Feasibility Study of Adaptive Inflatable Structures for Protecting Wind Turbines

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Abstract

Collisions with small ships are one of the main dangers for offshore wind turbines. Installing torus-shaped inflatable structures that surround a wind turbine tower at water level is one method of effective protection. Such structures contain several separate air chambers equipped with devices for fast inflation and pressure release. The system can be adapted to various impact scenarios by adjusting the level of internal pressure in each chamber and by controlling the release of compressed air during collision. This paper presents simulations of ship collisions with wind turbine towers protected by pneumatic structure. The numerical analysis is conducted using ABAQUS/Standard and ABAQUS/Explicit. Several methods of precise pressure adjustment are introduced. The performed feasibility study proves that inflatable structures can protect the wind turbine tower and the ship against serious damage.

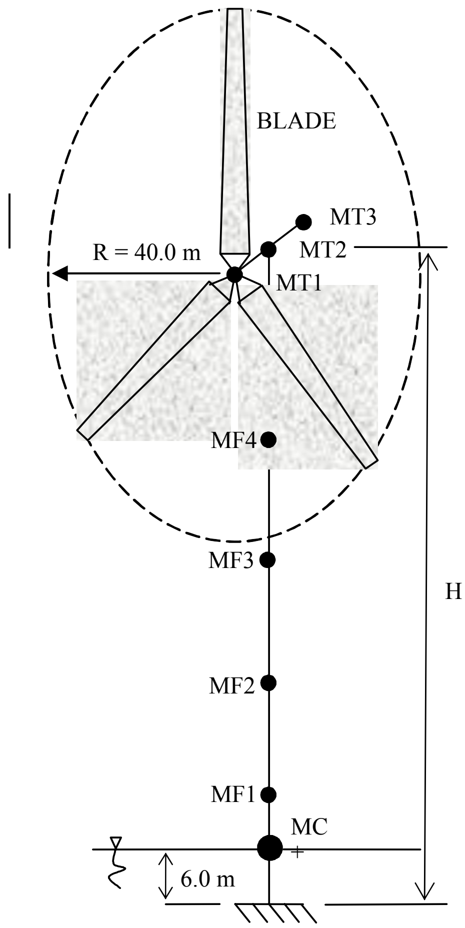
INTRODUCTION

Wind turbines are the main source of renewable energy. Moreover, the contribution of wind energy to global energy production is still increasing. The European Commission priorities assume that the present wind energy production of 40 GW will have grown to 150 GW by 2020. The largest wind generators currently operating provide up to 3.6 MW power. An increase of their effectiveness is still required, which 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 smoothly and briskly. Additional advantages of locating wind turbines offshore include the availability of large open spaces and the lack of noise and aesthetics-related inconveniences for inhabitants. Wind turbines are usually situated in shallow continental shelves in the vicinity of large ports (for example near Copenhagen). Such locations incur a relatively low cost for wind turbine installation and energy transportation, cf.[1].

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. Additional dangers are collisions involving small 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 and can lead to serious damage to both the wind generator tower and the ship. Therefore, an additional structure providing safety for docking operations is required. In this paper, an Adaptive Inflatable Structure (AIS) attached to the wind turbine tower is proposed and its feasibility verified.

MODEL OF THE WIND TURBINE

Let us commence with the finite-element model of a typical wind turbine, as shown in Fig. 1, which was introduced in [2]. The tower consists of beam elements with circular sections and a radius varying from 1.16 to 2.11 m. Flanges on the tower and the turbine are modelled by point masses. The blades are 40 m long and they are modelled by shell elements.



✓ **Blade** (S4R5 shell elements):
Material properties and shell thickness were chosen so that the first own frequency and weight of blade are ω_1 = 1.30 Hz, G = 7 006 kg

✓ **Tower** (B33 beam elements):
47 elements with circular section were used, radius R = 1.161 ÷ 2.111 m, thickness t = 0.014 ÷ 0.040 m.
Weight of tower G_T = 186 782 kg

✓ **Point masses** (MASS elements):
MT1 = 13 000 kg
MT2 = 31 800 kg turbine
MT3 = 35 000 kg
MF1 = 4 200 kg
MF2 = 3 200 kg flanges
MF3 = 1 900 kg
MF4 = 2 300 kg
MC = 49 620 kg - cone + water

The **total weight** of the structure is:
186 782 + 3 x 7006 + 141 020 = 348 820 kg

Figure 1. Dynamic model of the wind turbine tower by A. Mróz [2].

For each vibration mode, the wind turbine tower can be reduced to one dimensional object on the water level, cf.[3]. The mass, stiffness and damping of the reduced model are given by the formulae:

$$M = \frac{1}{\phi_{nC}^2} \int_0^H m(z) \cdot \phi_n^2(z) dz = \frac{M_n}{\phi_{nC}^2} \tag{1a}$$

$$K = \omega_n^2 M = (2\pi f_n)^2 M \tag{1b}$$

$$C = 2\xi \omega_n M \tag{1c}$$

where: ϕ_n is the eigenvector (mode shape), $\phi_{nC} = \phi_n(z_C)$ is the normalized value of the mode on the water level, M_n is the generalized mass calculated for this mode, ω_n is the first circular frequency and ξ is the damping coefficient. The values of the parameters ϕ_{nC}, M_n, f_n, can be obtained directly from finite element analysis of the structure from

Fig. 1. The resulting mass, stiffness and damping parameters of the reduced model are presented in Table 1.

