Composite Tidal Turbine: Compromise between hydrodynamic efficiency and impact damage safety

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Résumé :

Le but consiste d'exploiter le savoir-faire et les outils développés pour l'étude hydrodynamique des hélices marines pour la conception des hydroliennes. Une conception d'un rotor doté d'un système de carénage judicieusement optimisé a été proposée. L'approche adoptée prévoie que l'ajout d'une tuyère accélératrice à encombrement constant sur un rotor optimisé peut apporter un gain hydrodynamique mais peu significative compte tenu de l'investissement fourni mais néanmoins procure un rôle protecteur en périphérie des pales. Si la conception de la géométrie externe du carénage de l'hydrolienne fait entrer en jeu des considérations hydrodynamiques, sa tenue structurale dépend de la résistance aux chargements hydrodynamique et hydrostatique. Cependant, les chargements obtenus dans l'étude hydrodynamique deviennent des entrées dans l'analyse structurale et ont été implémentés à la frontière du maillage structural par le biais d'une routine numérique sous Abaqus. Lors de l'optimisation structurale, l'objectif était de minimiser le ratio «puissance/masse» introduit lors de la conception tout en respectant la condition de résistance et de déflexion maximale du système conçu en matériaux composites. Le meilleur ratio à encombrement constant plaide en faveur des sections cambrées plutôt que l'incidence. Nous avons poursuivi le développement afin de quantifier les risques d'endommagement dû à faibles vitesses d'impact d'objets projetés sur la structure par le courant marin. Un modèle d'endommagement 3D combinant les dommages inter/intralaminaire a été proposé et ensuite validé avec des mesures d'impact sur des structures composites tubulaires. Le modèle a été ensuite appliqué pour l'optimisation et l'analyse structurale de la conception proposée du carénage de l'hydrolienne en présence des chargements hydrodynamiques liés à l'environnement marin et sous chargement dynamique complexe de type impact pour retranscrire l'état réaliste de fonctionnement de l'hydrolienne. La méthodologie de calcul utilisant conjointement une technique submodeling avec un modèle de comportement endommageable des composites stratifiés a montré son aptitude à prédire l'état d'une structure composite soumise à des un choc accidentel ce qui a permis une meilleure sureté de la conception proposée.

Abstract :

A propeller in-house panel method code coupled with the blade element momentum theory (BEM) was used to design a bare tidal turbine which reaches 88% of the Betz limit. The addition of a duct at the same overall cross section area has been investigated. The numerical results show that the ducted turbine's power coefficient, which was computed using the overall cross section area, can be slightly increased if a camber duct profile with a flare angle is used. The hydrodynamic pressure obtained with the panel method code was then implemented as boundary conditions into the FE model in order to compute the static mechanical behavior of the composite duct. However several iterations of material distribution have been performed to satisfy two main criteria which are the damage initiation *according to Hashin criteria and the maximum deflexion at the exit of the duct. This approach leads to introduce the ducted configuration presenting the best ration ‹‹power/mass». Furthermore, to understand the dynamic behaviour and the effects of the low velocity impact damage on the duct structural constraints, a damage model involving inter/intralaminar combination has been developed. The proposed damage model has been validated through low velocity impact experimental measurement. A submodeling approach has been used to reduce significantly the computational time of the duct certification involving damage assessment.*

Mots clefs: Tidal turbine, hydrodynamic, composite materials, impact, damage modelling, design and certification.

1 Introduction

The concept of underwater turbine, called tidal current turbine, designates the device which allows the conversion of kinetic energy produced by marine currents into electric energy. The know-how and the tools used for marine propulsion devices find a new range of applications in this field. An academic panel method code developed for the design of marine propeller was used to design a marine current turbine. The turbine dimension and the tidal current velocity have been taken to comply with the conditions in the Race of Alderney which is the most promising tidal site on the French coast. The site allows the device to have 20 meter diameter without maritime traffic perturbation and the current velocity reaches 3 m/s. The wing section theory and the optimum rotor theory based on the blade element momentum theory were used to obtain the design condition and a first geometry for a bare turbine was obtained. The boundary element method was then used to verify the power coefficient obtained in the presence of the 3D effects and if the cavitation constraints are respected. Subsequently, an iterative procedure has been developed with the same panel code and used to verify if the addition of a duct, at the same overall section with bare turbine, could improve the power output per unit surface. To compute the rotor within the duct an iterative procedure has been developed. The hydrodynamic analysis of the proposed design is carried out to determine the power coefficient and the load distribution along the duct which is basically higher than wind turbine load due to the higher density of the sea water.

