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Adaptive Pneumatic Fenders for Extreme Off-shore Docking Operations

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ABSTRACT

Collisions with small service ships are serious dangers for offshore wind turbines. Installing of the adaptive torus-shaped pneumatic fender that surrounds wind turbine tower at water level constitutes one method of effective protection against such events. Innovative pneumatic fender proposed in this paper contains several internal air-chambers equipped with fast inflators and high-performance valves allowing for control of gas migration and release. The system can be adapted to various impact scenarios by adjusting the level of initial pressure in each chamber and by controlling transfer of compressed gas during impact. The paper presents numerical simulations of ship collision against wind turbine tower protected by adaptive fender conducted by means of FEM-based software. Several control strategies aimed at mitigating tower and ship response are introduced. Performed feasibility study proves that inflatable structure can effectively protect the wind turbine tower and the ship against serious damages.

Keywords: *Adaptive Inflatable Structures (AIS), pneumatic fenders, Adaptive Impact Absorption (AIA), offshore collisions, off-shore docking operations*

1 INTRODUCTION

Wind turbines are one of the main sources of renewable energy. Current wind energy capacity installed in the EU countries equals 84GW (as of end 2010) and provides energy production of 142TWh (4,2% of European demand) [1]. Moreover, the contribution of wind energy to a total energy production is still increasing and it is expected that installed capacity will exceed 200GW before 2020. The largest wind generators currently operating provide up to 5MW of power and the increase of their effectiveness is still required. This can be achieved by locating wind turbines in regions where the wind conditions are more beneficial, for instance in offshore regions, where the wind flows with higher and more constant velocity.

In offshore regions wind turbines are exposed to harsher environmental conditions. The main threats for offshore wind generators are very strong winds and ice loading in winter [2]. Typical method of reducing ice forces acting on a structure is using ice braking cones which serve as passive or semi-active tuned mass dampers as proposed by Kärnä et al [3] and Mróz et al [4,5]. Moreover, the concept of reducing the effects of strong wind gusts by using adaptive blade-hub connection controlled by magneto-rheological clutch was proposed [6]. Another threat is the possibility of large tanker vessel collision and the risk of resulting environmental pollution. The indications for the design of offshore wind turbines which reduces the probability of the tanker vessel damage were given by Lehmann et al [7,8]. Additional dangers for offshore structures are collisions involving small service ships which have to dock to wind turbine towers for the purpose of maintenance and monitoring. Such collisions occur especially often during rough sea conditions

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and can lead to a serious damage to both the wind generator tower and the ship. Therefore, an efficient system providing safety for docking operations is required. In this paper the concept of innovative adaptive torus-shaped pneumatic fender attached to the wind turbine tower is proposed and its feasibility is verified.

The introduced solution belongs to so called Adaptive Impact Absorption (AIA) approaches [9, 10] which overcome the disadvantages of classical passive energy absorbing structures. The essence of AIA is real-time adaptation of energy absorbing structures to actual impact loading by using system of sensors detecting and identifying impact in advance, hardware controllers and controllable dissipaters (the so-called structural fuses) which allow to execute optimal adaptation strategy during short period of impact. Nowadays, the design and practical realisation of AIA systems is possible due to a broad accessibility and low cost of functional materials and required electronic devices. Adaptive impact absorbing structures are based on miscellaneous adaptation techniques such as application of MR fluids or piezoelectric actuators.

The paper is based on the previous journal paper of the authors [11] where more details concerning modelling of the pneumatic fenders and development of the control strategies can be found. The theoretical background for fluid-structure interaction based modelling of adaptive pneumatic structures, as well as detailed analyses of dynamics and control of particular types of these structures (adaptive pneumatic cylinders, adaptive inflatable thin-walled barriers, flow-control based airbags and controllable valves) are presented in the doctoral thesis of the first author [12].

2 THE CONCEPT OF ADAPTIVE PNEUMATIC FENDER

As opposed to standard Yokohama-type fender (Figure 1a), the adaptive pneumatic structure proposed to be used for protecting offshore wind turbine against collisions of small ships is torus-shaped and surrounds the tower at the water level (Figure 1b,c). The fender may float on water and it may be partially submerged. The dimensions of the fender are limited to c.a. 2m in height and 1m in width due to requirements of fast inflation and pressure release during impact. Moreover, maximal operating pressure is arbitrarily confined to 20atm.