Table 1. Parameters of the 1D model on the water level.

	f_n[1/s]	ϕ_{nC} [m]	M_n[kg]	M[kg]	K[N/m]	C[Ns/m]
Mode 1	0.33147	1.584 e-3	116 748	0.4653e11	0.2018e12	0.9690e9
Mode 2	0.38503	1.021 e-3	34 646	0.3318e11	0.1942e12	0.8029e9

DESIGN OF ADAPTIVE INFLATABLE STRUCTURE

The Adaptive Inflatable Structure (AIS) that will be used for the purpose of protecting the offshore wind turbine against collisions from small ships is torus-shaped and surrounds the tower, as illustrated in Fig. 2. The AIS is located on the water level and it is partially submerged. The AIS is 2m in height and the thickness can vary from 0.5 to 1m. The walls of the pneumatic structure are made of rubber reinforced by steel rods which provide high durability and allow large deformations during ship impact. To achieve better adaptation for various impact scenarios, the inflatable structure can be divided into several separate air chambers located around the tower, as shown in Figs. 2 and 3. The exact dimensions of the AIS are determined by the tower mass and stiffness, and they are set considering the conditions necessary for optimal impact absorption.

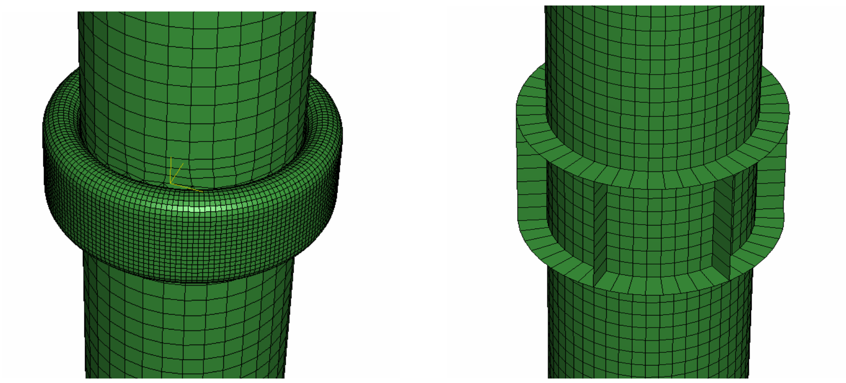


Figure 2. Adaptive Inflatable Structure surrounding the wind generator tower

The inflatable structures should be permanently inflated at a relatively low pressure to provide mitigation of lighter impacts and to maintain the desired shape of the pneumatic structure. Additional inflation is planned before any stronger collisions, which is executed for each chamber separately by a compressor or alternatively by a fast-reacting pyrotechnic system acting similarly to the one in a car air bag. The gas pressure acting outwards increases the stiffness of the pneumatic structure and prevents its huge deformation caused by the impact of the colliding object. In this way, the inflatable torus helps avoid direct collision between the ship and the tower and potential excessive forces and accelerations. The idea of using compressed air makes pressurized structures easily adaptable for various impact forces and scenarios. The adaptation is achieved by adjusting the internal pressure and varying its level between the chambers according to the velocity, the mass and the area of contact with the ship.

During collision, when the contact of a colliding object with the inflatable structure occurs, a controlled release of pressure is executed. For this purpose, the AIS is equipped with controlled piezo-valves located in its walls and internal divisions which allow the flow of gas between the cells and outside the structure. This way we can control the stiffness of the pneumatic structure in the subsequent stages of impact and we can stop the penetrating object at an appropriate distance. The second purpose of executing the release of pressure is to control energy dissipation.

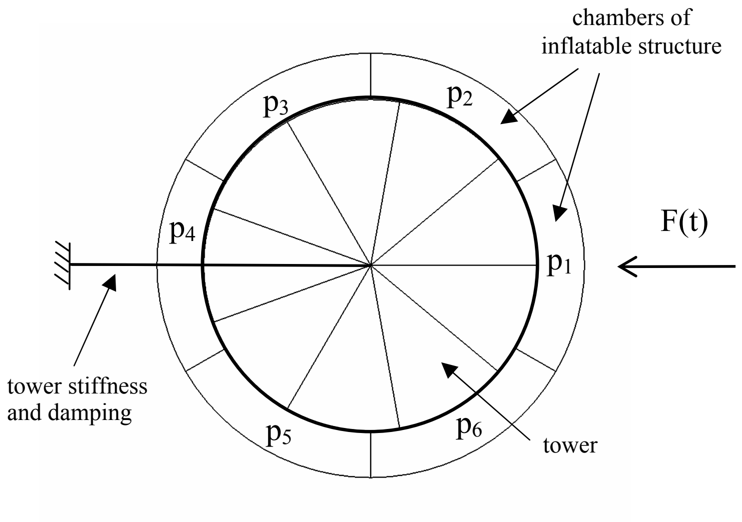


Figure 3. Two-dimensional model of inflatable structure for protection of a tower.

The purpose of applying pneumatic structures is to mitigate the response of both the ship and the wind turbine tower. In particular, the inflatable structure helps to dissipate the impact energy, minimize forces acting on the ship, decrease stresses arising at the location of the collision and mitigate tower vibrations.

EQUATIONS DESCRIBING INFLATABLE STRUCTURES

Numerical analysis of the pneumatic structure subjected to an impact load requires considering the interaction between its walls and the fluid enclosed inside the chambers. An applied external load causes deformation of the structure and a change of the capacity and pressure of the fluid. The pressure exerted by the fluid affects, in turn, the deformation of the structure and its internal forces. The dynamics of the inflatable structure is described by the nonlinear equation of motion, whose general form reads:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{K}(\mathbf{q})\mathbf{q} = \mathbf{F}(\mathbf{p},\mathbf{q}) + \mathbf{F}_I \qquad (2)$$

$$\mathbf{q}(0) = \mathbf{q}_0 \,,\, \dot{\mathbf{q}}(0) = \mathbf{V}_0$$

Vector $\mathbf{p} = \{p_1(t), p_2(t), ..., p_n(t)\}$ indicates gauge pressures in the cavities. The impact can be modelled by an r.h.s. force vector $\mathbf{F}_I$ or by initial conditions. In any case, the $\mathbf{F}(\mathbf{p},\mathbf{q})$ vector is always present in the problem, since it provides the coupling between the fluid and the structure. The interaction with the fluid can be correctly taken into account only by assembling the equilibrium equations in actual configuration so the equation of motion has to be considered in a nonlinear form.