Designing composite tidal turbines involves balancing between hydrodynamic performance and structural constraints. Composite materials are used in such application because they mainly provide the following characteristics:

- Excellent corrosion resistance.
- Considerable savings in weight compared with equivalent metal systems.
- Very high strength to weight ratio.
- Simple and effective jointing and lower installation costs.
- Can be relatively modelled into complex shapes.

This paper seeks to develop a design methodology for ducted horizontal axis tidal turbines based on combined hydrodynamic/structural constraints and to provide a compromise between hydrodynamic efficiency and structural integrity as well as the dynamic behaviour since the device is intended to accidental choc due to several sea events. However, the duct of a tidal turbine can be prone to accidental low velocity impact. This event may be critical enough to cause internal damage not visible on the material surface leading to reduce completely the structural integrity. Damage modeling [1] of light weight structure is an active challenge in many applications such as marine, aerospace and naval sectors. Though, these structures are very susceptible to degradation of their properties and consequently a catastrophic brittle failure can occur with more than one damage modes [2].

2 Tidal turbine design

Most marine current turbine designers use the Blade Element Momentum (BEM) theory to predict their hydrodynamic performances. The BEM theory, well described in Jamieson [3], does not take the 3D effects into account. A first account of the 3D effects is given by the lifting line theory with some restriction on the blade aspect ratio (Λ). This restriction is minimized when using 3D panel method based on potential flow theory [4] which is faster and easier to operate than Navier-Stokes solvers [5] which require 3D mesh and turbulence models. The numerical results of the panel method code have been compared to the experimental measurements of Bahaj et al. available in the literature [6] and a good agreement has been found up to the area where there is no flow separation [7]. However, there is no reason to propose a design which presents flow separation and stall because we also know that flow separation is closely linked to the cavitation inception which dramatically decreases the hydrodynamic performance of tidal turbines.

Once the hydrodynamic analysis is completed and the material selected, a static finite element analysis (FEA) is performed to take the structural design constraints into account. The ABAQUS DLOAD user define subroutine has been used to implement our interpolation procedure in order to use the hydrodynamic pressures computed with the panel method code as boundary conditions for the FEA. However, the second part deals with the design of the duct to find a balance between hydrodynamic performance and structural integrity using composite materials. However several iterations of material distribution have been performed to satisfy two main criteria. These criteria are the maximum deflection (allowable maximum strain not greater than 2% of the chord) and the Hashin failure criteria. The proposed static approach leads to introduce the ducted configuration presenting the best ration ‹‹power/mass» which increase the design efficiency.

2.1 Design procedure of the bare configuration

The design of tidal turbine is mostly imposed by the cavitation inception criterion and flow separation has to be avoided. Therefore the angle of attack of each blade section and the minimum pressure must be respected. Starting from a given profile, it must be ensured that its angle of attack does not vary outside the cavitation-free range. The 15% thickness NACA63-415 profile which presents a recompression on the suction side at 30% of the chord after the leading edge when its lift coefficient, Cl, is equal to 0.4 has been retained. Once the profile is chosen, its pressure coefficient, Cp, distribution around the targeted Cl is known and the minimum pressure coefficient value together with the immersion allow the computation of the maximum velocity which the profile can sustain without cavitation from which the rotational speed is extracted and therefore the TSR of design. Using such a profile, the minimum Cp should not drop below -3 and with an immersion of 15 meters, the maximum velocity can safely reach 12 m/s which gives the design TSR, TSR = 4.