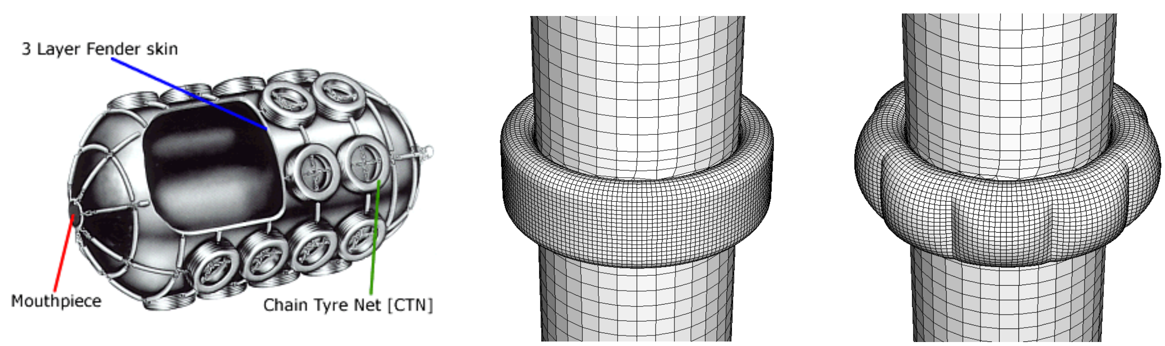

Figure 1 - Pneumatic fenders: a) standard passive Yokohama-type fender, b) deflated torus-shaped fender, c) torus-shaped fender with uniform inflation of all chambers.

The walls of the pneumatic structure can be made of rubber reinforced by steel fibres or any other material which provides high durability and allows for large deformations during impact of a ship. In order to achieve the possibility of better adaptation to various impact scenarios, the inflatable structure is divided into several separate air chambers located around the tower (Figure 1 and Figure 2). The exact design of the fender and the required internal pressures are determined by the range of possible impact energies and they will be precisely defined while considering the conditions for optimal impact absorption.

Proposed pneumatic fender is intended to be permanently inflated to a relatively low pressure which provides mitigation of ship impacts of small kinetic energy. Additional inflation is planned before any stronger collision. It is executed for each chamber separately by a compressor located inside the tower or, alternatively, by a fast-reacting pyrotechnic system. The pressure of gas increases a total stiffness of the fender, which thus counteracts movement of the ship more effectively. As a result, appropriately inflated structure allows to prevent direct collision between the ship and the tower and to avoid corresponding excessive forces and accelerations. The usage of compressed air causes that the proposed protective structure can be easily adapted to various impact energies and scenarios. Value of initial internal pressure can be adjusted and varied between the chambers according to ship velocity, its mass and the area of contact with pneumatic structure.

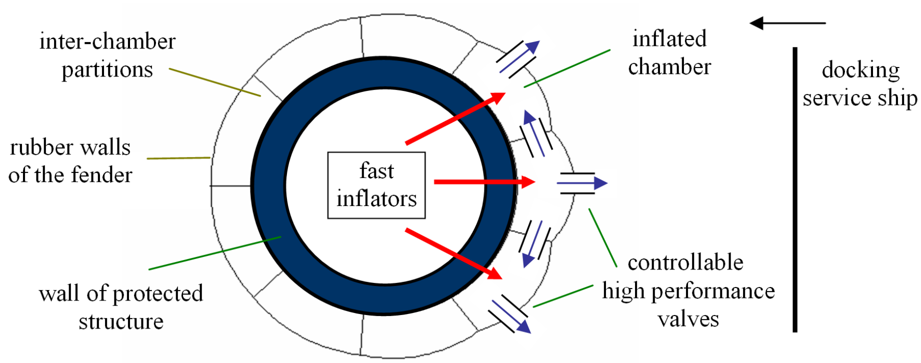

Figure 2 - Horizontal projection of the pneumatic fender protecting the tower.

During collision or docking of the ship controlled release of pressure is executed by opening controllable high performance valves. Such valves are mounted inside external walls of inflatable fender, as well as in internal inter-chamber partitions such that they enable the gas flow between the chambers and outside the structure. Release of pressure allows to control global stiffness of the pneumatic structure (resulting from stiffness of rubber and internal pressure) during the subsequent stages of impact. Consequently, total force acting on docking ship and its deceleration can be controlled and impact energy can be dissipated.

The purpose of applying pneumatic structure is to mitigate the response of both the ship and the wind turbine tower. In particular, the inflatable structure allows to minimise ship deceleration, to avoid ship rebound, to decrease stresses arising at the location of the collision and, finally, to mitigate tower vibrations.

