Modelling a foil load spectrum using recorded data on a racing foiling yacht

A thesis presented for the degree of Master of Science in Naval architecture

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Abstract

The intent of this Master Thesis is to investigate foil loadings on racing foiling yacht based on recorded data. This work was done by means of recorded microstrains along the foil and other recorded data such as boat speed and fly height. Composite foils are developed by the company GSea Design using an in-house software called Sofia which uses Fluid Structure Interaction (FSI) to design deformable appendages. In this Master Thesis, a tool that enables to get a numerical model of the foil adjusted to the recorded strains at a given time was designed. For that, recorded strains along the foil were first evaluated and post-processed to calculate the corresponding bending moments along the foil. Then an optimization loop based on the Sofia software was implemented. This loop automatically adjusts the numerical model of the foil to the recorded bending moments and computes the global Up and Side forces (vertical and anti-leeway forces, respectively) applied on the foil that contribute to the boat’s equilibrium. This approach was set up and tested during this Master Thesis. It enabled to show that building a representative load case in terms of global Up and Side forces with the corresponding numerical model using recorded data at a given time was possible. This work also highlighted some remaining constraints such as long calculation times to get an adjusted model automatically on recorded data. It implies that future work on data processing or optimisation improvements will constitute the next steps developed by GSea Design to be able to set up a foil design in terms of lifetime.

This is a degree project in Naval Architecture (course code SD271X).

Acknowledgements

I wish to extend all my gratitude to the GSea Design company for their warm welcome and the unique learning experience they made me live during my internship. I wish to thank more particularly my internship supervisor at GSea Design, Rémy Balze who has guided me in my work, taught me and provided me with many advice. I also would like to thank Denis Gléhen, CEO of GSea Design who gave me the opportunity to do this internship and took the time to guide me in my work.
Symbols and abbreviations

\( C_d \) Drag coefficient \( C_d = \frac{D}{\frac{1}{2} \rho v^2 S} \) with \( D \) the lift, \( \rho \) the fluid density, \( v \) the speed and \( S \) the surface area

\( C_l \) Lift coefficient \( C_l = \frac{L}{\frac{1}{2} \rho v^2 S} \) with \( L \) the lift, \( \rho \) the fluid density, \( v \) the speed and \( S \) the surface area

\( C_m \) Moment coefficient \( C_m = \frac{M}{\frac{1}{2} \rho v^2 S c} \) with \( M \) the pitching moment, \( \rho \) the fluid density, \( v \) the speed, \( S \) the surface area and \( c \) the chord

\( E \) Young modulus (MPa)

\( F_y \) Side force (T)

\( F_z \) Up force (T)

\( M_x \) Bending moment (N.mm)

\( t_{FAI} \) Fairing thickness (mm)

\( t_{tot} \) Total thickness of the foil section (mm)

\( z_{NA} \) Neutral axis position (mm)

\( \mu_s \) measured microstrains by Fibre Optic Sensors

\( \mu_s \) microstrains in the UD

\( \mu_s \) microstrains

\( \text{EXT} \) EXTrados side = suction side of the foil profile

\( \text{FEA} \) Finite Element Analysis

\( \text{FSI} \) Fluid Structure Interaction

\( \text{INT} \) INTrados side = pressure side of the foil profile

\( \text{SF} \) Side Force (T)

\( \text{Sofia} \) Structural Optimization using Fluid-structure Interaction for Appendages (Software Name)

\( \text{UD} \) UniDirectional carbon fibers

\( \text{UF} \) Up Force (T)

\( \text{VPP} \) Velocity Prediction Program

\( w_1 \) Static load case

\( w_2 \) Dynamic safety factor
I Introduction

I.1 The company GSea Design

The design and construction of sailing ships is a very complete activity which draws on expertise in the fields of aerodynamics, hydrodynamics, structure, composite materials, etc. The America’s Cup, which is equivalent to Formula 1 in sailing, gives the impetus to innovation in the sailing world. GSea Design is at the heart of this race by studying the composites and the structure of these boats.

GSea Design is an engineering consulting firm specialised in composite structure calculation for racing sailboats. The company is based at Lorient (Bretagne, France) and results from the fusion between HDS Design, created by Hervé Devaux in 1994 and GSea Design, created by Denis Gléhen in 2009. The company benefits from its experience over 20 years in the world of sailing races which enables it to be well-known in naval construction. GSea Design has calculated structures for boats which participated in the America’s Cup, the Vendée Globe or the Volvo Ocean Race (see Figure 1).

The sailing race market is very dependent on the calendar: every team wants to build their boat at the same time for the next race. Gsea Design has thus decided to widen its field of application to other industries (aeronautics, naval…) to be less dependent on the sailing sponsoring and its hazards. About 15 people work at GSea Design at full time and intern students regularly come to work on research studies. To satisfy the specific needs of clients, GSea Design promotes Research and Development by developing in-house software such as:

- **Ophelia** (top left of Figure 2): it is a dedicated FEA design and optimisation tool for any beam pattern and hence masts. This tool relies on project references that have been tried and tested since 1986 and can perform multiple calculations (linear static, non-linear static, linear buckling, linear dynamics, modal analysis, optimisation module). Each load case influenced by the marine environment can thus be studied.

- **Alamo** (top right of Figure 2): it is a prediction tool to assess the mechanical properties of multi-layered composite. It can predict stiffness properties via various homogenisation methods, strength properties using various mesoscopic criteria (Tsai-Hill, Tsai-Wu…). Prediction of durability and fatigue properties under mechanical and thermal cyclic loading is also in development. It relies on a large database resulting from many tests conducted on various matrices, fibres and under different loading conditions.