The BEM is then used to indicate the first pitch distribution to obtain a maximum power coefficient. Subsequently, the panel method is used to assess the hydrodynamic performance taking the 3D effects into account and to determine how far we are from the Betz limit and if we respect the cavitation constraints. Several adjustments to the geometrical parameters as the chord distribution are then needed to obtain a final bare water turbine geometry which reaches 88% of the Betz limit. The rotor design procedure is presented in Table 1.

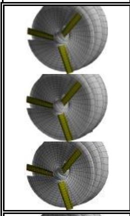
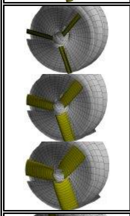
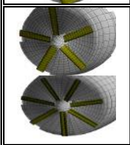
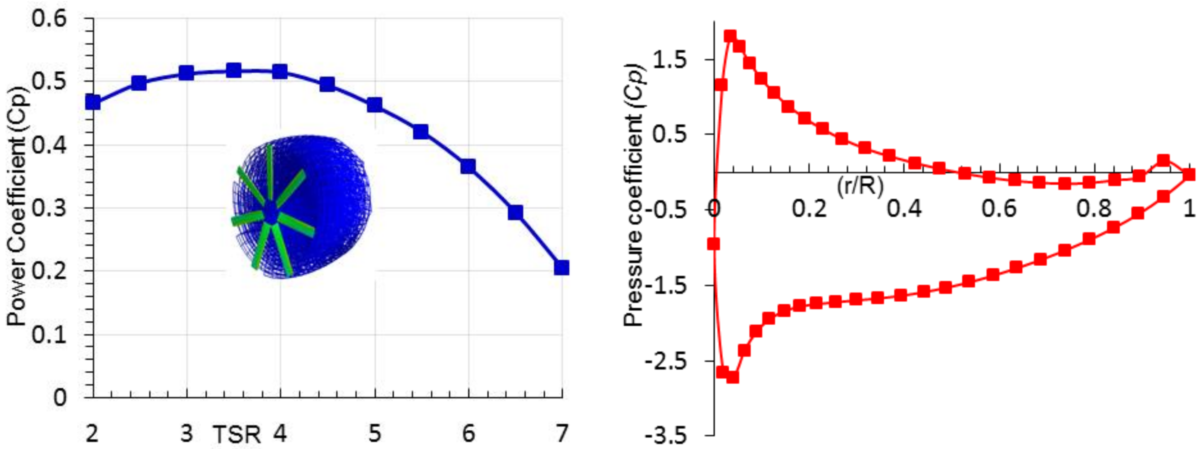
20m rotor diameter	blade number	geometrical pitch at 70% of the blade	chord distribution	aspect ratio	torque coefficient	power coefficient	power coefficient in % Betz	Power output
	Z	P/D	C/D	AER	K_q	C_p	$C_{p\%\ Betz}$	P (Watts)
	3	0.5	0.1	0.095	0.011	0.361	60.842	1.57E+06
	3	0.4	0.1	0.095	0.013	0.431	72.790	1.88E+06
	3	0.6	0.1	0.095	0.008	0.271	45.791	1.18E+06
	3	0.4	0.07	0.067	0.012	0.395	66.591	1.72E+06
	3	0.4	0.166	0.159	0.013	0.438	73.908	1.90E+06
	3	0.4	0.25	0.239	0.012	0.398	67.144	1.73E+06
	5	0.4	0.1	0.159	0.015	0.492	82.987	2.14E+06
	7	0.4	0.07	0.159	0.016	0.523	88.197	2.24E+06

***Table 1:** Rotor design procedure*

Following the design procedure, a 7 blade tidal turbine was obtained which should be able to extract half the flow power at its design TSR (TSR=4), i.e. 2.24 MW and hence more than 7.13 kW/m² (*Figure 1*).