3 NUMERICAL MODELLING OF SHIP COLLISION AGAINST THE TOWER

3.1 Three-dimensional model of ship collision

For the purpose of precise modelling of the influence of pneumatic fender and its properties on the process of ship impact against the wind turbine tower, a three-dimensional finite element model was developed, cf. Figure 1,3. The model contains only the lower part of the wind turbine tower and the upper part is modelled by additional masses attached at the upper edge. The tower consists of shell elements with thickness increased at the water level, while the torus-shaped fender can be modelled with either shell of membrane elements. Compressed gas enclosed inside the fender is modelled in a simplified way under assumption that its pressure, temperature and density are uniform within a single chamber (see [12]). Typical deformation of the torus caused by initial inflation is presented in Figure 3.

Impact of the ship is defined as a contact problem. The ship is modelled as a rigid surface with a prescribed mass and area which is approaching the tower with initial velocity, Figure 3b. The contact conditions are defined between the ship and the rubber wall of inflatable structure and between the rubber wall and the wall of the tower. When ship collision occurs the walls of the fender deform, chamber volume decreases and pressure rises. During this stage, the release of the gas to environment and migration of gas between the chambers can be controlled by changing opening of the valves. Finally, the ship is stopped and possibly bounces from the inflatable structure. In case when the impact energy is too high or the control is adjusted improperly, the pneumatic structure is not able to stop the ship and collision against the tower wall occurs.

The numerical tool used for 3D simulations was the FEM code ABAQUS/Explicit which is well suited for this type of problems due to applied explicit scheme of integration and the feature of 'surface-based cavities' which allows for modelling fluid-filled chambers.

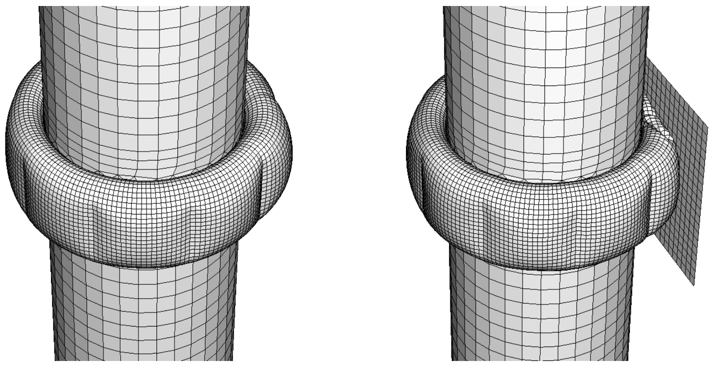

Figure 3 - Three dimensional model: a) initial fender inflation, b) deformation during ship impact

3.2 Two-dimensional model of collision

Two-dimensional model corresponding to water level (Figure 4) was implemented to reduce the time of analysis and to examine various options for inflatable structure design. The model consists primarily of elastic beam elements used for modelling of tower and fender walls. Since the mass obtained from reduction of the full 3D model is located in the middle of the structure, the additional elements connecting the mass with the walls of the tower are required. The stiffness of the tower is modelled by an additional element connected to its middle point. The numerical software used for the analysis of 2D model of the adaptive pneumatic fender was ABAQUS/Standard with additional Fortran subroutines (used for controlling gas transfer) or, alternatively, ABAQUS/Explicit coupled to MATLAB.

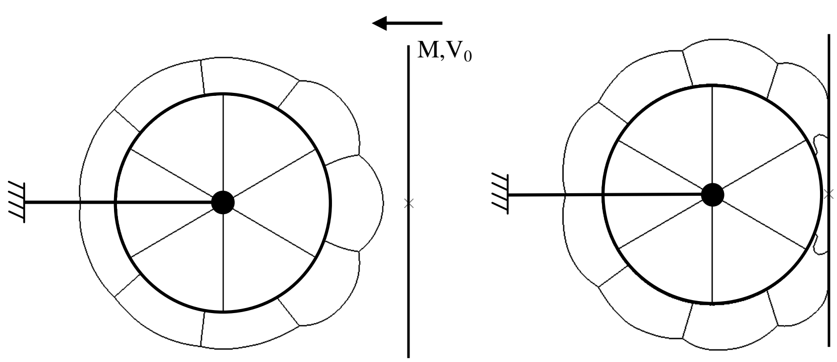

Figure 4 - Two dimensional model of collision: initial state and resulting deformation.

