

FLUTTER OF RACING YACHT KEELS AND APPENDAGES

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In the field of aeroelasticity, flutter is a well-known instability phenomenon. Flutter is a synchronized vibration which takes place in a flexible structure moving through a fluid medium. It occurs when two regular, rhythmic motions coincide in such a way that one feeds the other, drawing additional energy from surrounding flow. A classic case of wing flutter might combine wing bending with either wing twisting.

Flutter appeared for the first time on racing yacht keels with composite fins, so in water, in 2004, on both the IMOCA 60 POUJOLAT-ARMORLUX, which lost her keel, and SILL. Following these problems - particularly following the loss of the keel of Bernard STAMM sailboat, accident that could have dramatic consequences for the skipper - HDS company focused on the phenomenon.

This paper will introduce the strategy of HDS faced to the problem and the analytical and numerical methods implemented to estimate the flutter critical speed. Our model is based on a truncated modal basis for the most energetic modes which are generally, for a bulb keel, the lateral bending predominant mode and the torsion predominant mode. One of our requirements was to make a simple model in order to integrate the calculation of the flutter critical speed in the first design loops of a composite or steel keel. Besides, an other requirement was to be able to calculate flutter critical speed on other type of appendages: hydrofoils, daggerfoils, daggerboards, rudders... This model has worked well for the two cases of flutter appeared on IMOCA sailboat keels. Besides, to verify the quality of the model and to complete our analysis of flutter phenomenon on racing yacht keels, a 3 dimensional multiphysic simulation has been developed using the software ADINA.

NOMENCLATURE

Xb, Yb, Zb	Boat axis system
Xk, Yk, Zk	Keel axis system
x, y, z, t	Space and time variables
ux, uy, uz	Translation degree of freedom
$\theta_x, \theta_y, \theta_z$	Rotation degree of freedom
Ct	Torsional center (neutral line position)
F	Lift center
Λ	Keel sweep angle
K	Stiffness matrix
M	Mass matrix
V	Fluid velocity
i	Incidence angle
A	Slice area
c	Linear lift coefficient
ρ_w	Water density
j	Complex number $j^2 = -1$
ξ_i	Damping terms
η_i	Damping rates $\eta_i = 2 \cdot \xi_i$
ω_i	Eigen frequencies in rad/s
F _i	Eigen frequencies in Hz
F _w	Eigen frequencies in water in Hz
ϵ_i, Ω_i	Real (imaginary) part of the roots
α_i	Global "damping" rates including flow
M _a	Added mass due to bending
I _a	Added inertia due to torsion
ϵ	Symbol used for a value close to zero
δ_{ii}	Phase
a _{ii}	Amplitude

1 INTRODUCTION

In September 2004 'Cheminées Poujoulat - Armor Lux' lost her composite keel in mid-Atlantic. Her skipper Bernard Stamm recalls: 'I was going down below at the end of a surf at 27 knots when I felt the keel making horrendous thrashing vibrations, almost immediately the keel broke and the boat capsized. I just had time to call Mark Turner (race director) before water flooded in and the boat inverted.' Earlier that year Roland Jourdain on 'Sill et Veolia' had disturbing vibration problems in the composite keel when sailing at around 20 knots in calm sea. His experience raised concern for Jean Le Cam aboard 'Bonduelle' - an identical sistership to 'Sill et Veolia' - although she had never had such problems. Because of safety precautions, both pulled out of The Transat race even before it started. An increase of the torsional rigidity of the foil, by adding to the laminate permitted thereafter, on these two boats, to overcome the problem. But the composite keel flutter phenomenon remained an open question for yacht designers.

Following the composite keel flutter problems, HDS tried to better understand what are the sailing conditions and the parameters of a keel design that could cause flutter. The main questions asked are 'Why are composite keels susceptible to flutter, and is it possible to predict and prevent this behaviour?', then 'Can a fair indication of the flutter critical speed be given at low cost and in the first design loops of a keel?'

In this paper, we describe firstly the semi analytical model we implemented to predict keel flutter at an early stage of a keel design. Secondly, we present results obtained with a 3 dimensional multiphysic simulation on a keel flutter case and we compare it with the results obtained with our semi analytical model. Thus, the multiphysic simulation allows us to confirm some assumptions we take to build our model. Besides, it permits to have some estimation of some terms that are important in our semi analytical model to predict flutter phenomenon in the heavy fluid water is, especially fluid damping at zero flow velocity.