- **Sandra** (bottom of Figure 2): it calculates the mechanical properties of hollow sections with slender shells such as booms, trimaran’s beam and it is specially adapted to the specific features of composite materials, thus enabling the properties of a section associated with stacking to be quickly outlined.

- **Sofia**: it is a software suite for the design of deformable lifting appendages (Foils, Rudders, Daggerboards for the watersports, blades on a wind turbine, etc.) using fluid structure interaction, it is presented in more details in III.2.3.

The development of these software is done in partnership with research centers and universities like IFREMER (French Research Institute for Exploitation of the Sea), EMC2 (French industrial cluster for advanced manufacturing technologies) and UBO (University of Western Brittany).

![Figure 1: From left to right: Groupama Team France for America’s Cup (2017), IMOCA Maitre Coq (2016-2017), Ultim Trimaran Macif (2015)](image-url)
I.2 Foils on multihulls

First foiling boats were built during the 20\textsuperscript{th} century but it is in 1994 with the trimaran Hydroptère (see Figure 3) that foils became essential in the sailing world. On September 4, 2009 in Hyères (France), the Hydroptère and her “V-shaped” foils broke the absolute speed record on 500 meters with 51.36 knots (this record is now owned by Sailrocket since 2012 with a speed of 65.45kn). Foils on multihulls continued to develop and made their appearance in 2013 in the America’s Cup won by Oracle Team USA and her “L-shaped” foils (see Figure 3). More recently, 7 boats out of 29 participants of the Vendée Globe 2016 had foils which now opens new perspectives for foils on monohulls.
A foil is then a wing shaped appendage under water that enables to ease the pressure on the hull and sometimes enables the boat to fly. As boat speed increases, the incidence of water on the foil produces a lifting force in the same manner as air incidence on aircraft wings produces lift. By lifting the hull, the wetted surface is reduced, and resistance decreases significantly: the boat goes faster. This lifting force is called the Up force $F_z$ in the sailing design field. For sailing boats, the goal of a foil is also to provide a hydro Side force $F_y$ to counteract the aero side force due to the wind the sails and reduce the boat’s leeway (see Figure 4).

The setting of a foil can be done with several parameters such as the foil percentage of extension or angles of rotation. On foiling catamarans with a crew (AC45, AC50...), some angles of rotation can be changed dynamically. The anti-leeway force, also called Side force $F_y$, mainly applies on the vertical part of the foil named the “shaft” whereas the lift, also called Up force $F_z$ mainly applies on the horizontal part of the foil named the “tip”. The junction between the shaft and the tip is called the “elbow” (see Figure 4). The foil is hold in position thanks to the top and bottom bearings, and its angles of rotation with respect to the hull (Cant, Rake and Yaw angles) can be adjusted through those bearings (see Figure 9 for angles definition).
Mechanically, a typical foil section is a structure made of composite sandwich design (see Figure 5):

- The Fairing: its role is mostly hydrodynamic, it ensures the foil hydrodynamic profile on the extrados and intrados. It also takes on most torsional stresses. Its thickness is small relative to the total thickness.
- The Stock: its role is structural as it takes on bending stresses due to the Side and Up forces which make the foil to bend. The stock is made of:
  - The UD Stacking: it is composed of UniDirectional composite fibres (UD) aligned with the foil span and take most bending stresses.
  - The Shear Zone: as its name suggests, this part takes on shear stresses.

In conclusion, with a given foil geometry (shape and position in space) and a foil given structure, the two important parameters in foil design are the global Up and Side forces as they contribute to the boat’s equilibrium and performances. This Master thesis was developed in relation to this subject.

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1 The extrados corresponds to the suction side (pressure decrease) of the foil and the intrados corresponds to the pressure side (pressure increase) of the foil that appears when the fluid arrives on the profile at a certain speed.
II Thesis objective

So far, foil design is done using methods that are not always compared to the reality seen by the foil. Design methods rely on the designer’s experience and safety factors are used to design and make sure the structure will hold no matter what. Safety factors account for dynamic effects, uncertainties on material’s behaviour and all remaining unknowns.

Now, with the growing development of boat instrumentation and the improvement of measurements, a lot of data becomes available on racing sailboats during navigation. The goal of GSea Design is to use this recorded data to develop its working methods in terms of foil structural design. Recorded data can be exploited to confront the reality seen by the foil to numerical models developed during its design.

The objective of the thesis is to set up an approach for post-processing recorded data on foiling boats to improve the design of foils and better account for the actual load spectrum seen by a foil during its lifetime. The chosen approach to achieve the objective is the following:

1. To model a navigation load case in Sofia using recorded data at a given time
2. To automate the process of model re-creation for any time to be able to run it on a large dataset

III Designing a foil

In this chapter, the evolution of foil designing methods at GSea Design will be described to understand the context in which this Master thesis was done.