A parametric analysis performed with the use of 2D model was utilised to investigate basic features of the pneumatic fender. Various dimensions, number of chambers, material properties and thickness of the fender wall were considered. Taking into account results of this study, maximal admissible pressure, allowable stress of rubber and the maximal initial increase of chamber volume, the inflatable fender was designed as composed of nine chambers of a width 0,7m with walls of thickness 1cm made of reinforced rubber of alternate Young's modulus equal 150MPa.

4 CONTROL STRATEGIES FOR MINIMISATION OF SHIP DECELERATION

Further, we will consider exemplary impact of 60 ton ship approaching the tower with the velocity 6 m/s, two semi-active and two active strategies of adaptation. All simulations will be conducted with the use of the previously introduced two-dimensional model (Figure 4). Inflation of the chambers will be executed during initial 200 ms of the analysis and collision of the ship with pneumatic fender will occur directly afterwards. Distribution of pressures inside fender chambers will be fixed (100% in front cavity, 50% in adjacent cavities, and 10% in the other ones) and it will not be subjected to optimisation. The control problem considered in detail in a further part of this paper will be minimisation of ship deceleration during impact.

4.1 Control strategies utilizing sealed chambers and constant valve opening

In the simplest semi-active system only initial pressure is adjusted and mass of the gas inside fenders chambers remains constant. Optimal initial pressure is searched in the range of allowable initial pressures $\left(p_0^{\min}, p_0^{\max}\right)$ by means of gradient-based method. Minimal ship acceleration of 58,84 m/s^2 (Figure 5) is obtained for the highest allowable initial pressure ($p_0^{\max} = 4\text{atm}$), which is the consequence of significant expansion of the front chamber after inflation. Thus, semi-active system without pressure release is equivalent to the passive one. Minimal ship acceleration corresponds to the case when only a part of the inflatable structure stroke is used, which indicates the possibility of further system improvement.

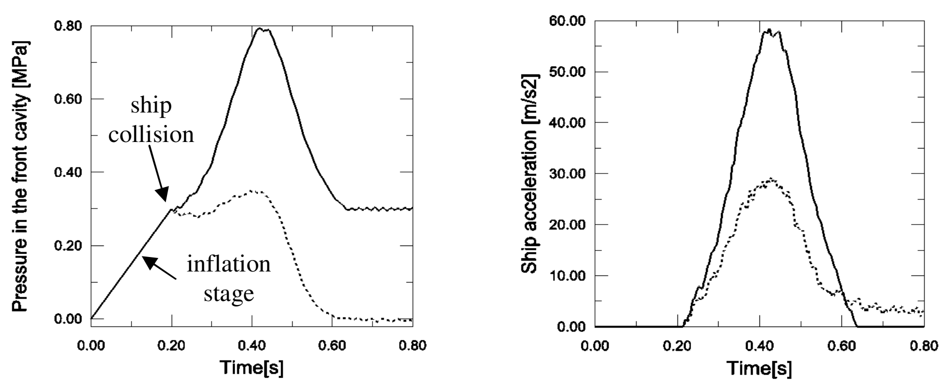

Figure 5 - Semi-active acceleration mitigation without (continuous line) and with pressure release (dashed line): a) overpressure in the front chamber, b) corresponding ship acceleration.

More advanced type of semi-active system includes the exhaust valves which are opened at time instant when the ship approaches the inflatable structure. The opening of the valves is adjusted to particular impact scenario, but it remains constant during the whole event. In considered case the gas is released from three front chambers, which are essential for impact absorption, directly to environment. Performed release of gas causes decrease of pressure inside fender chambers, reduction of global force acting on the ship and increase of fender compression. Minimal ship acceleration of 29,14m/s^2 (Figure 5b) is obtained for the case when maximal ship displacement achieves its limit, i.e. when the ship is stopped exactly before the tower wall. Accomplishment of the above strategy requires valve opening corresponding to maximal mass flow rate of gas equal to $1{,}27 kg/s$.

4.2 Control strategies utilizing real-time change of valve opening during the impact process

Further decrease of ship deceleration can be obtained by active control of valves opening during impact. In this strategy the valves remain closed until ship acceleration achieves the level, which maintained constant allows to stop the ship by using the remaining stroke of the fender. Therefore, determination of the time instant of valve opening is based on actual ship velocity, deceleration and distance to the tower.