2 KEEL DESCRIPTION

IMOCA 60' keels are vertical weighted wings, on the bottom of the hull. This wing is properly called keel fin and the weight on the bottom of it is called 'bulb' because of its shape.

Anti-drift and stability functions are usually dissociated. Thus the keel fin is more a bulb support than an anti-drift profile (Daggerboards are actually the anti-drift profiles of the yacht). This allows to increase the maximum righting moment using canting keels (Figure 1), which means that we can change the keel's angle to the vertical axis.

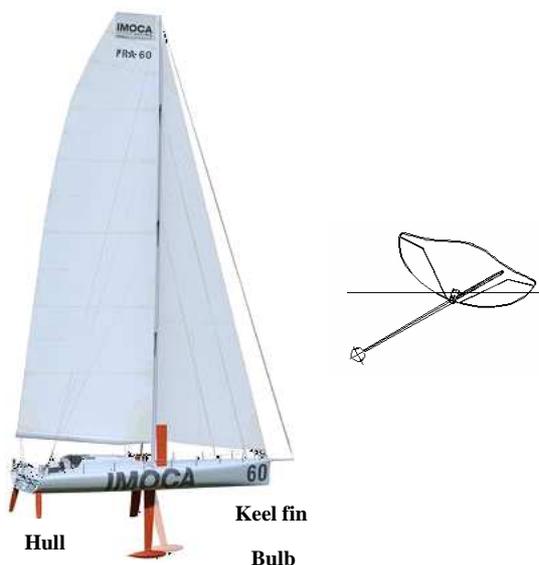


Figure 1 : IMOCA 60' Keel description (left) and canting keel (right)

The main features of an IMOCA 60' keel are the following one: keel length is about four meters (m), keel fin mass about five hundred kilograms (kg), bulb mass about three tons (T) and bulb inertia about one thousand two hundred kilograms square meters (kg.m²).

3 HDS' MODEL PRINCIPLE

HDS' model able to calculate flutter critical speeds is based on the equations introduced by R. MAZET in 'Mécanique vibratoire' [1], applied to airplanes' wings vibrations. In our case, hydrodynamic efforts are simplified and represented as distributed along the keel fin over two-dimensional slices. The systems' dynamic is represented just by the first two eigenmodes. In fact, the first eigenmode will mainly represent bending behavior, and the second will represent torsional behavior. This explains why Mazet assumes that these two modes represent pure bending and pure torsion respectively.

However, while dealing with IMOCA 60' keels, the presence of a solid bulb and the possible gap between its center of gravity to the main fiber of the keel fin, leads to important coupling between bending and torsion. HDS's model, takes this coupling into account for the calculation of bending and torsional displacements before projecting the equations on the truncated modal basis.

Hydroelastic vibration's equations give us the movements' "damping" rates for each speed. Flutter phenomenon appears when one of these rates becomes zero (self-maintained vibrations).

4 DEFINITIONS AND NOTES

We will now only focus on the part of the keel under the hull. We use the axis system presented on Figure 2.

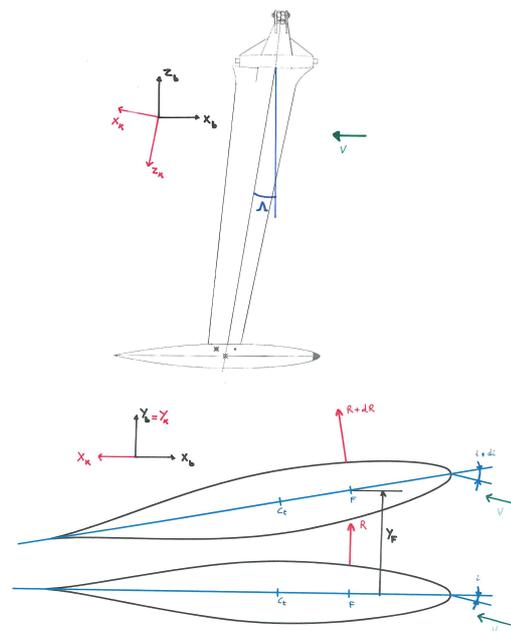


Figure 2 : Useful notes and axis system used in the model (Profile view on the top, upper view on the bottom)

The keel axis system is defined by a rotation of an angle $\pi+\Lambda$ around Yb axis. Λ is the sweep angle and is generally between 0 and 15°.