III.1 Previous method (1990-2010)

When GSea design started to design foils between 1990 and 2010, they received from architects a global geometry (an outline). It was discretised into beam elements and each section of the foil was associated with calculated mechanical properties (see Figure 6). The calculation of the load case was done analytically and fluid lineic loading on the foil \( q_y \) (N/mm) was calculated as follows:

\[
q_y = 0.5\rho C_l v^2 b(x)
\]

Where \( \rho \) is the fluid density, \( b(x) \) is the cord along the foil span, \( v \) is the speed and \( C_l \) is the lift coefficient that was chosen to be the same for all sections along the foil. The maximum load case was applied on the initial geometry and static finite element analysis was then performed to compute stresses along the foil. Safety factors were then applied on stresses to account for all the uncertainties in the material behaviour, dynamic effect and fluid loading.
III.2 Current method using Fluid Structure Interaction FSI (2010-today)

III.2.1 General principle of Fluid Structure Interaction

The foils of a sailboat take on very large stresses as most foiling boats during flight rely on three appendages (two T-rudders and one foil). As racing boat performance increased, foil design became more and more critical to ensure boat’s equilibrium and boat’s flight. To optimize even more the foil design, the interaction with the fluid needs to be considered: indeed, a foil (especially L-shape foils) will deform under fluid loading, which will lead to a new fluid loading as angles of attack of the foil’s sections with respect to the fluid will have changed. The deformed shape of the foil will result in different global forces \([F_y, F_z]\) contributing to the boat’s equilibrium and different boat’s performances. The foil structure thus needs to be designed regarding stresses and deformation based on its final deformed shape at equilibrium to optimize even more the structure.

Fluid Structure Interaction (FSI) is an iterative method that searches the equilibrium position for a deformed structure in a fluid. Figure 7 displays the general principle of FSI: first, fluid loading is applied to the undeformed structure. A new fluid loading is calculated on the computed deformed geometry and this new loading is applied again to the structure. The first loop is then complete and the process is iterated again until it reaches convergence in deformation. At the end of this process, we get the final deformed shape and final stresses in the foil at equilibrium. Safety factors are then again applied to stresses to account for all the remaining uncertainties in the material behaviour and dynamic effect. Since foil behaviour is now better accounted for using FSI, safety factors are lower than in the previous method presented in III.1.
III.2.2 Current design procedure

The design procedure of a foil at GSea Design today is the following:

1. Static load cases are discussed with the architect: Global Up and Side forces \( [F_y, F_z] \), fly height, speed, Cant angle (see Figure 9). These global forces are estimated regarding the boat weight, the maximum forces the sails can resist and the repartition of these forces between the different boat’s appendages (rudders, foils...).
2. Section type and section materials are chosen regarding the shipyard capabilities which gives the first version of the foil geometry.
3. Safety factors are decided in discussion with the architect and the racing team:
   - A first safety factor accounts for the dynamic behaviour of the foil with respect to its static load case
   - A second safety factor accounts for uncertainties on the material behaviour
4. Calculation of stress distribution of the foil under the static load case is done using Sofia (which is going to be presented in III.2.3) with FSI. This stress distribution is called \( w_1 \). The first safety factor (dynamic behaviour) is applied on \( w_1 \) and a new stress distribution \( w_2 \) is obtained. Eventually, the second safety factor (material) is applied on \( w_2 \) which gives the final stress distribution.
5. Failure and stiffness criteria are checked on the final stress distribution on the designed foil.
6. Iterations are done on the foil structure until there is compliance with requirements.
7. GSea Design then makes the 2D drawing of the foil for the shipyard

The safety factors currently used in the design process mainly rely on the designers’ experience and can be adapted through discussions with the architect and the racing team. It is a compromise between boat’s performance and boat’s safety as high safety factors lead to an oversized foil. One of the long terms objectives of GSea design is to get more knowledge on the actual foil loadings to improve their safety factors.
III.2.3 The FSI tool: Sofia (Structural Optimization using Fluid-structure Interaction for Appendages)

The first problematic during this Master thesis was to understand the FSI tool Sofia developed by GSea Design which is going to be presented in this part.

Sofia (Structural Optimization using Fluid-structure Interaction for Appendages) is a software developed in C#, Fortran and Python by GSea Design since 2014. Its goal is to calculate the deformed geometry and the stresses in the foil using the non-deformed geometry as input. Sofia is a graphical interface (see Figure 8) that gathers several software previously developed by GSea Design:

- PAMPA (Program for Analysis of Mechanical Properties of Appendages): it is a Python script that calculates the equivalent mechanical properties of sections (inertia, moduli…) from a given layup.
- FSA (Fluid Structure for Appendages) is a Fortran script that calculates the deformed geometry, internal efforts (bending and torsion moments, normal and shear forces) and stresses applying on the appendage using fluid-structure interaction loops.

![Figure 8: A window of Sofia’s graphical interface](image)

III.2.3.1 Inputs

Sofia needs different inputs to be able to compute the final deformed and stress state of the for the design load case:

- The geometry:
  - the discretized line in nodes called the spine
  - the chord length at each node
  - the twist angle at each node (initial twist given to the structure, it corresponds to the initial section angle of attack)
  - the section profile at each node
  Those data enable to rebuild the 3D geometry of the foil by interpolation (top left window of Figure 8) and calculate the corresponding fluid loading.
- The section layup to calculate the mechanical properties of each section (bottom left window of Figure 8)
- External conditions:
  - Cant angle (see Figure 9)
  - Boat speed
  - Fly height
  - Target global Side and Up forces \( [F_y; F_z] \) (see I.2) corresponding to the design load case.
III.2.3.2 Calculation using “Target Loads” module

As explained in III.2, when designing a foil, engineers at GSea Design receive from naval architects static load cases specified in terms of target Up and Side forces \([F_y, F_z]\) at given speed, Cant angle and fly height (see Figure 10). Sofia includes a “Target Load” optimisation loop that calculates the deformed foil shape corresponding to the target global forces. Figure 11 describes the principle of this optimisation loop: the algorithm makes an initial guess on the Yaw and Rake angles that define the global position of the foil regarding the fluid (see Figure 9). Then, a first FSI loop is performed with these foil settings: fluid loading is calculated using hydrodynamic coefficients for each foil section and the structural response to this loading is calculated. The resulting global forces \([F_y, F_z]\) are then calculated as the resultant from fluid loading on deformed geometry. These calculated global forces are compared to the target values and the “Target Load” optimisation loop will iterate on foil settings (Yaw, Rake angles) until there is convergence between calculated and target global forces. At the end of this process, the final deformed shape of the foil under the specified load case is obtained and compliance regarding stresses and stiffness criteria are checked.