The proposed methodology of maintaining constant ship deceleration utilises proportional control of valve opening during the second stage of impact. In the applied strategy the size of valve opening and the length of time interval of constant valve opening are adjusted in several consecutive steps in order to achieve approximately constant deceleration level, Figure 6. Alternatively, another strategies of proportional control or on/off control can be applied, however they require valve of considerably higher operating speed.

The adaptation procedure is initiated at 110 milliseconds after the contact between ship and inflatable structure occurs (t=0,310s), when ship acceleration equals 21,2m/s^2, Figure 6 (continuous line). During controlled stage of impact, the valve opening (represented by inverse of the flow resistance coefficient) and corresponding mass flow rate of gas gradually decrease, Figure 6a,b. Optimal value of pressure declines for several dozen milliseconds due to initial fast increase of ship/fender contact area and then it remains at similar level, Figure 6c. As a result, ship deceleration is maintained nearly exactly constant (Figure 6d) and its small oscillations are caused by vibrations of inflatable structure walls and discrete nature of applied control procedure. Maximal acceleration obtained by this method is eventually reduced to 21,56 m/s^2, however high mass flow rate of gas (3,9kg/s) is required at the initial stage of impact.

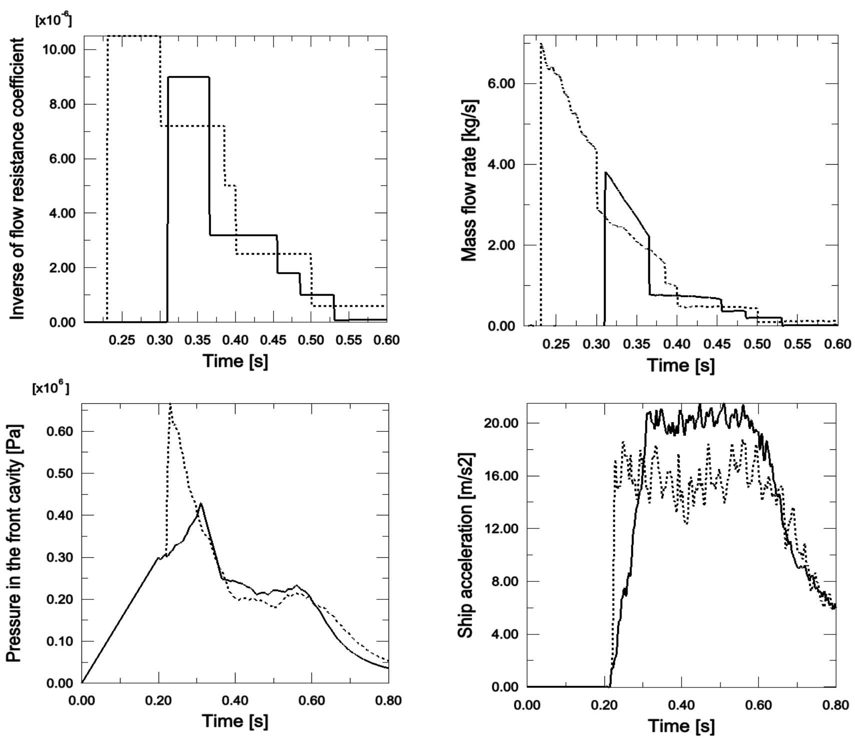

Figure 6 - Two strategies of active acceleration mitigation: i) pressure only released during impact (continuous line), ii) additional inflation at the beginning of impact (dashed line).

Finally, an attempt to keep constant ship deceleration during the whole period of impact was made. Disadvantageous slow increase of acceleration in passive stage of impact (200-310ms) can be avoided by additional inflation of the main chamber at time instant when the ship approaches inflatable structure. Due to the fact that in current strategy the whole stroke of the fender is optimally utilised, required level of ship deceleration is now lower than previously and theoretically equals $a^* = 16{,}4\text{m/s}^2$. To obtain desired deceleration level, the internal pressure inside front chamber is increased to 7,6atm at the initial stage of impact, immediately after ship contact,

Figure 6c. In a further stage of impact, large valve opening and corresponding mass flow rate of gas (7kg/s) are required to maintain constant level of deceleration, Figure 6a,b. Since fast initial inflation causes strong vibration of the whole pneumatic fender, precise control of deceleration was aggravated. Eventually, ship deceleration was reduced to 18,76m/s^2 which constitutes 32% of acceleration in passive case.