In the following sections, we only present the case $\Lambda=0$.

5 EIGENMODE CALCULATION

The calculation of Eigenmodes is done by following the discretized finite elements method, using six degrees of freedom beam elements (one translation and two rotations by node, representing bending and torsion).

The beam model element used is the bending-torsion beam model presented by G. BEZINE in ‘La méthode des Eléments Finis en Calcul des Structures’ [2].

We can consider tow type of keel:

- Cantilever keel
- Canting keel: the keel is pinned at the upper edge and at the hull bearing, and unable to twist at the hull bearing.

On the Figure 3, the point N represents the intersection between the main fiber of the fin neutral fiber and the bulb axis. The point G represents the bulb’s center of gravity. We assume that the segment NG is infinitely stiff and that the bulb’s weight and inertia are transported to the point N using Huygens theorem. (Segment NG is not represented in the beam FEA model).

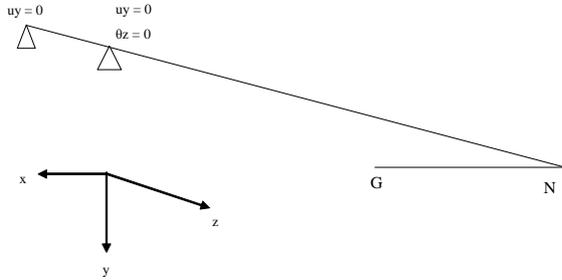


Figure 3 : The canting keel beam finite element model

We have to solve the following classical system:

$$M\ddot{X} + KX = 0 \quad \text{or} \quad (K - \omega^2 M)X = 0 \quad (1)$$

This method of eigenmode calculation gives good results for keels, compared to eigenmodes experimentally obtained or calculated with a complete 3D composite finite element model, provided the composite material properties of the finite element beam model are properly input.

6 LIFT FORCE

To calculate the hydrodynamic lift force, we use the slice method. It’s not possible to give a strictly accurate linearized expression of the resultant of water pressures on the slice except if the slice is motionless, animated with a uniform translation or animated with a sinusoidal vibration. However, an approximate expression of a lift force can be given, considering that we are in quasi-static regime.

Thus, for a flow velocity V, this lift force is applied on the Lift Center F and can be decomposed into two forces:

- The first one is related to the incidence angle i between the slice and the flow’s direction:

$$-\frac{1}{2}c \times \rho_w \times A \times V^2 \times i \quad (2)$$

- The second one is linked to translation speed of the lift center F, orthogonally to flow direction:

$$-\frac{1}{2}c \times \rho_w \times A \times V^2 \times \frac{\dot{y}_F}{V} \quad (3)$$

The global lift force is the sum of the two previous expressions. The coefficient c is the linear lift coefficient, equal to $2.\pi$ for a flat plane in linear theory without viscous effects ([3]). For a 3D wing profile with viscous effects, this coefficient, averaged on the height of the keel, is lower and depends on the wing aspect ratio.

7 RESULTS

Applying the theorem of virtual works on both the two eigenmodes at each flow velocity, we obtain a system of two homogeneous second order equations and whose determinant must be zero. This determinant has four roots, two to two conjugated complexes:

$$-\varepsilon_1 \pm j.\Omega_1 \quad \text{and} \quad -\varepsilon_2 \pm j.\Omega_2 \quad (4)$$

The following ratios represent the “damping” rates for a particular flow velocity V:

$$\alpha_1 = \frac{\varepsilon_1}{\Omega_1} \quad \text{and} \quad \alpha_2 = \frac{\varepsilon_2}{\Omega_2} \quad (5)$$

Flutter phenomenon appears when one of these “damping” rates becomes zero. In fact, to find the critical speed, we will iterate on the speed until one of these “damping” rates becomes zero. On the Figure 4, α_1 becomes zero at 18 knots flow velocity.