(a) Power coefficient versus TSR

(b) Pressure coefficient (ITTC Cp) at TSR=4 (cavitation avoided)

***Figure 1:** Hydrodynamic design of the rotor involving panel method coupled BEM*

2.2 Design procedure of the ducted configuration

The flow around the propeller is computed in the presence of the duct induced velocities. We then compute the propeller induced velocities on the surface of the duct. The procedure is repeated until convergence which occurs after a few iterations (CPU ~ 45mn on a laptop). Using the best rotor geometry obtained in the bare design procedure, we investigated if the addition of a duct could significantly improve the total output power. The duct section induces a circulation which accelerates the flow into the rotor increasing the available power. The duct uses a significant part of the cross-section area and in order to be of advantage, the power output has to be superior to the one of a bare rotor using the same overall cross-section area which is in the present case 20m overall diameter for both bare and ducted turbine. A flowchart of the hydrodynamic design of the ducted configuration is shown in Figure 2.

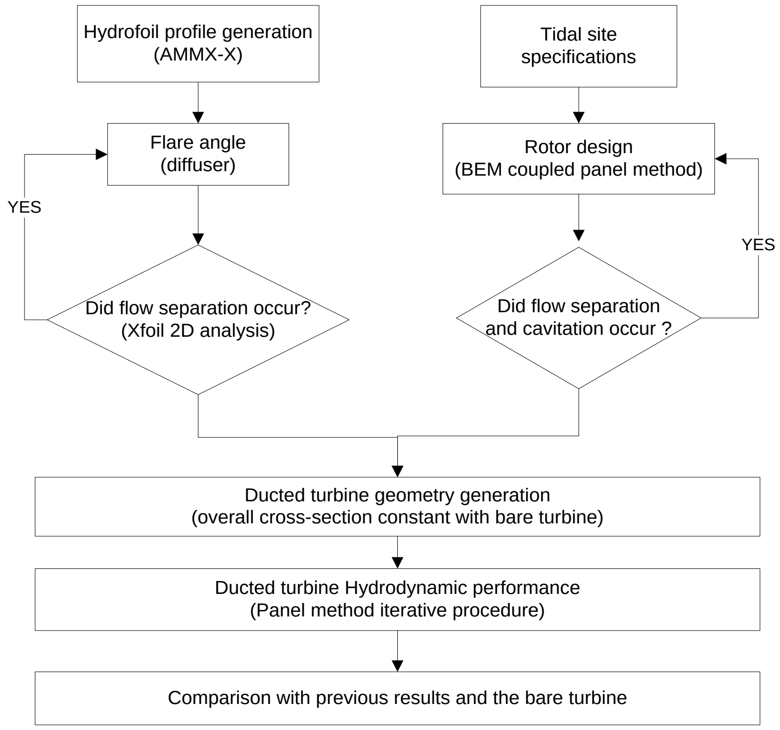


Figure 2: *Flowchart of the hydrodynamic modelling process of ducted turbine*

Several duct configurations were generated and computed into the panel method program at water velocity 3 m/s to assess the power coefficient of each design and the generated hydrodynamic load. The potential flow code cannot predict the flow separation and can produce erroneous figures for the section's largest lift coefficients. If we consider the duct as a wing with an infinite span, the flow separation occurrence should coincide with the 2D section. A software code like Xfoil indicates that flow separation occurs for a 7° angle of flare for the 2D duct profile. We compare various flare angles (Table 2) with the same profile (AMM6-12) which according to the Xfoil 2D section analysis there is no occurrence of flow separation. The Xfoil code combines second-order panel method and fully-coupled viscous interaction. The viscous effects on the duct could be fully analysed with Computational fluid dynamics (CFD) analysis but here we are only interested to know whether flow separation occurs since it may be linked to the occurrence of cavitation which could seriously affect the hydrodynamic performance of such a system. After the first stage a blade geometry presenting neither flow separation nor cavitation was obtained. The best rotor design was then equipped with a duct respecting the same overall diameter.