We assume that the structure is filled with a compressible (pneumatic) fluid with no viscosity. The fluid in each cavity is not discretized into finite elements but described analytically by the equation of the state for ideal gas, cf. [4]:

$$\bar{p}(t) = \rho(t) \cdot R \cdot \bar{\theta}(t) \tag{3}$$

$$\text{or } \bar{p} \cdot V(t) = m(t) \cdot R \cdot (\theta(t) - \theta_Z)$$

where absolute pressure $\bar{p}$ is defined as $\bar{p} = p + p_A$ where p_A is ambient pressure and p is gauge pressure, the absolute temperature is defined as $\bar{\theta} = \theta - \theta_Z$ where θ is current temperature on the Celsius scale and θ_Z is absolute zero temperature. The gas constant R is related to the universal gas constant $\bar{R}$ and molecular weight MW by the formula: $R = \bar{R} / MW$. Moreover, the variables ρ, V, m indicate gas density, volume, and mass, respectively. The initial conditions for the fluid are given by: $\bar{p}(0) = p_0$, $\theta(0) = \theta_0$. In the case of fluid flow, we also consider conservation of mass given by:

$$m(t) = m_0 + \Delta m(t) \tag{4}$$

The increase of the fluid mass in the cavity $\Delta m(t)$ is described by the following integral:

$$\Delta m(t) = \int_0^t q(\bar{t}) d\bar{t} = \int_0^t q_{in}(\bar{t}) - q_{out}(\bar{t}) d\bar{t} \tag{5}$$

where q_{in} is the mass flow rate into the cavity and q_{out} is the mass flow rate outside the cavity. The direction of the flow is dependent on the sign of the pressure difference. The relation defining the mass flow rate depends on the assumed model of the flow. In the simplest case, it is given by the formula:

$$\Delta p(t) = C_V q(t) + C_H q(t) |q(t)| \tag{6}$$

where $\Delta p(t) = p_{out} - p(t)$, C_V is the viscous resistance coefficient, and C_H is the hydrodynamic resistance coefficient. Both these coefficients are dependent on the area of the orifice. In general, control of the inflatable structure properties is executed by changing the diameter of the orifice thus also by changing the flow resistance coefficients C_V, C_H. Under the assumption of an isothermal process (or arbitrarily given change of temperature) a set of equations (2-6) fully describes the coupling between the fluid and the surrounding structure.

The balance of the heat transferred to the system ΔQ, increase of the gas internal energy ΔE and the work done by gas ΔW are given by the first law of thermodynamics:

$$\Delta E = \Delta Q - \Delta W \tag{7a}$$

For rapid changes of gas state, an adiabatic process, which assumes conservation of the gas energy, should be considered. When this assumption is applied, the temperature change is calculated from the condition that no energy is added to or removed from the cavity except the gas flow between or outside the cavities. An additional equation reads:

$$\frac{d(m\overline{E})}{dt} = q_{in}\overline{H}_{in} - q_{out}\overline{H}_{out} - \dot{W} \tag{7b}$$

where specific energy $\overline{E}$, specific enthalpy $\overline{H}$ and work done by gas W are given by:

$$\overline{E} = \overline{E}_I + \int_{\theta_I}^{\theta} c_v(T)dT \tag{8a}$$

$$\overline{H} = \overline{H}_I + \int_{\theta_I}^{\theta} c_p(T)dT \tag{8b}$$

$$dW = \overline{p}dV \tag{8c}$$

In many practical cases, the heat capacity at constant pressure c_p and heat capacity at constant volume c_V are considered as temperature independent and equal for the air: $c_p = \frac{7}{2}R$, $c_V = \frac{5}{2}R$. Having taken into account the above definitions and assuming that there is no mass exchange in the cavity we obtain:

$$mc_v \cdot d\theta = -\overline{p} \cdot dV \tag{10}$$

$$\text{or } \overline{p} \cdot V^{\chi} = const.$$

where χ is an adiabatic exponent $\chi = c_p/c_V$ and for the air it is equal: $\chi = \frac{7}{2}R / \frac{5}{2}R = 1.4$.

SIMPLIFIED 1D MODEL OF COLLISION

In this section, a ship collision with a tower protected by a pneumatic structure is reduced to a one-dimensional model on the water level. This kind of modelling is a very rough estimation of the real situation, but it provides a basic assessment of the AIS efficiency. The system consists of a linear spring describing stiffness of the tower and an air spring modelling the inflatable structure (see Fig. 4). The parameters of the wind turbine tower M and K were found in one of the previous sections. Additionally, u_1 indicates displacement of the tower and u_2 indicates displacement of the ship.

The force from the air spring is acting on the tower and the ship when the air spring is compressed such that $\overline{p}(t) - p_A$ is positive. Hence, the response of the system can be divided into two phases: the first one indicating impact and the second one when the mass M is performing free vibrations.