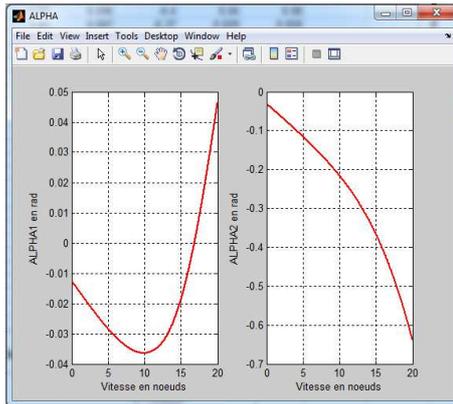


Figure 4 : Curves of the damping rates α_i versus flow velocity (knots)

8 MULTIPHYSIC SIMULATION MODEL

To verify the quality of our semi analytical model and to have an estimation of some of its terms, we built some multiphysic simulations with the software ADINA. We present here one of these simulations.

8.1 SOLID MODEL

We have modeled a cantilever keel as follows:

- Keel's fin with constant profile
- Upper section embedded
- Solid bulb concentrated on a single node (inertia matrix)

The profile used is a typical keel fin profile and the keel height is 4m. Besides, the bulb mass is 3.1T and its inertia is 900 kg.m² as an IMOCA 60' keel bulb.

The 3D keel model is presented on Figure 5. Most of the elements are hexahedral (8 nodes per elements, 3 degrees of freedom per node). The material model chosen is composite orthotropic one.

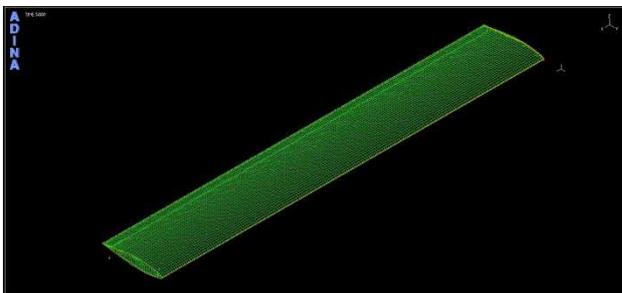


Figure 5 : Keel model

We placed the bulb at two different positions for depending on each simulation:

- on the torsional center C_t of the bottom section of the keel
- behind this torsional center (in the boat axis system)

The time integration scheme for the structure is a Newmark one with the classical values $\beta=0.25$ and $\gamma=0.5$ which permit to conserve energy, so to avoid numerical damping on the structure.

8.2 FLUID MODEL

Fluid model dimensions are the following: L=7m, W=2m, H=4m. The 3D CFD mesh used and its close-up around the profile are shown on Figure 6.

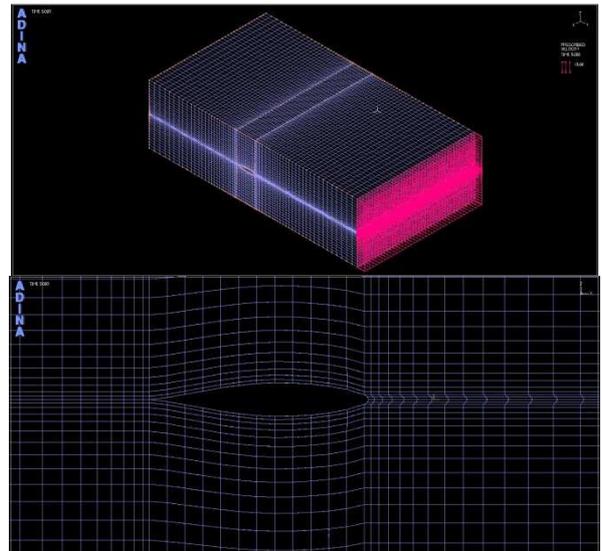


Figure 6 : 3D CFD Mesh

The fluid is modeled as a laminar incompressible Navier-Stokes fluid and is discretized using the ADINA FCBI-C ([4]) fluid elements. The time integration method is an Euler α -method in which we make vary the parameter α to evaluate the numerical damping. A priori the choice $\alpha=0.5$ allows to avoid numerical damping but causes convergence problems unless the velocity is extremely small.

The fluid inlet velocity is a parameter that we make vary from 8 m/s to 12 m/s (Except for fluid damping analysis in that the inlet velocity is 0 m/s). The outlet is set to be traction free and the rest of the fluid boundaries are modeled as sliding wall boundary conditions.