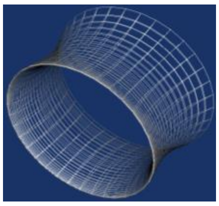
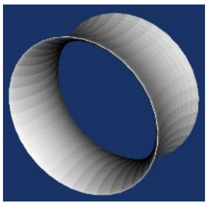
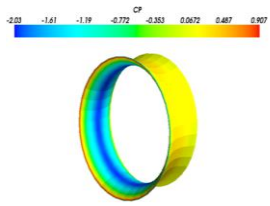
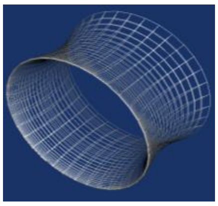
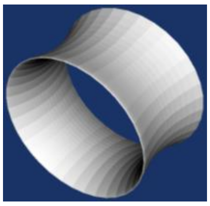
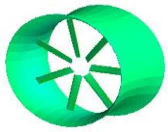
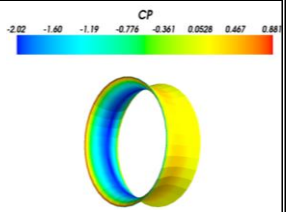
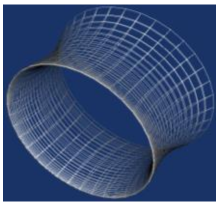
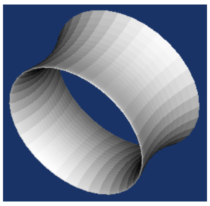
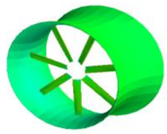
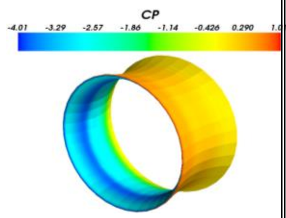
Flare angle°	duct generation AMM 12-6 profile	surface mesh	power coefficient of the ducted configuration	hydrodynamic pressure coefficient (ITTC)
0°			 $C_p = 0.5388$ TSR=5.5	
2°			 $C_p = 0.5426$ TSR=5	
5°			 $C_p = 0.5531$ TSR=6	

Table 2: *Duct geometries and hydrodynamic pressure computed with the panel method program*

3 Structure constraints

The panel method coupled finite element analysis (PM-FEA) allows using the hydrodynamic pressure obtained in the hydrodynamic design as input condition into the FEA software. The PM-FEA coupled method computes the structural response of the composite duct at any given hydrodynamic loading conditions. Once the hydrodynamic analysis has been carried out, the DLOAD subroutine was implemented into Abaqus software to project the hydrodynamic pressure on the duct panel structural mesh. The procedure consists to project these integration points on the panel method mesh and then we compute the pressure on these points projected by interpolation from known values on the control points of the panel method mesh (Figure 3).

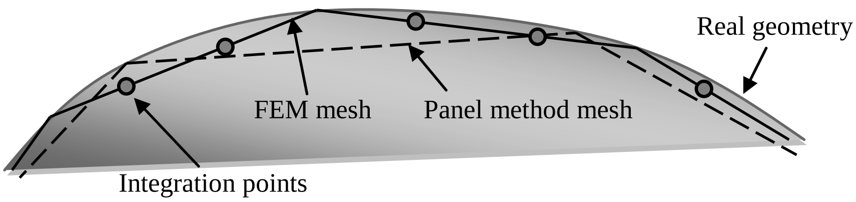
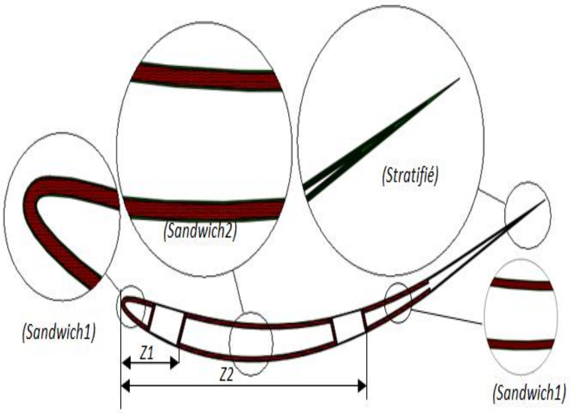
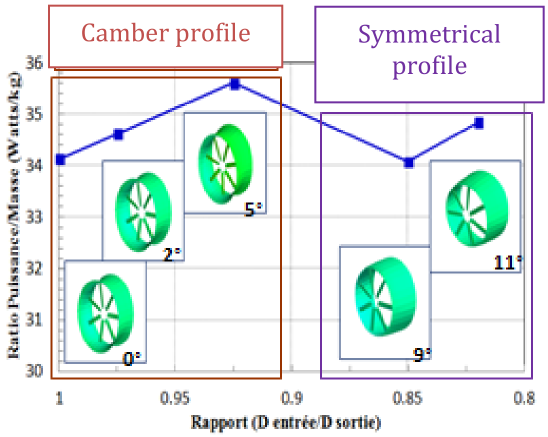