![Figure 9: Appendage Coordinate System in Sofia](image)

**Figure 9:** Appendage Coordinate System in Sofia

### TARGET LOADS

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target SideForce (F_y) (N)</td>
<td>(-1.020E+04)</td>
</tr>
<tr>
<td>Target UpForce (F_z) (N)</td>
<td>(2.810E+04)</td>
</tr>
<tr>
<td>Parameters To Vary</td>
<td>Yaw and Rake</td>
</tr>
<tr>
<td>Convergence Criteria</td>
<td>0.01</td>
</tr>
<tr>
<td>Max Iterations</td>
<td>100</td>
</tr>
</tbody>
</table>

![Figure 10: Sofia interface for "Target Load" calculation](image)

**Figure 10:** Sofia interface for "Target Load" calculation
III.2.3.3 Outputs

The available outputs in Sofia are the following:

- The deformed geometry (see Figure 12):
  - X, Y, Z nodes positions
  - Final twist angles of sections

- Loadings:
  - Hydrodynamic coefficients: Lift, drag and moment coefficients of each section ($C_l, C_d, C_m$) on final deformed geometry
  - Structural loadings: lineic loadings $q_x$ and $q_y$ (N/mm) resulting from the projection of the hydrodynamic loadings in the local section coordinate system on final deformed geometry

- Internal efforts (see Figure 12):
  - Bending and torsion moments
  - Shear and normal forces

- Stresses:
  - Normal stresses
  - Shear stresses

- Top and Bottom bearing reactions

- Final Yaw and Rake angles
III.3 Future design procedure (horizon 2025?)

The goal at GSea Design is to design foils that are always more competitive to increase boat speed and stability. In the future, to improve even more their foil design, GSea Design intends to design its foils in terms of lifetime: a foil running the America’s Cup will not be designed in the same way as a foil running for ocean races. To do so, several topics are explored at GSea Design: PhDs are conducted to work on material behaviour and develop models for durability in composites. Another field of research that is explored concerns the recorded data on foils which is getting available now. By having a better knowledge of the actual load spectrum seen by a foil during its lifetime it should be possible to implement it later in fatigue models. It is in this context that the Master thesis was performed: the objective was to set the first steps in the exploitation of recorded data on foiling boats to gain knowledge on actual foil loadings.

IV Recorded data on a racing foiling yacht

GSea Design designed the foils of a racing catamaran meant to run the America’s Cup and had access to data that were recorded during its trainings. There are two types of recorded data: data regarding the boat in herself and data regarding the foils:

- **Boat data**: the recorded boat parameters are many (around 320 variables) but only a few were kept in this master thesis work:
  - Time (s)
  - Boat speed (kn), calculated from GPS coordinates
  - Heel (°)
  - Fly Height (mm)

- **Foil data**: the port foil was instrumented with fibre optics to measure microstrains in the foil span direction at different locations along the foil on the extrados and intrados (see Figure 13: SXX_EXT = extrados, SXX_INT= intrados). As seen on the figure, there are 13 measuring points on this foil. The points S1_EXT and S1_INT are located close to the lower bearing which is the limit between the foil and the hull when the foil is in full extension. The section of the foil under study is composed of a fairing and a UD stacking, as shown on Figure 13, there is no shear zone on this foil.

Figure 12: Final deformed geometry and internal efforts viewing in Sofia
Recordings were done with a 10Hz frequency and about 10 navigation days were available which makes 10 days x 24h x 60 min x 60 sec x 10Hz = 8 640 000 stored data points for each parameter.

On top of those recorded data, there is a report (see Figure 14) that indicates the division between different navigation phases of the day (e.g. Straightline Port Tack Upwind, Straightline Port Tack Reaching, Tack Port to Starboard...). For each navigation phase, the starting time, the duration the navigation phase and the mean value of variables are indicated which enables to select only the desired navigation phases. The Figure 15 shows an extract of recorded microstrains corresponding to 20min of recording with a series of different navigations phases: when microstrains equal zero, it means the boat is on starboard tack and thus the port foil on which strains are recorded is out of water and not loaded. The port foil is loaded as soon as it comes back into water during jibing, tacking or when the boat goes straight on port tack.

![Figure 13: Fibre Optic Measuring Points Location](image)

![Figure 14: Extract of a Racereplay report: different navigation phases are reported with mean values](image)
GSea Design now has recordings on foils they have designed but these recordings do not give directly the global forces $[F_x; F_y]$ acting on the foil. Instead, they give the strain state of the foil. The work in this Master Thesis is then to find a way to adjust the foil numerical model to the recordings to recreate the corresponding load case in terms of global forces. This approach is going to be presented in the next parts.

V  Modelling of a navigation load case using recorded data

V.1  Going from measured strains to bending moments

V.1.1  Creation of the “as built” foil Sofia model

The first step before exploiting recorded data is to build the Sofia model that corresponds to the foil on which data were recorded. When GSea Design designs a foil, a Sofia model is created. However, during manufacturing, there can be modifications regarding the initial design due for instance to manufacturing errors which imply that the Sofia model is no longer representative of the real foil.

As for the foil under study, some delamination appeared in the elbow due to errors during curing. Repairs had to be made: parts were removed and replaced by other plies. These modifications imply that mechanical properties of the foil are different compared to the initial Sofia model. Therefore, a new “as built” Sofia model needed to be created to make sure that calculated mechanical properties (inertia, neutral axis position) were as for the actual foil.