To generate a time response (damped for the stable regime or amplified for the unstable regime) of the keel, a small transverse perturbation load is applied on the bottom of the keel at the first time step.

9 ADDED MASS ESTIMATION

To have an estimation of the added mass generated by the bending and torsion of the fin, we calculated eigenmodes in both cases with and without water around the keel. The following tables compare the frequencies obtained without and with the water for a bulb placed on

the torsional center of the bottom section of the keel (bending and torsion being decoupled):

- Without water :

F1 (Hz)	F2 (Hz)
1.056	2.119

- With water :

F1 _w (Hz)	F2 _w (Hz)
1.013	2.112

F1 corresponds to the first eigen frequency (only bending here) and F2 corresponds to the second eigen frequency (only torsion here). The index w denotes a frequency in water.

By comparing the frequencies obtained in presence and in absence of water, we can estimate the added mass terms generated by bending and torsion motion of the fin:

M _a (bending) (kg)	I _a (torsion) (kg.m ²)
252	5.8

We can note that Ma is about the same order that the fin's own weight (240 kg in this simulation) and significantly less the bulb's own weight. Moreover, compared to bulb's inertia, Ia is negligible.

For a bulb placed 0.160m behind C_t (bending and torsion coupled):

- Without water :

F1 (Hz)	F2 (Hz)
1.041	2.148

- With water :

F1 _w (Hz)	F2 _w (Hz)
1.000	2.136

10 DAMPING ESTIMATION

For any vibrating structure subjected to damping, time response signals to a load impulse can be decomposed on exponentials sums taking damping under consideration. If we focus on the two first eigenmodes of the structure, signal analysis allows to know the damping rates of each mode

10.1 FLUID DAMPING

We analyze the time response of the keel after an impulse. There are two kinds of impulse, a transverse effort for a bending response of the keel and a torque for a torsion response of the keel, both applied on the bulb node. In order to turn the analysis easier, we decouple the eigenmodes by placing the bulb on the torsional center.

Therefore we can estimate separately the bending damping term η_1 (Figure 7) and the torsion damping term η_2 (Figure 8), each damping terms due to fluid model.

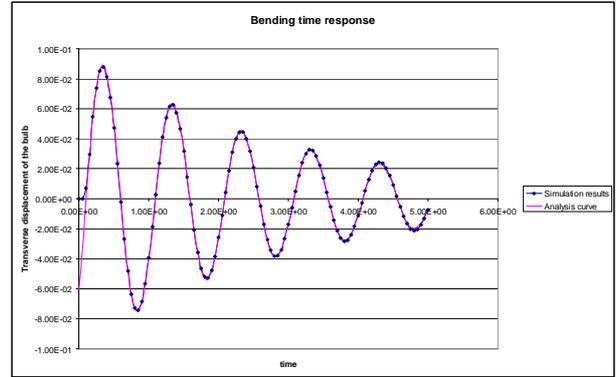


Figure 7 : Bending time response of the keel in water for Euler integration scheme parameter $\alpha=1$ and time step=0.01. The blue points are from simulation results, the pink curve is the analysis curve to estimate the bending damping rate.

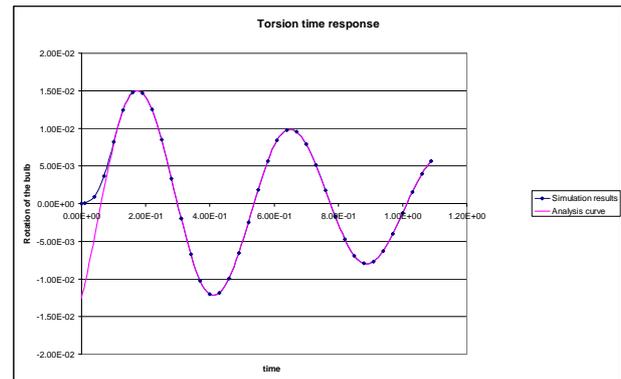


Figure 8 : Torsion time response of the keel in water for Euler integration scheme parameter $\alpha=1$ and time step=0.01. The blue points are from simulation results, the pink curve is the analysis curve to estimate the torsion damping rate.