Figure 3: *Interpolation implemented into the Dload subroutine*

However, several iterations of material distribution have been performed to satisfy two main criteria. These criteria are the maximum deflection ($\varepsilon_{allowable}$ < 2% of the chord) and the Hashin failure criteria. This approach leads to introduce the ducted configuration presenting the best ration ‹‹power/mass››, Figure 4. More information about the materials iterations can found in [8].



(a) material distribution along the chord (final iteration)

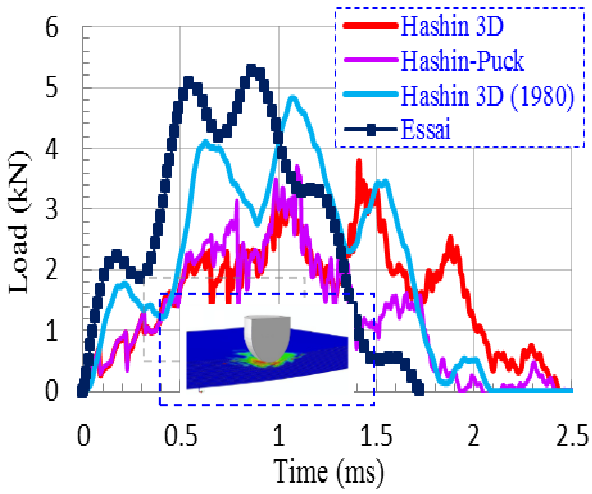


(b) Ratio <power/mass> versus <D-inlet/D-outlet>

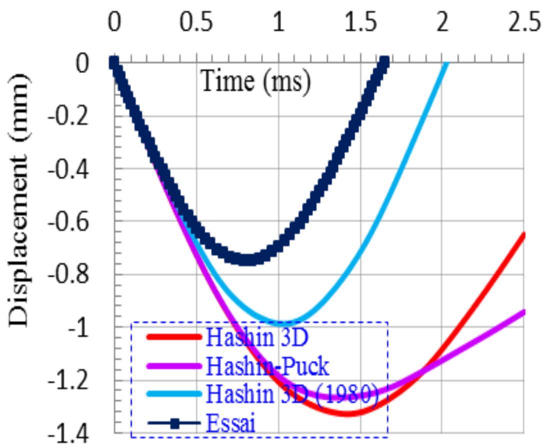
Figure 4: *Structural design of the ducted configuration using composite materials*

4 Dynamic behaviour of the composite duct

The dynamic part of this work presents a numerical investigation of the dynamic behaviour linked to the damage resistance and the certification of structural elements of an all composite ducted tidal turbine. The numerical analysis has been performed by means of advanced numerical models implemented into Abaqus/Explicit. The intralaminar damage model was implemented using a 3D damage model including damage onset and propagation implemented into a VUMAT subroutine using various 3D failure criteria. Hence, delaminations were modelled using the cohesive zone model (CZM) and a bilinear law available in Abaqus/Explicit. Validation of the numerical mesoscale damage prediction methodology has been performed by simulation of the experimental low-velocity impact cases on tubular structures performed by Tarfaoui et al. [8]. Figure 5 shows good correlation has been obtained between numerical results and experimental data. All the details concerning the damage model formulation and the validation curves for low velocity impact investigation are being under review in a journal.