V.1.2  Calculation of bending moments

From recordings, microstrains in the fairing are measured at different points along the foil by fibre optic sensors. The choice of measured microstrains can either be done in each time step or on averaged value over a time range (e.g. average over a steady straight-line navigation phase). These microstrains can be translated into stresses and then into bending moments. Those bending moments can then be compared to the bending moment distribution calculated by the Sofia software on the foil model.

Figure 15: Extract of recorded microstrains by sensors located on the Extrados (20min) of port foil
V.1.2.1 Neutral axis position and strain calculation at the extremities of the UD stacking

First, strains at the extremities of the UD stacking need to be calculated from measured microstrains $\mu_s FO$ in the fairing. To do so, the neutral axis position is needed. When there is both a measure on the Extrados and Intrados, the neutral axis position $z_{NA}$ can be calculated assuming simple bending (contribution of normal forces is neglected) and beam theory: the strain distribution is linear and the neutral axis position in the section corresponds to the axis where there are no longitudinal strains (see Figure 16). The neutral axis position is thus calculated as follows ($t_{tot}$ = total thickness of the section):

$$z_{NA} = \frac{\mu_s FO \text{ intrados}}{\mu_s FO \text{ intrados} - \mu_s FO \text{ extrados}} \cdot t_{tot}$$

If there is only a measurement on one of the sides (extrados only or intrados only), the neutral axis position cannot be recalculated from measurements. In this case, the neutral axis position is taken from Sofia which calculates the mechanical properties of the homogenised sections, including neutral axis position.

Once the neutral axis position is known, and knowing the fairing thickness $t_{FAI}$, strains at the extremities of the UD stacking can be calculated as follows (see Figure 16):

$$\mu_s UD \text{ extrados} = \mu_s FO \text{ extrados} \left(1 - \frac{t_{FAI}}{t_{tot} - z_{NA}}\right)$$

$$\mu_s UD \text{ intrados} = \mu_s FO \text{ intrados} \left(1 - \frac{t_{FAI}}{z_{NA}}\right)$$

![Figure 16: Microstrains in the foil section at the point S1_EXT/S1_INT](image)

V.1.2.2 Stress calculation

Using Hooke’s law [3], stresses along the section can be calculated knowing fairing and UD’s Young moduli. Simple bending and Bernoulli’s beam are assumed: there is a linear distribution of stresses within each material constituent and the contribution of normal forces is neglected.

$$\sigma_{UD} = E_{UD}\mu_s$$

$$\sigma_{fairing} = E_{fairing}\mu_s$$

Figure 17 shows the normal stress distribution in the studied foil section (a full type section with no shear zone). Maximum stresses occur at the extremities of the UD stacking as this material has a higher Young modulus (~$10^5 MPa$) than the fairing (~$10^4 MPa$).
V.1.2.3 Bending moment calculation

Knowing stress distribution in the section, bending moments are calculated as follows [4]:

\[ M_x = \sigma_{\text{max}, UD} \frac{I_{xx}}{z_{\text{max}, UD}} \]

With \( I_{xx}/z_{\text{max}, UD} \) is the elastic section modulus calculated by Sofia. Sofia computes elastic section modulus that accounts for the whole section including fairing, UD stacking and shear zone. Figure 18 shows the bending moment distribution along the foil calculated from the recorded microstrains averaged over a straight-line navigation phase.

*Figure 17: Normal stresses in the foil section at the point S1_EXT/S1_INT (full type section, no shear zone)*
V.2 Checking for wrong measurements

V.2.1 Elbow: neutral axis shift

As explained in V.1.2.1, the neutral axis position can be calculated from measured strains if the measure is done both on the extrados and on the intrados. In this case, this calculated neutral axis position can be compared to the one calculated by Sofia.

Figure 19 shows the comparison between the “measured” neutral axis position and the calculated one from Sofia. As one can see, the sections S1_EXT, S3_EXT and S4_EXT have close measured and calculated neutral axis (relative difference <10%). However, the sections S5_EXT and S6_EXT have more relative difference: there is a shift of the neutral axis towards the Intrados\(^2\) in the reality which leads to a measured \(z_{NA}\) smaller than Sofia’s. This difference can be explained by the fact that these sections are in the foil elbow where there is a strong curvature. As explained by Timoshenko [1],

\(^2\) The intrados corresponds to the pressure side (outer part of the elbow see Figure 13), so as the foil is bending, the intrados side is in traction whereas the extrados side is in compression.
curved beams under pure bending do not have a linear stress repartition anymore but a hyperbolic stress repartition. With this hyperbolic stress repartition comes also an offset of the neutral axis position. In Sofia, the model is discretized into a set of straight beams and thus it does not consider the effect of curved beams: the neutral axis is calculated as if the stress repartition was linear with simple bending which may be different from reality in the elbow. Differences on neutral axis could also come from a sensor problem (e.g. sensor not well positioned) or from a Sofia model that is not representative enough of the actual built section. As explained in V.1.1, the foil under study endured some damage in the elbow during manufacturing and repairs had to be made, the Sofia model was corrected to fit the “as built” configuration but it may not reflect enough reality. Comparing neutral axis position enables to judge whether the measurement should be considered or not to adjust the Sofia model on it. In this case, the points S5_Ext and S6_Ext were not taken into account because of two large differences on neutral axis position.

