

## Racing yacht appendages optimization using fluid-structure interactions

R. Balze, Nedeleg Bigi, Kostia Roncin, Jean-Baptiste Leroux, Alain Nême,

Vincent Keryvin, A. Connan, H. Devaux, D. Gléhen

### ▶ To cite this version:

R. Balze, Nedeleg Bigi, Kostia Roncin, Jean-Baptiste Leroux, Alain Nême, et al.. Racing yacht appendages optimization using fluid-structure interactions. 4th Innov'Sail conference, Jun 2017, Lorient, France. hal-01710681

## HAL Id: hal-01710681 https://ensta-bretagne.hal.science/hal-01710681

Submitted on 7 Feb 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

# RACING YACHT APPENDAGES OPTIMISATION USING FLUID-STRUCTURE INTERACTIONS

**R. Balze**, GSea Design F-56100 Lorient and Univ. Bretagne Occidentale, FRE CNRS 3744, IRDL, F-29200 Brest, France, remy@hds-design.com

**N. Bigi**, ENSTA Bretagne, FRE CNRS 3744, IRDL, F-29200 Brest, France, nedeleg.bigi@ensta-bretagne.org

**K. Roncin**, ENSTA Bretagne, FRE CNRS 3744, IRDL, F-29200 Brest, France, kostia.roncin@ensta-bretagne.fr

**J. B. Leroux**, ENSTA Bretagne, FRE CNRS 3744, IRDL, F-29200 Brest, France, jean-baptiste.leroux@ensta-bretagne.fr

**A. Nême**, ENSTA Bretagne, FRE CNRS 3744, IRDL, F-29200 Brest, France, alain.neme@ensta-bretagne.fr

V. Keryvin, Univ. Bretagne Sud, FRE CNRS 3744, IRDL, F-56100 Lorient, France, vincent.keryvin@univ-ubs.fr

A. Connan, GSea Design F-56100 Lorient, France

H. Devaux, GSea Design F-56100 Lorient, France, herve@hds-design.com

D. Gléhen, GSea Design F-56100 Lorient, France, denis@gseadesign.com

GSEA Design developed a fluid structure method (FSI) suitable for early design stage of appendage with complex shapes dedicated to the America's Cup flying catamarans. The aerodynamic loading and the boat weight are counteracted by the appendages and mainly the daggerboard. Consequently, the appendage structural design is very critical. Based on a 3D lifting line and a modified beam element method, the GSEA Design FSI method takes less than one minute to compute. An illustrating example on a L-shape appendage shows that the FSI results compared to a non-FSI results can be particularly different at the elbow. Thanks to the short computational time of the method, multi-objective optimizations can be performed. For instance, a second illustrating example shows the optimization of the appendage weight and stiffness.

#### NOMENCLATURE

$\operatorname{Symbol}$	Definition	(unit
$GI_{zz}$	Torsional Stiffness	( N.n
$S^*$	Internal Area of closed thin profile	$(m^2)$
$l_i$	Length of element i	(m)
$t_i$	Thickness of element i	(m)
$G_i$	Coulomb Modulus of element i	(N.m
ho	Density of water	(kg.n
Р	Pressure	(N.m)

#### 1 INTRODUCTION

A sailing boat is a wind driven vessel in permanent equilibrium between two fluids: air, that provides the power required for its movement through sails or wingsails, and water, on which the sailing boat is based. In addition to hulls, structural parts that allow this support are appendages: rudders, foils, daggerboards... The three last America's Cup (33<sup>th</sup>, 34<sup>th</sup> and 35<sup>th</sup> led engineers

of GSEA Design to design appendage in order to improve performance and stability of sailing catamarans of teams such as *Oracle Team USA*, *Artemis Racing* and  $n^2$ ) *Groupama Team France*. Although, the balance of these sailing boats can be relatively stable when their hulls remain in the water, it will be more precarious when they fly. The hydrodynamic loading of an appendage can lead  $n^{-2}$ ) to large deformations. When this appears, a coupling  $n^{-3}$ ) between the hydrodynamic loading and the appendage  $n^{-2}$ ) shape is necessary to compute the equilibrium of an appendage. Consequently, a Fluid Structure Interaction (FSI) model should be applied. From a structural engineering point of view, the aims of GSEA Design engineers with this tool is to :

- know the appendages equilibrium in water flow
- get closer to the real load-cases applied on the boat
- optimize appendage structure to stabilize boat fly

Since an optimization process requires several FSI calculations, a fast method in term of CPU time is needed.