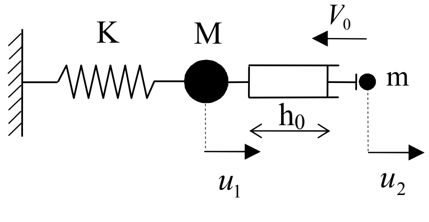


Figure 4. Two degree of freedom model of collision between ship and tower

When the pressure inside the chamber is arbitrarily assumed, the equations governing the problem are as follows:

$$M\frac{d^2u_1(t)}{dt^2}+Ku_1(t)+\left\{\begin{matrix}(\overline{p}(t)-p_A)A & for \quad \overline{p}(t)>p_A)\\ 0 & otherwise\end{matrix}\right\}=0 \tag{11}$$

$$m\frac{d^2u_2}{dt^2}-\left\{\begin{matrix}(\overline{p}(t)-p_A)A & for \quad \overline{p}(t)>p_A\\ 0 & otherwise\end{matrix}\right\}=0$$

$$IC: \dot{u}_2(0)=-V_0$$

Under isothermal conditions the force in the air-spring can be expressed as a function of the initial pressure, piston displacement and the mass of the gas added to the system:

$$\overline{p}(t)=\left(\frac{h_0\overline{p_0}}{\overline{\theta}_0}+\frac{\Delta m(t)\cdot R}{A}\right)\cdot\frac{\overline{\theta}_0}{h_0-(u_1(t)-u_2(t))} \tag{12}$$

Since in the problem considered, the tower displacements are relatively small in comparison to the ship displacements we can ignore the term $u_1(t)$ in the definition of the air-spring force. The equations (11) describing the system are then separated. The second, nonlinear equation can be solved in order to find the ship displacement. The solution to the first equation can be derived by treating its last term as time-dependent excitation. In the case where we consider the flow of gas through the valve with only the viscous resistance coefficient taken into account, the mass of gas added to the system is given by:

$$\Delta m(t)=\int_0^t\frac{p_{out}-\overline{p}(\overline{t})}{C_V(\overline{t})}d\overline{t} \tag{13}$$

The air-spring characteristic will be adjusted to provide optimal impact absorption. One restriction is that the ship must be stopped before hitting the wind turbine tower, which means that its maximal displacement must be smaller than the air-spring length.

Let us initially consider minimization of the ship accelerations. From the kinematics of the structure we can easily conclude that the minimal acceleration necessary to avoid collision of both masses is constant in time and equals: $\ddot{u}_2^{opt}(t)=V_0^2/2h_0$. The corresponding optimal pressure in the cylinder obtained from (11b) and the optimal ship trajectory calculated by integration of the accelerations equals:

$$\overline{p}^{opt}=\frac{mV_0^2}{2Ah_0}+p_A, \quad u_2^{opt}(t)=\frac{(V_0t)^2}{4h_0}+V_0t \tag{14}$$

The conclusion is that the optimal pressure is constant and depends on the initial kinetic energy of the ship and it is inversely proportional to the area of the piston and its length. In the case of an 80-ton ship moving at an initial velocity of 8 m/s and assuming a spring length of 0.7 m and its area of 6 m^2 we obtain a minimal acceleration: $\ddot{u}_2^{opt}=45.71\,m/s^2$, and an optimal pressure: $\overline{p}^{opt}=0{,}71\,MPa$. The time of impact can be calculated as: $t=4h_0/V_0$ = 0.35s. Using the derived optimal pressure and piston displacement, we can calculate the necessary change of mass of the gas in the chamber from Eq. (12):

$$\Delta m(t) = \frac{(h_0 + u_2^{opt}(t))Ap^{opt}}{R\theta_0} - \frac{h_0 Ap_0}{R\theta_0} \tag{15}$$

Finally, the flow resistance coefficient $C_V(t)$ and the area of the orifice can be computed according to (13). Let us notice that we had obtained the lowest pressure for which the ship is stopped before hitting the tower. Since the forces acting on the tower depend directly on the value of pressure, the problem of local forces minimization is also solved.

The optimization of pressure oriented towards minimization of the tower vibrations was also performed. Various pressure impulses satisfying Eq. (11) were considered. It was found that maximal tower displacement depends on the ship momentum and does not depend significantly on the shape of the pressure impulse. However, the impulse which causes the smallest tower displacement was the one of longest duration and the lowest minimal value, cf.[5].

TWO-DIMENSIONAL MODEL OF COLLISION

For the purpose of a more precise modelling of the inflatable structure's influence on the ship impact into the offshore wind turbine, a two-dimensional model was implemented, as shown in Figs. 3 and 5. The model consists of Timoshenko beam elements with a linear material model applied both for the tower and AIS walls. The mesh is finer in the front part of the pressurized structure where the impact was applied. The stiffness of the tower is modelled by an additional element connected at its middle point. Thus, additional elements connecting the tower with the walls of the tower are required. The additional mass obtained from a reduction of the full model (according to Table 1) is located in the middle of the structure.

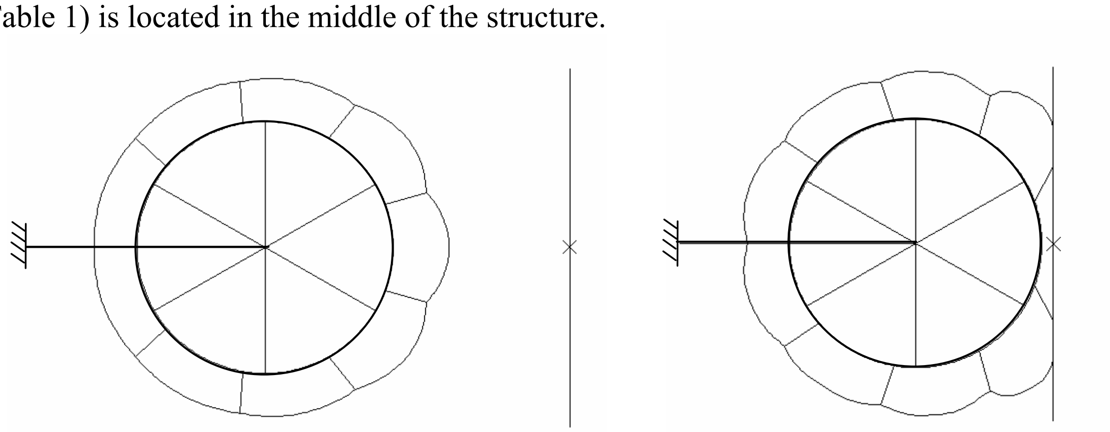


Figure 5. Collision modelled by contact: initial state and resulting deformation.

