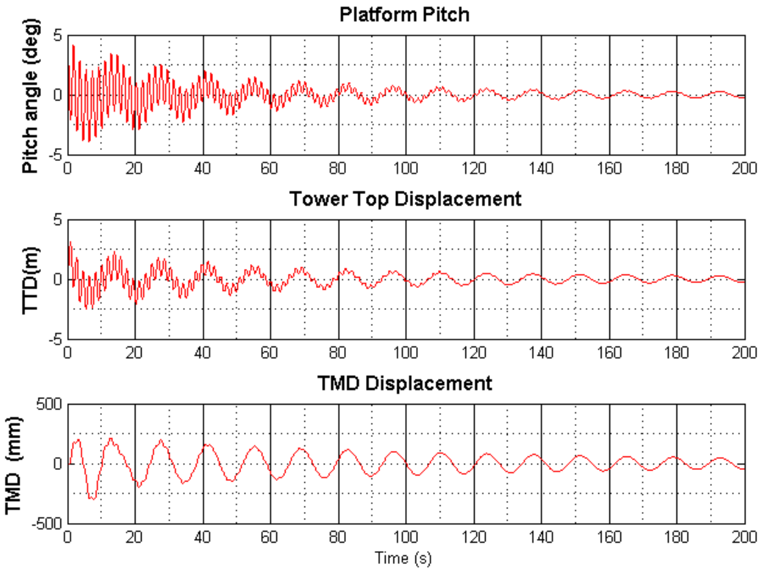

Fig. 4: Response of the system's dynamics with TMD and Inerter as structural control in the nacelle

Figure 5 clearly shows the advantages of using this approach. The figure shows the comparison of responses of the three rigid bodies when the nacelle contains a baseline TMD without inerter (blue doted line) and two responses when a TMDI in the nacelle in parallel to the TMD, the cases shown are for inertance values $b = 10000$ kg (red dashed) and $b = 50000$ kg (black solid). It is seen how the presence of an inerter in the nacelle improves the oscillation damping. For larger values of the inertance, the faster is the decay rate. These results are in accordance to those presented recently by the authors in [23] and [24].

On the other hand, whilst the nacelle is kept as in the initial case fitted with a TMD structural control, an inerter can located between the tower and the barge (diagram figure 2) exerting a force as in (5). Figure 6 shows the system states$'$ time history when the dynamical model has been modified to accomodate the force of an inerter between the tower and the barge as in equations (6)-(7). The time history of the states shows a clear improvement on the responses in both the tower top and the barge pitch oscillations: when an inerter is fitted between the tower and the barge, the rate of decay is faster and the system is stabilized in a shorter period

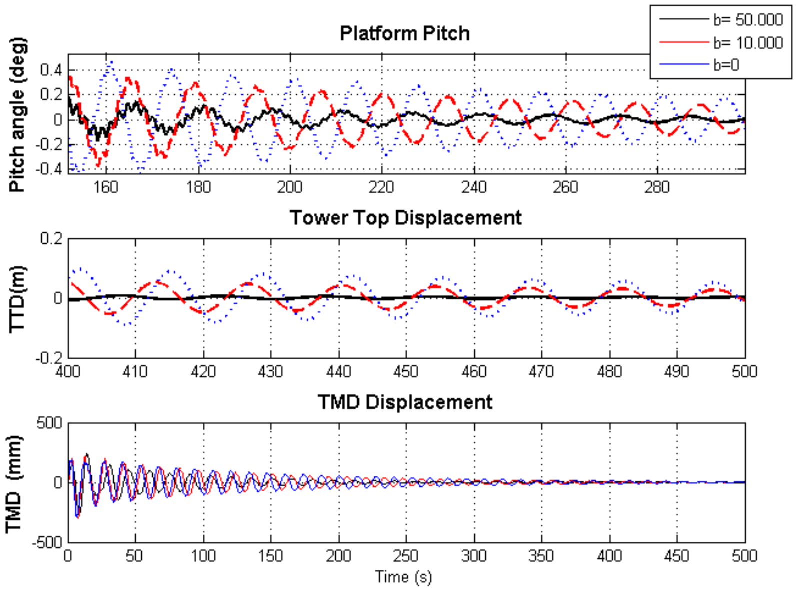

Fig. 5: Comparison between system response with a TMD (blue dotet, TMDI with inertance b=10.000 (red dash) and TMDI with inertance b=50.000 (black solid) in the nacelle.

of time. In this case, and mentioned before, the value of the inertance has been chosen to be b=10000 in both cases just for comparison purposes. A more realistic approach would be to consider various ranges of inertance values and take those into account. At the moment the authors are working on optimization methods for obtaining the best possible values for the inertance in both cases.

5 Conclusions

The work here presented deals with the problem of oscillations damping within the context of floating offshore wind turbines. These type of systems, due to its location in areas of deep waters, presence of large amplitude waves, strong currents and winds..etc, are subject to several external excitations that induce oscillations in the system. Power generation, therefore, is undermined by the oscillating nature of these systems and its hostile environment. Oscillations represent as well a source of fatigue and structural loads that could lead to system failure and ageing.

In this article, a passive mechanical device known as Inerter, has been included as complement to the existing structural control mechanism TMD. The control exerted by a standard TMD placed in the nacelle of the FOWT model, has been enhanced by including an Inerter between the tower and the platform barge.

Simulations carried out show the benefits of this new set- up, as oscillations

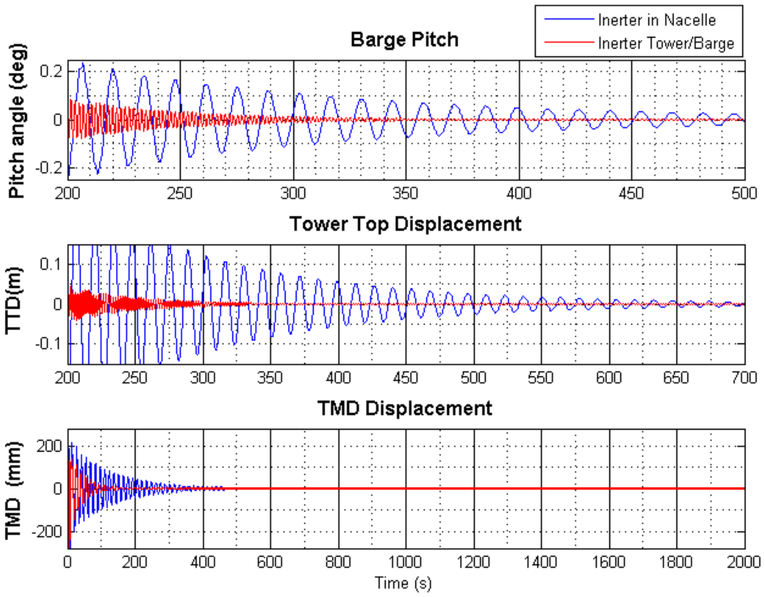

Fig. 6: Comparison between system dynamic response. TMDI (spring,damper and inerter parallel network) located in the nacelle (blue line) [24].TMD (spring and damper in parallel) in the nacelle and an inerter fitted between the barge and the tower (red line)

appearing on the barge pitch and tower top are mitigated in a shorter time when compared to the existing methods of classical TMD or TMD and Inerter in the nacelle only. Comparison to these previously existing results have demonstrated the improvement of the currently presented approach.

The choice of the inertance value, in this case has been ad-hoc as the interest in here was to show the benefits of this approach only. The authors are currently working on optimization methods for obtaining the best possible value of the inertance. These results will be presented shortly in a journal article.

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