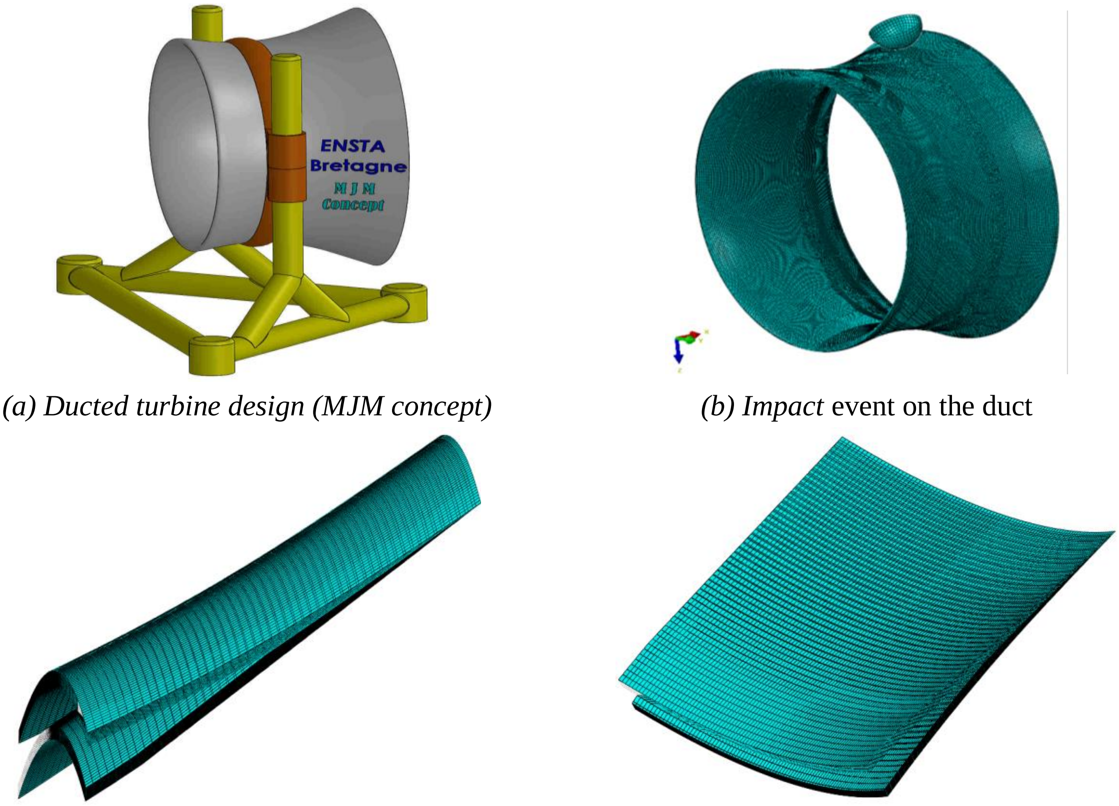
(a) Impact force



Displacement of the impactor

Figure 5: *Comparison between numerical model and experimental measurements under low velocity impact (V=1.55 m/s)*

Once the damage model is validated, a submodeling approach has been used to reduce significantly the computational time. The main objective of the numerical approach is to propose a structural design methodology leading to improve the design efficiency and reduce the certifications cost of ducted tidal turbine, keeping in mind a commercial scalability of the MJM concept (Mahrez-Mostapha &Jean-Marc design), see *Figure 6*(a). The proposed approach reveals some interesting points concerning the severity of the impact damage and the safety of the duct (*Figure 6*(b)). The results performed in this study concern only the degradation of the zone in contact with the impactor (*Figure 6*(c)) and the region in front of it (*Figure 6*(d)) but the procedure could be applied to other zone of the duct regardless of the impact scenario.