The gas inflating the cavities is modelled by the feature of *fluid-filled cavities* and *surface-based cavities* available in ABAQUS software and operating according to the formulas given in one of the previous sections. The reference density of the gas under pressure is $\overline{p}_R = 0.1 MPa$ and at the reference temperature of 20°C equals 1.18 kg/m^3 .

The inflation of the cavities was executed during the first step of the analysis where the pressure amplitude was adjusted. The flow of the gas usually depends on the flow resistance coefficients according to Eq.(6) and occurs outside the chambers and between them.

The impact is applied to the tower by means of contact formulation. The ship is modelled as a rigid surface with a prescribed mass and length and approaching the tower with an initial velocity, see Fig. 5. The contact conditions are defined between the ship and the rubber wall and between the rubber wall and the wall of the tower. Such a model describes the process of collision in a realistic way. After the contact occurs, part of the AIS wall has a common displacement with the ship. During this stage, the pressure increases, the ship is stopped and it bounces from the inflatable structure. When impact energy is high, the pneumatic structure is not able to stop the ship and contact between the rubber AIS wall and tower wall of the tower occurs.

The main numerical tool used for calculations was a finite element code ABAQUS/Standard, cf.[6]. Another solver was ABAQUS/Explicit which uses an explicit scheme of solution and hence is better suited for fast dynamics or strongly nonlinear problems, cf.[7]. FORTRAN subroutines for capabilities that are not available in ABAQUS were implemented.

ADJUSTMENT OF INFLATABLE STRUCTURE PARAMETERS

A parametric analysis performed on a two-dimensional model was used to investigate basic features of the new solution. The geometrical parameters of the inflatable structure were adjusted according to global properties of the tower and the initial value and release of pressure according to a particular impact. Initially, various options for pneumatic structure design were analyzed. The considered properties of the inflatable structure were the number of chambers (3–12), the width of the pressurized structure (0.5–1m), the Young modulus and thickness of the AIS wall (5–200 MPa, 0.5–5cm). Indications for a proper choice of these parameters are as follows:

- by using wide chambers we can decrease the pressure necessary to stop the ship
- short and wide chambers can absorb stronger impacts with the initial atmospheric pressure (no additional inflation required)
- using longer chambers is more beneficial for optimal reduction of local forces in the tower wall
- when we are using more chambers each of them can be more precisely adjusted to the actual loading conditions
- in long and narrow chambers large stresses appear after the initial inflating in the outer wall
- we cannot afford any large deformations after inflation, but on the other hand we have to ensure the possibility of a large deformation during impact

Taking into account all the mentioned conditions, the maximal allowable pressure, the maximal admissible stresses arising in the rubber and the maximal initial increase in chamber volume, it was decided to divide the inflatable structure into 9 chambers of a width of 0.7 m and construct a 1 cm wall made of rubber and steel fibres of a vicarious Young modulus of 150 MPa.

In further simulations, various impacts applied to a 2D model and several exemplary schemes of pressure were analyzed. The obtained results are the guidelines for AIS deployment and a controlled release of pressure. The tower protected by the pneumatic structure was subjected to impact of the same energy (0.64 MJ) but of various velocities, cf. Table 2. The pressure inside the packages was equal to 0.08 MPa in the front cell (the most exposed to impact), 0.05 MPa in adjacent cells, and 0.02 MPa in the other cells. We assumed that no flow of the gas occurs. The values of the maximal pressure, displacement of the tower top and maximal stresses in the wall were observed.

Table 2. Response of the structure to the impact of the same energy but various mass and velocity.

Mass [ton]	Velocity [m/s]	Energy [MJ]	Impulse [t*m/s]	Init. 'p' [N/m^2]	Max 'p' [N/m^2]	Accel. [m/s^2]	Stress [MPa]	Displ. [m]
20.00	8	0.64	160	80 e3	387.9e3	124.6	140.1	0.00191
35.56	6	0.64	213.36	80 e3	391.6e3	69.33	133.8	0.00255
80.00	4	0.64	320	80 e3	392.6e3	31.3	135.9	0.00379

The next problem considered was computation of initial pressure (applied only in the cell most exposed to impact) necessary to stop the ship just before the tower wall. Such a situation is beneficial since the pressure is long and its maximal value is relatively low. Various impact energies were taken into account. The first example shows the impact which can be absorbed by using atmospheric pressure in the chamber. This impact has the energy of 0.756 MJ which constitutes 29.5% of the maximal energy considered.

Table 3. Response of the structure calculated for various impact energies

Mass [ton]	Velocity [m/s]	Energy [kJ]	Impulse [t*m/s]	Init. 'p' [N/m^2]	Max. 'p' [N/m^2]	Stress [MPa]	Displ. [m]
42.00	6	756	252	0	609 e3	193	0.00299
67.00	6	1206	402	45 e3	1067 e3	340	0.00481
52.00	8	1664	416	95 e3	1404 e3	470	0.00499
66.00	8	2112	528	150 e3	1711 e3	611	0.00635
80.00	8	2560	640.00	195 e3	1951 e3	692	0.00770

The response of the system depends on the excitation in the following way:

- maximal acceleration of the ship increases nonlinearly with the ship velocity and decreases with the ship mass (due to a deeper penetration)
- maximal stress in the tower wall is proportional to the highest pressure in the main AIS chamber which depends on impact energy
- displacement of the tower top is proportional to the impulse of the ship and it is relatively very small

- the initial pressure at which the whole AIS package is crushed, is proportional to the impact energy

ALLEVIATION OF SHIP RESPONSE

In this section, our purpose is to dissipate the initial energy of the ship. Since after a collision most of the energy is accumulated as the kinetic energy of the ship, the loss of ship velocity is a good measure of dissipation. By minimizing the final ship velocity we will avoid bouncing of the ship from the wind turbine. During impact the kinetic energy of the ship is changed into gas energy, the energy of the tower and the strain energy of the strongly deformed AIS walls:

$$\Delta E^{ship} = \Delta E^{gas} + \Delta E^{tower} + \Delta E^{AIS} \tag{16}$$

At the moment when the ship is stopped, its energy E^{ship} equals zero, and the energies ΔE^{gas}, ΔE^{AIS} achieve their maximum values. Our purpose is to dissipate both these energies instead of being transferred back to the ship in the time of following impact.