![Neutral axis position comparison](image)

**Figure 19: Neutral axis position comparison**

V.2.2 Shaft: wrong measurement

As seen on Figure 18, bending moment at the point S2_EXT (middle of the shaft) is higher than the one calculated at the point S1_EXT/S1_INT, which is the foil lower bearing. This measurement at point S2_EXT seems odd as maximum bending moment should occur at the lower bearing and not somewhere else along the foil. Indeed, the foil is a beam fixed in translation at the upper and lower bearings and subjected to a linear loading for the part under water (see Figure 20) and for such a case, beam theory [4] gives a maximum bending moment at the lower bearing. Measurement at point S2_EXT was done only on the Extrados which means that “real” neutral axis position cannot be recalculated and checked like in previous part V.2.1 to see if there is a large difference between the “measured” neutral axis position and the calculated one from Sofia. As a result, measurement at point S2_EXT was not considered in the process of model adjustment.
V.2.3 Final set of considered measurements

Remaining measurement points considered to adjust the Sofia model to measurements are listed in Table 1 and an example of measured bending moment distribution is shown in Figure 21.

Table 1: Measurement points considered

<table>
<thead>
<tr>
<th>S1_EXT/S1_INT</th>
<th>S3_EXT/S2_INT</th>
<th>S4_EXT/S3_INT</th>
<th>S7_EXT</th>
<th>S8_EXT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower bearing</td>
<td>Shaft (middle)</td>
<td>Elbow (beginning)</td>
<td>Tip (middle)</td>
<td>Tip (end)</td>
</tr>
</tbody>
</table>
V.3 Modelling of the corresponding navigation load case in Sofia

This part is going to describe how the process of modelling the navigation load case in Sofia corresponding to recorded strains can be done manually:

At a given time, microstrains are recorded which give stresses and bending moments after some post-processing, as explained in V.1. The choice of recorded strains can either be done in each time step or it can be done on the averaged values during steady states such as straight-line navigation phases depending on the engineer’s intent.

To be able to tell with Sofia which couples of global forces \([F_y; F_z]\) was experienced by the foil to achieve this set of microstrains, other input data are needed in the Sofia model:

- Cant angle
- Boat speed
- Fly height
Those data are found in the recordings and are set into the Sofia model. Once this is done, the engineer makes an initial guess of \([F_y0; F_x0]\) and Sofia is launched in “Target Load” mode (see III.2.3.2). This calculation results, among other things, in a final calculated bending moments distribution along foil span. This bending moment distribution is compared to the measured one to see if they are close. The engineer will then vary \([F_y; F_x]\) manually and launch “Target Load” calculations until the calculated bending moment distribution is judged to be close enough to the measurements.

At the end of this process, the engineer gets an adjusted Sofia model with the global forces \([F_y; F_x]\) endured by the foil at the specified time corresponding to the recorded microstrains, Cant angle, boat speed and fly height.

**VI Automation of the modelling for any time**

This part will present how the process of recreation of the Sofia model of the foil and corresponding global forces \([F_y, F_x]\) on recorded strains has been implemented to be done automatically. This process can either be performed for any time or on averaged microstrains over a time range like a steady state.

**VI.1 Convergence criterion : least squares**

As explained in V.3, when the load case is modelled manually, the engineer changes the value of \([F_y; F_x]\) manually until he judges that the calculated bending moment curve fits the measured one. To automate this process of search for the right couple \([F_y; F_x]\), a criterion needs to be implemented to judge automatically whether the curves fit together or not. One criterion for fitting a parameterized function to a set of measured data points is to minimize the sum of the squares of the differences between the data points and the function (see ref [5]):

\[
\min_{a_1, \ldots, a_n} \left( \sum_{i=1}^{n} (y_i - f_i(a_1, a_2, \ldots, a_n))^2 \right)
\]

In our case the data points consist in the measured bending moments obtained from the post-processing of recorded microstrains. The function to fit corresponds to the bending moment distribution calculated by Sofia as a function of the global forces \([F_y, F_x]\). The criterion to judge for bending moment curve fitting is then written as:

\[
\min_{F_y, F_x} \left( \sum (M_x\text{measured}_i - M_x\text{calculated}_i(F_y, F_x))^2 \right)
\]

To run this process of automatic search for minimum, the function *least_squares* from the *optimize* library of Python is used (see ref [7]). The function *least_squares* implements the Levenberg-Marquardt method for nonlinear least squares curve-fitting problems (see ref [8]) which is a blend of Gradient descent (steepest-descent method) and Gauss-Newton iteration. The Levenberg-Marquardt algorithm starts using Gradient descent method and as the solution improves, it approaches the Gauss-Newton method and the solution accelerates to the local minimum. The idea of the automatic model adjustment is then to use this optimisation function from Python that will vary global forces \([F_y; F_x]\) in the Sofia model to minimize the sum of least squares differences between measured bending moments and calculated ones.

In our case, the *least_squares* function has the following inputs:

- **func**: function which computes the vector of residuals \(M_x\text{measured}_i - M_x\text{calculated}_i(F_y, F_x)\) as an array; the first argument of *func* is the parameter which *least_squares* is going to vary, in our case it is then the array \([F_y; F_x]\)
- **x0**: initial guess on independent variables \([F_y0; F_x0]\) for the minimization
- **args**: other arguments of *func* such as measurement data (strains, speed, fly height) and the Sofia model
- **ftol**: tolerance for termination by the change of the cost function, set to 0.1
- **xtol**: tolerance for termination by the change of the independent variables, set to 0.1
- **max_nfev**: maximum number of function evaluations before the termination, set to 100
- **diff_step**: determines the relative step size for the finite difference approximation of the Jacobian, set to 0.5: it means that the variation of \([F_y; F_x]\) is done between +50% and -50%.