(a) Ducted turbine design (MJM concept)

(b) Impact event on the duct

(c) Solid substructure 1of the duct (solid elements)

(d) Solid substructure 2 of the duct (solid elements)

Figure 6: *Substructure technique*

The duct of the tidal current turbine is especially confronted by the impacts due to its particular position. The impact damage aspect has been examined in detail in the present research study and a strategy has been developed and devoted to the certification of different structural parts of the composite duct such shown if **Figure 7**.

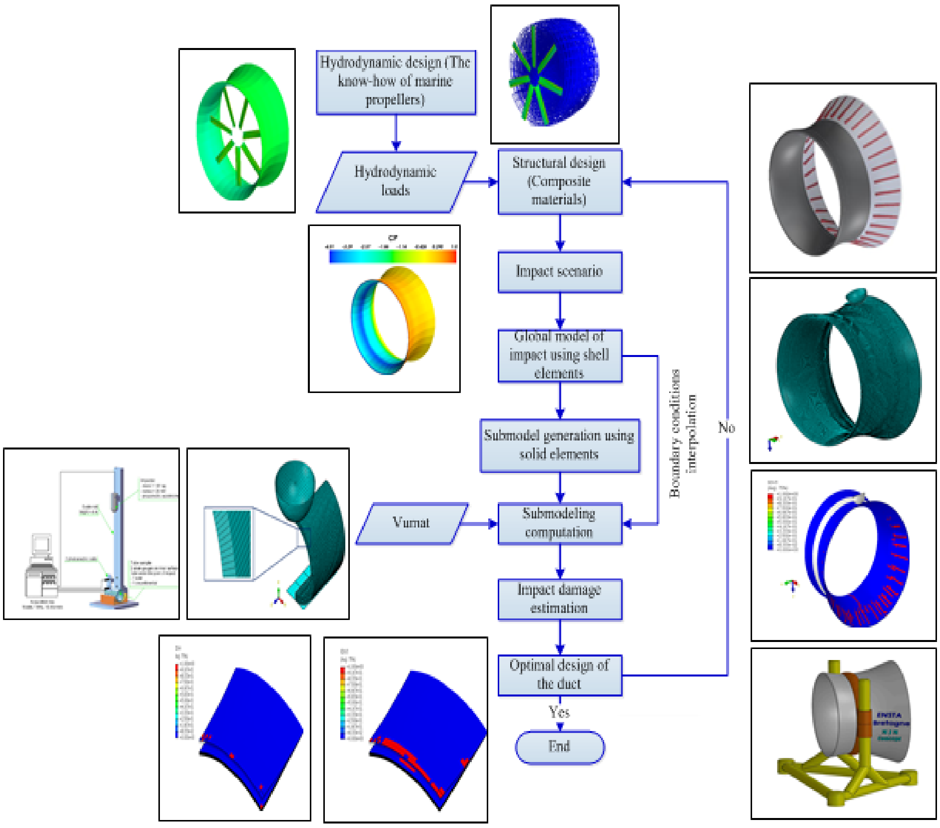


Figure 7: *Damage methodology certification involving 3D damage model inter/intralaminar combination and submodelling technics*

5 Conclusion

In order to understand the influence of the damage induced by an accidental impact of complex composite structures intended for marine renewable energy application, the damage certification methodology involving intra/interlaminar combination of an impact event on an all-composite duct has been performed in a realistic marine conditions. Though, the analysis of an impacted complete duct using a submodeling technic has given the chance to examine the duct behaviour under dynamic loads in realistic marine conditions and to take into account correctly the induced damage in the design of the MJM ducted tidal turbine concept which lead to minimize the certification cost linked to the dynamic behaviour. The MJM composite duct is intended to future lines of investigation that should guide the future program of experimental at the DGA and IFREMER experimental facilities in cavitation tunnel and towing tank which aims to well describe the hydroelastic behaviour and with our academic partners at Northumbria University for the development of a robust damage model based on the ONERA experiences feedback and the Langley research centre.

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