Figure 1: Groupama Team France catamaran AC45 Test (©*Eloi Stichelbault / Groupama Team France*)



Figure 2: Artemis Racing catamaran AC45 Turbo (©*Eloi Stichelbault / Artemis Racing*)

The flow around an appendage is generally three dimensional and lead mostly to bending and torsional deformations and displacements. A 3D RANS method for the flow computation coupled with a 3D finite element method could be appropriate to model the physical phenomenon. Nevertheless, these methods are out of the scope of the paper due to their long CPU time. A faster and consistent manner to deal with the FSI calculation in order to optimize a structural design is the use of a non linear 3D lifting line [2] coupled with the Timoshenko beam element method [6]. Duport et al. [2] show very accurate results for small angle of attack compared to the 3D RANS method. Moreover, it can be shown that the bending and the torsional stiffness of the structure has a high impact on the equilibrium. Consequently, a pseudoanalytical method has been developed to evaluate these properties. GSEA Design has thus developped a tool for appendage design using FSI calculation and called Sofia 1.

In a first part, the FSI method and the pseudoanalytical method to evaluate the bending and torsional stiffness are introduced. Then the iterative numerical scheme to reach equilibrium is presented. In a second part, two illustrating examples are presented, one on a simple FSI calculation and a second on the optimization of a dagger-board structural design in term of mass and stiffness.

#### 2 APPENDAGE MODELING

#### 2.1 APENDAGE DESCRIPTION

An appendage is a part of the boat beneath the hull. Classical appendages are *rudders* which enables to steer the boat and *dagger-boards* which counters the leeward thrust of sails (Figure 3).

Since the aim is to design a flying boat, appendages able to produce a vertical lift force are used: *T-Shaped Rudder* and *L-shaped dagger-boards* (Fig. 3). In addition to their vertical lifting force, they produce transverse components forces needed for the global equilibrium of the sailing boat.



Figure 3: Different types of appendages : *Daggerboard*, *C-Foil*, *T-Rudder* and *L-Foil* 

An appendage can be seen as a simple supported beam. The appendage orientation is parametrized with three angles depicted in Fig. 4. Altitude over the free surface is also an important parameter that can modify the loadcase distribution.



Figure 4: Appendage coordinate system

 $<sup>^1{\</sup>bf S}{\rm tructural}$  Optimisation using Fluid-structure Interactions for Appendage design

For a L-shaped foil, its vertical part of a foil is commonly called *shaft* whereas its horizontal part is called *tip*.

#### 2.2 HYDRODYNAMIC MODEL

The fluid flow around the sections along the span, except near the tip, behaves essentially as two-dimensional flow for lifting bodies with high aspect ratio. However, the pressure difference between intrados and extrados creates a more and more significant flow component along the span as we approach the end of the tip. This creates a flow enrollment around the tip edge creating the socalled tip vortex, which can be source of significant loss in lift and energy. Consequently, the fluid flow around the appendage should be considered as three-dimensional to be accurate. This phenomenon is particularly well represented on a straight appendage with the so-called lifting line method proposed by Prandtl [1] in 1918.

However, Prandtl lifting line method is strictly applicable only on straight span appendage. Since appendages used on high performance sailing boats are curved in order to allow the boat to fly over water, the non linear 3D lifting line method proposed in [2] (see also [4]) is here applied. Indeed, this extension of the lifting line theory is an iterative numerical method which takes into account the evolution of the dihedral and sweep angles. In Figure 5, the fundamental difference between the Prandtl's lifting line method [1] and the method proposed by Duport et al. [2] is that the bounded vortices are no longer aligned and parallel. The induced velocity at any collocation point may be dependent of the other bounded vortices. Then, using the iterative method presented in Anderson [3] to calculate the vorticity, the non-linearity of section lift coefficients, for example computed with 2D RANS method, can be taken into account.

The choice of this mode lsupposes not to taking into account the effects of ventilation due to free surface. We consider, here, that we are in fully attached regime (see [8]). This regime is that which is sought by naval architects, performance prediction analyst and navigators to obtain maximum efficiency of their appendages. It is also that which is the most dimensioning from a structural point of view when assuming a static equilibrium.

#### 2.3 STRUCTURAL MODEL

The hydrodynamic model is coupled with the Timoshenko beam model [6], which takes into account shear forces.

Figure 6 shows the element description : an element joins the nodes I and J. At each node corresponds a section, a laminate and mechanical properties such as:

- Young and shear modulus
- Section and reduced section considering local coordinate system



Figure 5: Vortex distribution along a wrap span

- Bending and torsion inerties considering local coordinate system



Figure 6: Beam model in Sofia

Section angle of attack is highly coupled with bending and torsion of the appendage. As a result, an accurate evaluation of the bending and torsional stiffness of finite beam element model has a high impact on the load-case, and so on the FSI calculations. Consequently, a pseudoanalytical method has been developed in order to obtain a good evaluation of bending and torsional stiffness of a composite material section [6][7][8]. For instance, torsion stiffness of fairing is the same as thin profile [8] and can be expressed as :

$$GI_{zz} = \frac{4 \cdot S^*}{\sum_i \left(\frac{l_i}{G_i \cdot t_i}\right)} \tag{1}$$

The mechanical properties of section obtained with this pseudo-analytical method has been validated using 3D finite element analysis.