4.3 Comparison of the proposed control strategies for ship deceleration minimisation

Three methods of ship deceleration minimisation which involve change of amount of gas inside pneumatic fender during the impact process (strategy with constant valves opening, strategy with initial gradual increase of deceleration level and strategy involving additional initial inflation) are compared in Figure 7. The comparison clearly proves the effectiveness of real-time control strategy and justifies the usage of the system of adaptive impact absorption.

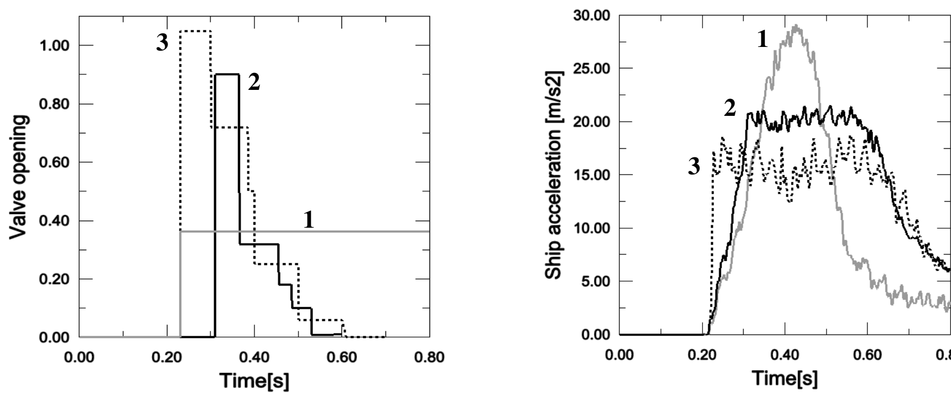

Figure 7 - Comparison of three control strategies involving pressure release: a) applied valve opening, b) resulting ship acceleration.

5 COMMENTS ON OTHER CONTROL OBJECTIVES AND STRATEGIES

Since the considered torus-shaped pneumatic fender serves as a docking facility the rebound of the ship is not a desired phenomenon. Thus, the subsequent control objective is to reduce ship rebound, i.e. to minimise ship velocity after collision, possibly to zero. The rebound of the ship is caused both by pressure inside fender chambers and elastic response of strongly deformed walls of the fender. Consequently, the proposed control strategy involves a compromise between minimisation of the internal pressure and minimisation of fender deformation at the final stage of impact, cf. [11].

Another, equally important purpose of applying adaptive pneumatic fender is optimal mitigation of tower response during ship impact. In particular, pneumatic structure reduces local stresses in the front tower wall by preventing direct contact of the ship and the tower. During fender compression front tower wall is subjected to bending caused by pressure loading and its internal forces depend approximately on actual value of pressure. Thus, minimization of stresses in tower wall is approximately equivalent to the minimisation of pressure inside the most compressed chamber of the fender.

The last considered objective of pressure adjustment is to minimise the amplitude of tower vibrations after impact. This objective can be alternatively understood as a minimisation of the energy transmitted to the tower during ship collision. Due to the fact that impact time is relatively short in comparison to period of tower vibration, maximal tower displacement depends on ship impulse. Impulse transmitted to the tower is proportional to mass of the ship and difference of its initial and final velocity. Hence, minimisation of tower vibrations is approximately equivalent to minimisation of ship rebound and vibration amplitude can be reduced maximally by 50%.

In order to familiarize with the methodologies of development of the above control strategies the interested reader is encouraged to see the paper [11] and thesis [12].

6 CONCLUSIONS

The proposed adaptive pneumatic fender surrounding the tower at the water level can effectively protect the offshore wind turbine and the ship in case of collision. Adjustment of initial pressure and controlling its release adapts the inflatable structure to various impact conditions and significantly increases system effectiveness. A controlled release of pressure helps to dissipate a major part of the impact energy and thus to decrease ship rebound and tower vibrations. Precise control of the valve flow enables minimisation of ship acceleration and reduction of stress in the tower wall.

Adaptation with constant valve opening is the most efficient when maximal admissible initial pressure is applied and valve opening allows to utilise the whole stroke of pneumatic structure. Conducted simulations clearly indicate the advantage of semi-active structure over the passive one since it reduces ship acceleration and stresses in tower wall by over 50% and ship rebound velocity by nearly 80%. In turn, adaptation strategies with real-time control of valve opening was found to be more effective for mitigation of ship response (profit up to 36% in comparison to semi-active case) than for alleviation of tower vibration and stresses (profit up to 12%). However, the execution of such strategies requires more sophisticated control system and more power supply.

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