The proper values of *ftol*, *xtol*, *max_nfev* and *diff_step* to get the function working were found after some manual iterations.
VI.2 Python script for automation of model adjustment

VI.2.1 Initial guess of parameters \([F_{y0}; F_{z0}]\)

One of the main problems of the Levenberg-Marquardt algorithm implemented in the `least_squares` function is that it finds a local minimum. The initial estimates \([F_{y0}; F_{z0}]\) are thus important regarding the final \([F_y; F_z]\) found. To choose a proper initial guess of \([F_{y0}; F_{z0}]\), data from the VPP (Velocity Prediction Program) are used. The VPP is given by the architects of the boat. It gives among other things the expected Side and Up forces acting on the boat for different speeds and fly heights at a typical point of sail (e.g. Upwind or Downwind). From this VPP, \(F_y\) and \(F_z\) are plotted regarding speed (see Figure 22, values are normalized) and the trend curves \(F_y = f_y(speed)\) and \(F_z = f_z(speed)\) are extracted. Those functions \(f_y\) and \(f_z\) are then used in the optimization script to calculate the initial guess \([F_{y0}; F_{z0}]\) for the measured speed.

![Predicted evolution of \(F_y/F_z\) with speed from VPP](image)

*Figure 22: Predicted evolution of \([F_y; F_z]\) with speed from VPP for a given point of sail (Upwind in this case)*

VI.2.2 Script algorithm

Figure 23 describes the algorithm that was implemented in Python to perform the automatic recreation of load case \([F_y; F_z]\) in Sofia corresponding to the measured strains:

1. First, microstrains, fly height, speed and Cant angle (resulting from heel) are extracted from recorded data. Microstrains are processed to calculate the measured bending moments \(M_x\) (see V.1.2). Fly height, speed and Cant angle are set into the Sofia model as fixed parameters.
2. Then, the Python script launches Sofia in “Target Load” mode (see Figure 11) using the initial guess of Side and Up forces: \([F_{y0}; F_{z0}]\). From this first “Target Load”, the bending moment distribution \(M_x\) is calculated and it is compared to the measured bending moments using the least squares criterion. The Python `least_squares` function will test the convergence between measured and calculated bending moments until convergence is achieved, i.e. the sum of squared differences is minimized. In the end, the Python script gives the final \([F_y; F_z]\) that corresponds to the load case seen by the foil at a specific time and the corresponding Sofia model is stored.
VI.3 Results

VI.3.1 Example on one set of recorded microstrains

Figure 24 shows an example of a calculated bending moment curve that was automatically adjusted on measured bending moment using the Python script described above (see VI.2.2). The measured bending moments in this case were calculated based on averaged measured strains recorded during a straight line with a speed of 25.5kn and a fly height of 650mm. The bending moment distribution was obtained in Sofia with the following Up and Side forces: $F_z = 2.98T$ and $F_y = -1.07T$ and these values were found by the adjustment Python script using \texttt{least\_squares} function. Forces are usually expressed in tons at GSea Design to be easily linked to the boat weight. We can look at first glance and judge that the calculated curve fits quite well the measuring points.

Figure 25 displays the evolution of $[F_y; F_z]$ and the sum of least squares differences of bending moments at each iteration of the \texttt{least\_squares} function. We can see that the \texttt{least\_squares} function first makes iterations with the same values of $[F_y; F_z]$ probably to set its parameters and determine in which direction $[F_y; F_z]$ should be varied. Then the function performs variations of $[F_y; F_z]$ and the sum of least squares differences is varying as well. The Python function stops when it has found the minimum of the least squares differences (one of the convergence criteria of the \texttt{least\_squares} function is fulfilled). The calculation time for this case was about 2min on a standard computer but it can take up to 10min, depending on the type of calculation selected in the Sofia software (hydro modelling, FSI...).
To check if the $[F_y; F_z]$ found by the adjustment script are indeed the one that minimize the sum of bending moment squared differences, the values of $[F_y; F_z]$ were manually varied around this optimum. The figures and tables in Appendix A show the evolution of the bending moment curve for different values of $[F_y; F_z]$ and the relative differences to the measuring points:

- When the Side force is varied and the Up force is fixed to the optimum value (see Figure 30), one can clearly see that the optimum bending moment distribution is indeed the one that best fits the measuring points. The bending moment curve is shifted only in the upper shaft part (around S1_EXT) when $F_y$ varies. This highlights the importance of the measured strains at the lower bearing (S1_EXT/S1_INT) and the fact that the found value of Side force $F_y$ is highly dependent on this data.

- When the Up force is varied and the Side force is fixed to the optimum value (see Figure 31), one can also see that the optimum bending moment distribution is the one that best fits the measuring points. The variation of Up force influences the bending moment distribution on the whole shaft (S1_EXT to S4_EXT) and on the tip, as expected.

- When the Up and Side forces are varied together (Up force is increased and Side force is decreased in absolute value and vice versa), the difference between the optimum bending moment curve and the one with different $[F_y; F_z]$ is less obvious at first glance though the computed sum of least squared differences remains minimum for the optimum values of $[F_y; F_z]$.

So, we can conclude that the values of $[F_y; F_z]$ are indeed the one that minimize the sum of bending moment squared differences in this presented case.
Figure 24: Measured and modelled bending moment distribution
VI.3.2 Influence of the sensor position at the lower bearing

Knowing the exact position of the sensor close to the lower bearing seems to be important as it is the area where maximum bending moment occurs. An influence study has been made on the automatically found \([F_y; F_z]\) with respect to the location of the point S1_EXT/S1_INT close to the lower bearing. Its developed length was increased up to +10% and decreased up to -10%. In the latest case, -10%, the measuring point becomes located before the lower bearing which could happen if the foil was not in full extension (see Figure 26).