Thanks to these time response, we can deduce the damping rates η_i (%) for each eigenmodes:

$$\eta_1 = 10.6\% \quad \text{and} \quad \eta_2 = 13.4\% \quad (6)$$

These damping rates are not negligible but contain both fluid and numerical damping here linked to time step choice, Euler integration scheme parameter α choice and mesh. We searched to evaluate the influence of time step (Figure 9) and Euler integration scheme parameter α choice (Figure 10) on these damping rates.

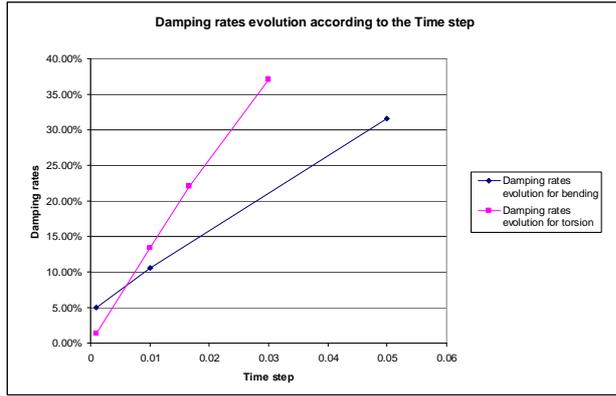


Figure 9 : Damping rates evolution according to the time step with an Euler integration scheme parameter $\alpha=1$

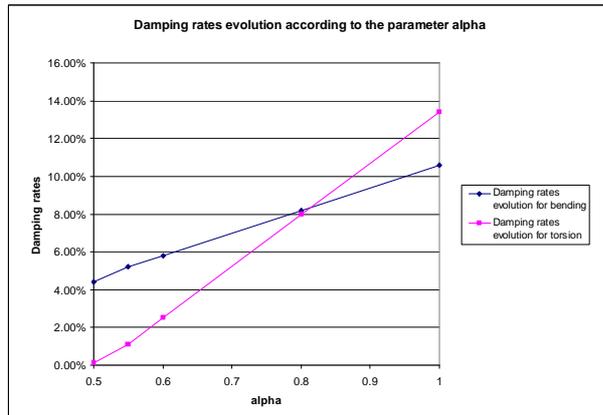


Figure 10 : Damping rates evolution according to the Euler integration scheme parameter α with time step=0.01

The evolution of damping rates according to time step and to Euler integration scheme parameter α shows that fluid damping rates at zero flow velocity tend to the values:

$$\eta_1 = 4.4\% \quad \text{and} \quad \eta_2 \approx 0.2\% \quad (7)$$

These damping rates have to be taken into account in our semi analytical model to compare the estimated flutter critical speed given by both simulation model and semi analytical model. However, to avoid convergence problems in the multiphysic simulation model, we have to choose a parameter $\alpha > 0.5$ which implies the unavoidable presence of a slight numerical damping. We choose the smallest parameter α for convergence and low numerical damping and take into account this damping in our analytical model to allow proper comparison of results.

10.2 SOLID DAMPING

This damping term is not taken into account in the multiphysic simulation model. However, thanks to keel eigenfrequencies measurement, recently imposed by the IMOCA 60' rules, structural damping term can be

estimated using the time response curves of the behavior of the keel after an impulse excitation. We note that these terms are strongly variable among the different keels; they particularly depend on the chosen materials and the construction method.

11 CRITICAL SPEED COMPARISON

In the following two paragraphs, the bulb is placed at 0.160m of the torsional center C_t .

11.1 MULTIPHYSIC SIMULATION

Figure 11 (resp. Figure 12) shows the bulb time response for a flow velocity of 9 m/s (resp. 10m/s). Blue curves represent the transverse displacement of the bulb, while pink ones represent the bulb rotation.

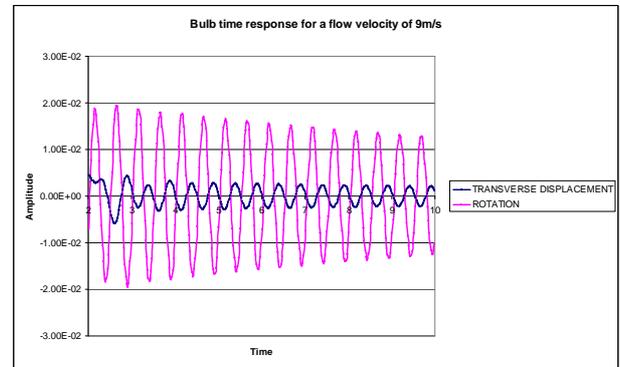


Figure 11 : Bulb time response for a flow velocity of 9m/s ($\alpha=0.6$ and time step=0.01).