#### 3 FLUID STRUCTURE INTERACTION NU-MERICAL SCHEME

#### 3.1 CLASSICAL ITERATIVE PROCESS

GSEA Design focused on hydro-elastic phenomena and FSI on lifting structures in water in order to provide answers to performance, efficiency and stability issues.



Figure 7: Numerical scheme of the quasi steady fluid structure interaction

Here, the fluid-structure interactions model developed is a quasi static and iterative process (Figure 7). At each iteration, an equilibrium is reached. The assumption are :

- Slender structure
- Sections are not deformable
- Small perturbations (linear stiffness matrix)

A hydrodynamic loading is firstly calculated, considering the appendage attitude in the fluid flow. This hydrodynamic loading is then applied to the non-deformed or deformed geometry of the beam model. The iterative process ends when the convergence criteria, between two successive fluid-structures loops, is lower than a user defined convergence criteria. At the end, the internal forces and deformed geometry calculated allow to design the appendage regarding stresses or stiffness.

#### 3.2 TARGET LOADS

A second type of calculation considers side force denoted by  $F_y$  and lift force denoted by  $F_z$  as inputs. Sofia is able then to optimize appendage position in the fluid in order to reach the target loads. It can give for instance the corresponding Rake and Yaw angles for the boat to take off the free surface:

$$\begin{pmatrix} F_y(yaw, rake) \\ F_z(yaw, rake) \end{pmatrix} - \begin{pmatrix} F_{y-target} \\ F_{z-target} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$
(2)

Equation (2) is solved numerically. This method works with all the developed hydrodynamic loading and calculation methods.

#### 4 ILLUSTRATING EXAMPLE

In order to prepare the  $35^{\text{th}}$  America's Cup, *Franck Cammas* and *Groupama Sailing Team* have decided to build a C Class catamaran (Figure 8). These catamarans are powered by a 27.8 m<sup>2</sup> wing-sail. They are 7.62 meters length and 4.20 meters width. Groupama C Class has been designed with a close collaboration between several architects and has won two times the *Little Cup* (2013 and 2015).



Figure 8: Groupama catamaran Class C (Groupama Sailing Team)

#### 4.1 FSI RESULTS

Each load-cases are characterized by a boat speed, an altitude over free surface and a Cant angle. *Sofia* can then calculate yaw and rake angles. The corresponding loadcase enables to design this appendage (Fig. 9) regarding stiffness.

Figures 10 and 11 show respectively the bending moment and the shear stress along the span for two method of calculation. The first method in red line represents the results without FSI, *ie*, only the first loop of the FSI iterative algorithm Fig. 7 is performed. The second method, in blue line, represents the result with full FSI calculation.

For this illustrating example, the FSI calculation leads to lower internal forces at the bottom bearing and at the elbow, the connection between the tip and the shaft. Therefore, by considering this more accurate loading distribution, the appendage design can be lighter.

In term of CPU time, the FSI computation takes around one minute on classical PC.

#### 4.2 OPTIMIZATION RESULTS

Optimization can be proceeded with *Sofia*. In this illustrating example, UD quantity in appendage stock is optimized, the objective is to minimize mass and to maximize stiffness regarding failure stresses. The multi-optimization results are plotted in Fig. 12 in term of Pareto-efficient frontier. The best designs are distributed near the red curve. It can be shown that a lighter appendage has a lower stiffness and a stiffer appendage is heavier. The final design is chosen in agreement with the requirement specifications and the designer experience.



Figure 9: Class C foil geometry (on the left and middle) and deformed geometry (on the right)



Figure 11: Shear force distribution along the span



Hotopolitical and the second s

Figure 12: Pareto-efficient frontier to optimize UD quantity along an appendage's span

Figure 10: Bending moment distribution along the span

The necessary calculation the Pareto-efficient frontier in Fig. 12 takes around 6 hours on classical PC.

#### 5 CONCLUSION

A fast and efficient fluid structure interaction method has been presented. This method is based on an iterative algorithm using a 3D non-linear lifting line for the hydrodynamic loading and a modified beam element method. The beam element method has been modified in order to represent with good accuracy the bending and torsional stiffness. It has been shown that it is necessary to tune the initial position of the appendage in order to reach a target load. The two illustrating examples shows that the method is fast in term of computation time, which is necessary to study a wide range of design.

A simple multi-objective results has been presented in order to optimize the appendage mass and stiffness. Further investigations to optimize the boat speed and stability can be performed with a velocity prediction program coupled to the presented FSI method.

#### 6 ACKNOWLEDGEMENT

The authors would like to thank *Artemis Racing* and *Groupama Team France* for their help to validate this tool.