The dissipation can be obtained in two manners: by removing compressed gas from the pressurized structure to the environment and by releasing stresses in the AIS walls. The first method is executed by opening the valves in the pressurized structure wall. The whole gas energy is dissipated when its pressure equals atmospheric pressure, since it has no capability of expansion. The second method is performed by changing the stiffness of front AIS partitions (short elements between the chambers). This helps to reduce significantly high strain energy accumulated in the tensioned outer AIS wall and transfer it into strain and kinetic energy of other parts of the AIS. In reality it can be executed by applying pistons with controllable valves as AIS partitions. The above changes are applied according to the formulae:

$$C_V = \begin{Bmatrix} 1e10 & for & V < 0\,(ship\ approaching) \\ 2e5 & for & V > 0 \end{Bmatrix} \quad E = \begin{Bmatrix} 150MPa & for & V < 0 \\ 1.5MPa & for & V > 0 \end{Bmatrix} \tag{17}$$

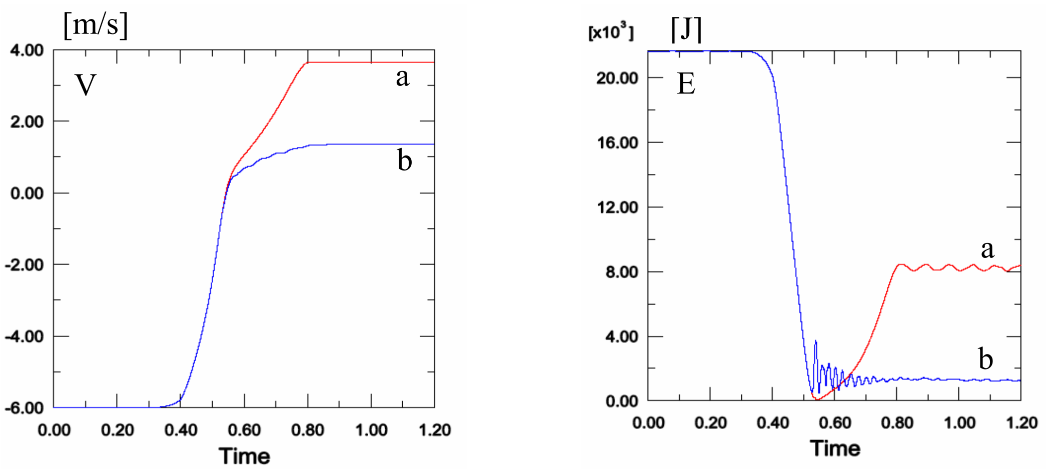


Figure 6. Change of ship velocity and system kinetic energy: a) dissipation by pressure release, b) dissipation by pressure release and change of partitions stiffness.

To apply a change of these parameters during a finite element analysis, FORTRAN subroutines were implemented. The URDFIL subroutine was used to read the actual velocity of the ship during simulation. The UFIELD subroutine was utilized to open the valve and to weaken the pneumatic structure partitions when the velocity of the ship approaches zero.

In the numerical analysis, we considered the impact of a 60-ton ship moving at a velocity of 6m/s. The final kinetic energy of the ship was compared in the two following cases. In the first one, dissipation was executed by pressure release in the chamber and ship energy was reduced by 41%. In the second example considered, the dissipation was due to pressure release and change of AIS partition stiffness. By applying this method, the velocity of the ship was decreased to 1.32 m/s, which means an energy reduction of 78%.

The following purpose of the pressure adjustment was to decrease ship accelerations. The most profitable situation is stopping the ship before hitting the tower wall by using constant accelerations of minimal value. Pressure causing such accelerations is not constant, as in the case of a rigid piston due to various areas of contact between the ship and inflatable structure and the forces coming from rubber deformation.

The impact considered was the same as in the previous example (a 60-ton ship, velocity 6m/s). In the reference case, the value of pressure during the whole period of impact was 0.24 MPa which kept at a constant level stops the ship just before approaching the tower. In this case, the whole AIS between the ship and the tower is crushed and maximal ship acceleration is equal to 34 m/s^2. After inflation, the main chamber is expanded by 0.4 m so the total distance h_0 at the moment of the ship impact equals 1.1m. To stop the ship with a constant decelerating force we have to use the acceleration of $a^* = V_0^2 / 2h_0 = 16.4 m/s^2$ during the time of impact $t^* = 4h_0 / V = 0.73 s$. The appropriate pressure change can be calculated directly by considering the actual state of the system (18a) and the optimal state achieved by pressure modification (18b):

$$Ma(t) - P(t) = 0 \tag{18a}$$

$$Ma^* - P(t) - A(t)\Delta p = 0 \tag{18b}$$

where $P(t)$ denotes the overall value of forces acting on the ship, Δp is the additional pressure and $A(t)$ is the area of contact between the ship and the inflatable structure. By subtracting these two equations, we obtain:

$$\Delta p(t) = \frac{M\Delta a}{A(t)} = \frac{M(a^* - a(t))}{A(t)} \tag{19}$$

In this case, the most convenient method of numerical implementation is controlling pressure directly instead of changing the valve resistance coefficient. The URDFIL subroutine was utilized to read the actual value of ship acceleration and DISP subroutine was used to change the actual pressure, which was treated here as a boundary condition. The area of contact between the ship and inflatable structure was estimated by using the geometry of the structure and expressed in terms of ship distance from the tower wall.