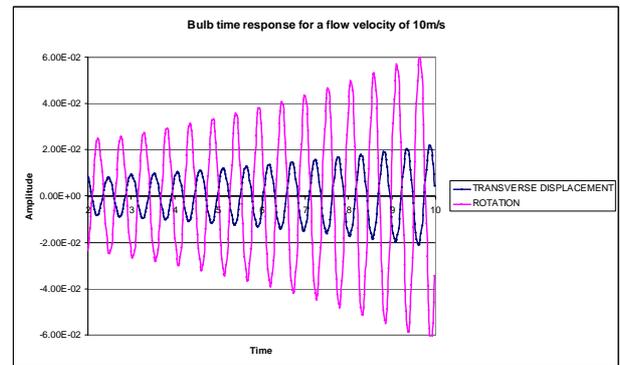


Figure 12 : Bulb time response for a flow velocity of 10m/s ($\alpha=0.6$ and time step=0.01).

We note that for a flow velocity of 9m/s, the bulb oscillations are decreasing, while for a flow velocity of 10 m/s oscillation amplitude grows with time; there is flutter instability. Therefore, with this choice of time step and Euler parameter α , **Flutter critical speed is between 9 and 10 m/s.**

It's also interesting to note that the frequencies of transverse displacement and rotation of the bulb are almost mixed up, that is characteristic of the flutter

phenomenon, and that the phase between the two signals is about $\pi/2$.

11.2 SEMI ANALYTICAL MODEL

Eigen frequencies calculated with our model are the following:

F1 (Hz)	F2 (Hz)
1.041	2.147

With a linear lift coefficient of $2.\pi$ and with, **our model predicts a critical speed of 15.0 knots, corresponding to 7.7m/s.** This result takes into consideration damping rates previously predicted by the multiphysic simulation model, but it considers added mass as negligible. If we consider the bending added mass (resp. torsional added inertia) previously computed into the mass (resp. inertia) of the bulb, we obtain the following eigenfrequencies:

F1 (Hz)	F2 (Hz)
1.002	2.140

Therefore the critical speed becomes **15.3 knots, corresponding to 7.9m/s.**

In fact, if we consider the 3D effects (especially aspect ratio), the average linear lift coefficient will be smaller. For such a keel, the average lift coefficient is approximately 5.2. With this lift coefficient and taking into account the added mass, we find a critical speed of **16.9 knots, corresponding to 8.7m/s.** All main headings should be in bold capitals.

12 CONCLUSION

In this paper, we presented a rather simple semi analytical model which provides a good estimation of the flutter critical speed of a bulb keel at low cost. This model, based on some strong assumptions, especially concerning structure dynamic and calculation of hydrodynamic pressure loading, is confronted to a complete 3 dimensional multiphysic simulation and the comparison shows good agreements in terms of results.

With this semi analytical model, it is possible to calculate a good estimation of the flutter critical speed of a keel in about half a day contrary to the full multiphysics approach which takes several days.

The damping terms – fluid damping at zero flow velocity and solid damping – are important parameters that must be well estimated for a good prediction of flutter. We give an estimation of fluid damping rates to use in the prediction of flutter critical speed for an IMOCA 60' keel. We also show that the added mass effects due to the fin deformation appear to be negligible in prediction of keel flutter but it's not the case for other appendages.

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Hervé Devaux is a Mechanical engineer Doctor and the CEO of HDS Design, in Brest. He has a background in structural dynamics. He can boast about a beautiful prize list in the world of racing yachts. Among HDS' success stories, the Hydroptere (1 mile distance world speed record), Banque Populaire 5 (Jules Verne Trophy and 24 hours distance record), Groupama 4 winner of the Volvo Ocean Race, IMOCA 60 MACIF recent winner of the Vendée Globe and many others. He was involved in the last revolution of the America's Cup with multihulls and wingsails.