#### REFERENCES

- Prandtl, L., *Tragflügel Theorie*, Nachrichten von der Gesellschaft der Wisseschaften zu Güttingen, Geschäeftliche Mitteilungen, Klasse, pp. 451–477, 1918.
- [2] Duport, C., Leroux., J. B., Roncin., K. & al. Comparaison of 3D non-linear lifting line method calculations with 3D RANSE simulations and application to the prediction of the global loading on a cornering kite, 15<sup>ème</sup> Journées de l'hydrodynamique, 2016.
- [3] Anderson, J. D., & Corda, Numerical lifting line theory applied to drooped leadingedge wings below and above stall, Journal of Aircraft, 17(12), 898-904, 1980.
- [4] Phillips, W. F., & Snyder, D. O. Modern adaptation of Prandtl's classic lifting-line theory, Journal of Aircraft, 37(4), 662-670, 2000.
- [5] Young, L. Y., Brizzolara, S., Numerical and Physical Investigation of a Surface-Piercing Hydrofoil, 3<sup>rd</sup> International Symposium on Marine Propulsors, 2013.
- [6] Timoshenko, S. P., & Young, D. H. Theory of structures, New York: McGraw-Hill, 1, 1965.
- [7] Vallat, P., Résistance des Matériaux appliquée à l'aviation, Librairie Polytechnique CH. Béranger, 1950.

- [8] Young, W. C., & Budynas, R. G. Roark's formulas for stress and strain, New York: McGraw-Hill, Vol. 7, 2002.
- [9] Dhatt, G., & Touzot, G. Une Présentation de la méthode des éléments finis, Collection Université de Compiègne, 1984.

#### 7 AUTHORS BIOGRAPHY

**R. Balze** is a Doctor in Mechanical Engineering in GSea Design and university lecturer and researcher at Univ. Bretagne Occidentale. He received his Ph.D. degree (2012) with Honours from the Ecole Centrale Lyon, France. His research skills mainly cover hydroelasticity and FSI analysis on soft lifting structures.

**N. Bigi** is Ph.D. Student of Naval Hydrodynamics at the graduate and post graduate school of engineering, Ecole Nationale Supérieure de Techniques Avancées Bretagne (ENSTA Bretagne), Brest, Brittany, France. His Ph.D. thesis is on the dynamic simulations of ships towed by kite.

**K.** Roncin is Associate Professor of Naval Hydrodynamics at the graduate and post graduate school of engineering, Ecole Nationale Supérieure de Techniques Avancées Bretagne (ENSTA Bretagne), Brest, Brittany, France. He is currently the head of the Master of Science in Naval Hydrodynamics and gave during several years specialized lectures in naval construction and design. He received his Ph.D. degree (2000) with Honours from the University of Nantes, France. His research skills cover seakeeping, manoeuvrability and sail yacht dynamics.

**J. B. Leroux** is Associate Professor of Naval Hydrodynamics at the graduate and post graduate school of engineering, Ecole Nationale Supérieure de Techniques Avancées Bretagne (ENSTA Bretagne), Brest, Brittany, France. He is currently in charge of fluid mechanics courses. He received his Ph.D. degree (2003) with Honours from the University of Nantes, France. His research skills mainly cover hydodynamics and cavitation of lifting bodies.

**A.** Nême is Associate Professor of Engineering and Materials Science at the graduate and post graduate school of engineering, Ecole Nationale Supérieure de Techniques Avancées Bretagne (ENSTA Bretagne), Brest, Brittany, France. He is currently in charge of mathematics and strength of materials courses. He received his Ph.D. degree (1994) with Honours from the Ecole Normale Supérieure de Cachan, France. His research skills mainly cover linear and non-linear analysis in structural engineering.

**V. Keryvin** holds the current position of Professor in Mechanics of Materials at the University of South Brittany, France. His research areas include the mechanics of glasses and composite materials.

**A.** Connan is an Engineering student at Ecole Centrale Nantes. He is currently doing a placement year which has included an 11-month Engineering internship on the Sofia software program in GSea Design and the University of South Brittany. Antoine will finish his Degree next year with a specialization in Hydrodynamic engineering and as a next step is looking for an opportunity to work with racing boats.

**H. Devaux** is a Mechanical Engineer Doctor. He founded HDS Design in 1994 and is honorary president of GSea Design. He has a background in structural dynamics. He can boast about a beautiful prize list in the world of racing yachts. He was involved in the last revolution of the America's Cup with multihulls, daggerfoils and wingsails.

**D.** Gléhen is a Mechanical engineer, CEO of GSea Design, in Lorient. He was the right-hand-man of Hervé Devaux in HDS Design since 1994 before founding GSea Design in partnership with HDS Design in 2010. He has a background in structural analysis and dynamics. His successes in offshore racing yacht structural design are numerous.