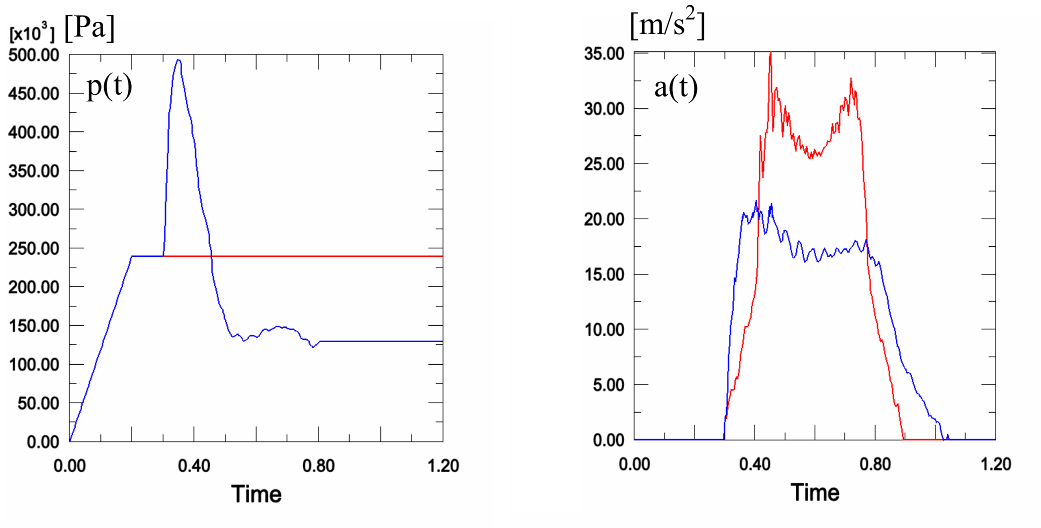


Figure 7. Pressure change and corresponding ship accelerations: initial pressure adjustment (red line) and full adaptation procedure (blue line).

The results achieved by applying this subroutine are presented in Fig. 7. The red line concerns the case without adaptation with pressure equal to 0.24MPa. Maximal acceleration is quite low during the initial stage of impact but increases significantly to the level of 35m/s due to high forces coming from rubber deformation. The blue curve is obtained as a result of the described control procedure. Pressure increases strongly at the initial stage of impact, which helps to achieve the desired level of acceleration. At the moment when the deformed rubber strongly stops the ship, the pressure decreases below the initial level. It can be observed that the maximum value of acceleration was decreased by about 37%. To obtain the assumed level of acceleration $a^* = 16.4\ m/s^2$ we have to apply very sudden changes of pressure, which causes convergence problems in the analysis.

MITIGATION OF THE TOWER RESPONSE

Another purpose of applying the inflatable structure is minimization of the local forces arising in the front tower wall during collision. These forces are reduced significantly by avoiding direct contact of the ship with the wind turbine tower. However, various changes of pressure can be applied in order to stop the ship and different maximal forces in the tower will appear. Since the inertia of the tower wall is relatively small, the level of stresses will depend mainly on the actual value of pressure. Thus, the most beneficial solution is to keep the pressure at a constant level during the whole impact.

A numerical example was performed for the impact of the 40-ton ship with an initial velocity of 7 m/s. The distribution of pressure within the chambers which causes the ship to stop just before the tower wall was found by conducting several ABAQUS simulations. Several different combinations can be found, since no unique solution exists. The pressure distribution which will we consider further is the following:

0.19MPa in the main chamber, 0.09 MPa in the adjacent chambers and 0.04MPa in the other ones. The main chamber is crucial for the overall response, and therefore it will be analyzed most precisely.

The inflation process was executed during the initial 200 ms of the analysis and the pressure increase was linear. The change of volume obtained from the numerical simulation was used to calculate the mass of the gas in the chamber (see Fig.8a) from the ideal gas law:

$$m(t) = \frac{(p^{opt} + p_A)V(t)}{R\bar{\theta}_0} \tag{20}$$

The mass of the gas increases strongly during the inflation stage, then it is almost equal (oscillations are due to rubber vibrations), and it is reduced strongly when the ship crushes the chamber and increases again when the ship is bounced off. The mass flow rate can be found as the mass derivative:

$$q(t) = \frac{dm}{dt} = \frac{(p^{opt} + p_A)}{R\bar{\theta}_0} \cdot \frac{dV(t)}{dt} \tag{21}$$

The function of the mass flow rate was subjected to a high-frequency filter to eliminate excessive oscillations. The last step was to compute the flow resistance coefficient that provides appropriate mass exchange under given conditions of pressure difference. The inverse of this coefficient is proportional to the valve area:

$$1/C_V(t) = \frac{q(t)}{\Delta p} = \frac{A(t)}{C_V^*(t)} \tag{22}$$

and C_V^* indicates the valve coefficient independent on valve area. The pressure difference equals here 0.19 MPa both for the inflow and for the outflow. A positive value of this function indicates a flow from the internal chamber with higher pressure (0.38 MPa) to the main chamber and a negative value indicates flow to the environment.

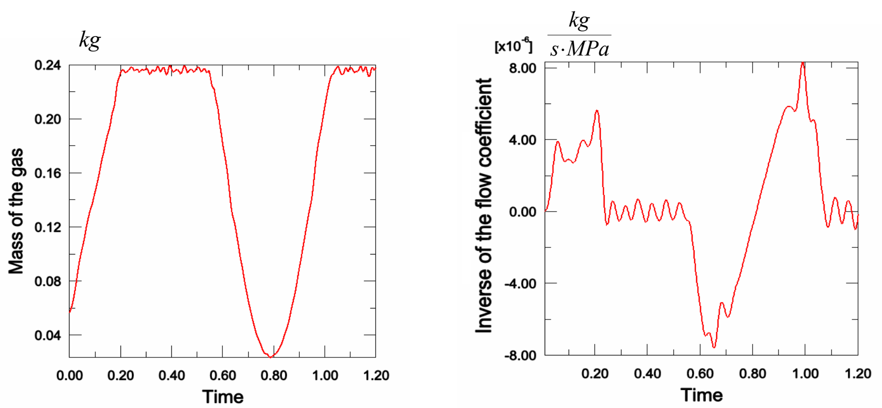


Figure 8. a) mass of the gas in the cavity, b) inverse of flow resistance coefficient.

Maximal tensile stresses arising in the tower wall adjacent to the main chamber were observed, as shown in Fig. 9. In the case where an inflatable structure is not applied, the stresses achieve an extremely high value significantly exceeding the yielding limit. In the case where the initial pressure is optimally adjusted but the valve remains closed, maximal stresses achieve 229 MPa. Finally, when the applied flow resistance coefficient is adjusted, as presented in Fig. 8b, we are able to reduce the maximal stresses to 104 MPa.

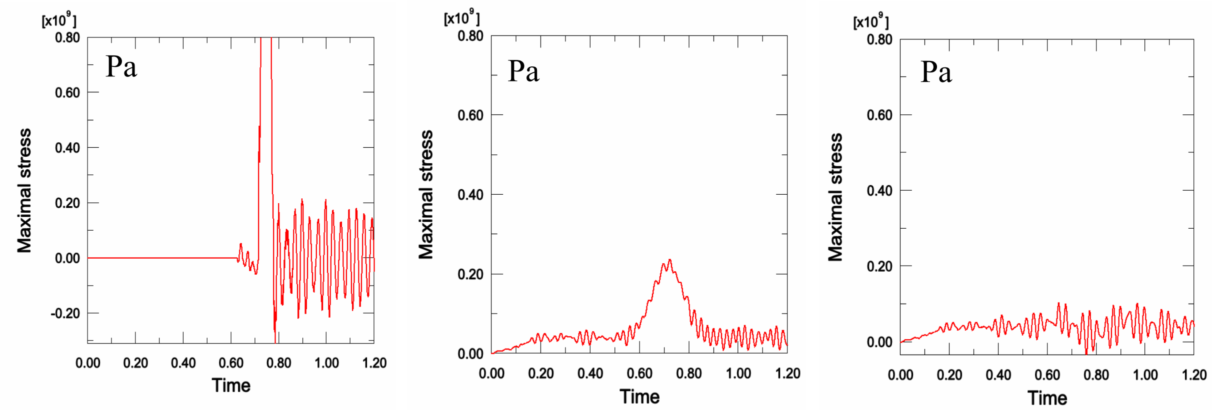
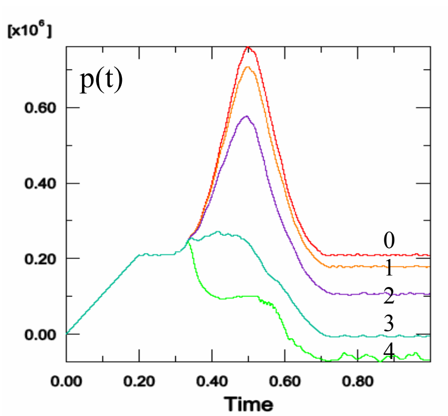


Figure 9. Stresses in the tower wall during collision a) without AIS, b) AIS with closed valve, c) adjusted valve area.

Finally, our goal was to minimise the tower displacements. Alternatively, it can be understood as a minimization of the energy transmitted to the tower during impact. For the assumed properties of the wind turbine tower, the impact time is generally too short to achieve a significant change of tower response. However, a simple method for optimisation of the flow coefficient is proposed.

The initial pressure in the main chamber was assumed at a relatively high level to make the outflow of the gas possible. In each case, the valve was opened only for the period when the ship is in contact with AIS and it is approaching the tower (time: 0.35–0.5s). The resulting pressure impulses are presented in Fig.10. In the initial case, the flow coefficient is large and the valve is closed. The pressure impulse is similar to a sine function and its amplitude is relatively high. When we decrease the flow coefficient, the maximum pressure value becomes lower and the whole pressure impulse is flatter. In the last case, the pressure in the chambers becomes too low and the ship finally hits the wind turbine tower.



No.	Cv [Pa*s/kg]	Max press. [Pa]	Displ. [m]
0	100 E+10	7.574E+05	0.00431
1	100 E+5	7.078E+05	0.00422
2	25 E+5	5.772E+05	0.00397
3	5 E+5	2.720E+05	0.00365
4	1 E+5	2.437E+05	0.00378

Figure 10. Change of pressure and corresponding response of the tower.

The conducted analysis confirms the previous results obtained from the 1D model. Maximal reduction of the tower displacement was equal only to 15.5%, as shown in the table in Fig.10. Nevertheless, the method is promising for structures with a shorter period of vibrations.

CONCLUSIONS AND FUTURE STEPS

The proposed Adaptive Inflatable Structure surrounding the tower can effectively protect the offshore wind turbine and the ship in case of collision. By adjusting the initial pressure and controlling its release we can adapt the inflatable structure to various impact conditions and increase system effectiveness. A controlled release of pressure helps to dissipate a major part of the impact energy and avoid bouncing of the ship from the wind turbine. By applying precise control of valve flow, we can minimize ship accelerations and significantly decrease stresses in the tower wall. The AIS can possibly help to decrease vibrations of the structures whose period of vibrations is comparable to impact time.

In the following stages of research, a three-dimensional model of the tower surrounded by an inflatable structure is desired to analyze the impact more precisely. More accurate modelling of the composite rubber material reinforced by steel fibres is required. The description of the flow should be adjusted to the experimental data. The possibilities of opening and closing the valve within the time of impact (~200 ms) should be examined. Finally, an experimental verification of the whole system is necessary to test out its functioning and effectiveness.

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