Table 2 shows the results of this influence study: one can notice that the Up force \(F_z\) is almost not modified when the sensor location at the lower bearing is changed. This can be explained by the fact that the other measuring points were left at the same location which implies that the remaining part of the measured bending moment distribution is the same. As shown in VI.3.1, it is the Side force that influences mainly the bending moment distribution close to the lower bearing whereas the Up force acts on the whole shaft and on the tip. So, one can see in Table 2 that by changing the location of the S1_EXT/S1_INT sensor, the corresponding Side force \(F_y\) is changed by ±5% for this specific case of recorded microstrains. It shows that eventually the measuring point location around the lower bearing is significant regarding estimated Side force but not critical in this case of recorded microstrains.

By adding a second measuring point before the lower bearing, it would give more confidence in the measurements around the lower bearing where maximum bending moment occurs and thus give more confidence in the model adjustment.
VI.3.3 Validation using recorded data of another boat

To validate the results of the automatic model adjustment script, recorded data from another boat were also used. This boat is a foiling trimaran meant to do ocean races. The location of optics fibre sensors is shown in Figure 27. The measured strains were processed as explained in V.1.2 to get the corresponding bending moments and then the automatic model adjustment script was used on the corresponding Sofia model of the foil. Figure 28 shows an example of a calculated bending moment distribution that was automatically adjusted on measured bending moments using the Python script. This load case was obtained for a “static” case called w1 during an upwind straight-line at 25kn, a fly height of 0mm (the boat is not flying) and a heel angle of 10°. The Side and Up forces calculated by the Python script were respectively of -7.2T and 11.6T. A first estimation of these forces had previously been obtained by GSea Design by manually adjusting the calculated strains to recorded data. The values found by the automatic model adjustment tool are close to the previously estimated values (respectively -6.7T and 12T). Hence the script seems to give values of Up and Side forces that are in the range of the expected global forces for an ocean racing foiling trimaran in equilibrium at this specific point of sail (upwind).
Figure 27: Location of measuring points on the ocean racing foiling trimaran

Figure 28: Bending moment distribution along foil span: Example of automatic adjustment of Sofia model to measured data on the ocean racing foiling trimaran
VII Future works and challenges

The implemented script described before is a tool that enables to post-process recorded micro strains along a foil. It adjusts the corresponding foil numerical model to recorded data and gives the global Side and Up forces acting on the foil for the recorded speed, fly height and heel angle. GSea Design will then exploit this tool to improve its foil design. For now, design load cases are estimated based on experience. Using this automatic model adjustment tool could enable to get to know the actual load cases seen by the foil. So far only one navigation case (straight line upwind) was tested to develop the tool because of time constraints. If the tool was used on various similar navigation cases, it could give a good estimation of the global Up and Side forces for this type of navigation case which could be compared to the designed load cases used so far.

Another application could be to run the adjustment script for each recording steps and thus plot the evolution of Side and Up forces regarding time and to get the corresponding numerical foil models. Once this is done, loads levels and frequencies could be extracted for each navigation phase and be used in future fatigue design. This step will certainly require some signal processing before calculating the Side and Up forces. Indeed, for now the adjustment script was tested for one set of recorded value at a given time. It can take up to 10min to calculate and give the corresponding \([F_y; F_z]\) on the standard computer used during the Master Thesis, depending on the type of calculation chosen in Sofia (FSI or not). So, if we imagine running the adjustment script for a whole regatta that lasts for instance 20min at a recording frequency of 10Hz, it would take (20min x 60sec x 10Hz) x 10min = 2000h. Data filtering thus seems necessary to reduce the number of data but also to reduce measurement noise and limit uncertainties in the calculation of measured bending moments. Script optimisation is also possible by launching calculation in parallel and not necessarily in sequence.

Besides, in this Master thesis it was chosen to use an in-built Python function \(\text{(least squares)}\) to perform the automatic variation of \([F_y; F_z]\) to adjust the Sofia model on recordings. However, the operator has a limited power on the function parameters and on how it works to achieve convergence so further research can be done to use other optimisation tools with better performances and thus improve calculation times.

Another application of the adjustment tool would be to adjust dynamic safety factors that are used when designing a foil. For now, when GSea Design’s engineers design a foil, they check that the foil will support a static loading, called w1 specified in terms of Side force, Up force, fly height, heel angle and speed. Knowing this static loading, Sofia is run on the foil model and stresses along the foil are taken as output. Dynamic effects such as small perturbations around equilibrium position are accounted for through a dynamic safety factor applied on stresses. Once the dynamic safety factor is applied, engineers then verify that stresses remain below the stress limit. The value of the dynamic safety factor is decided by GSea Design based on its experience and is discussed with racing teams and architects. By running the adjustment tool on recorded strains, the evolution of Side and Up forces regarding time could be plotted and ratio of dynamic \([F_y; F_z]\) versus static \([F_y; F_z]\) could be identified and compared to the one used empirically so far. Safety factors could then be adjusted regarding data exploitation. For now, safety factors are always too conservative and adjusting them more accurately regarding reality would lead to even more efficient foils in a context of racing foiling boat design where performance is very important.

VIII Recommendations for future foil instrumentation

The methodology that was presented earlier highly depends on the measured strains and the post-processing performed on it to calculate the corresponding bending moment. Instrumentation of foils is yet in early stages and the work performed in this Master Thesis enabled to develop recommendations for future foil that will be instrumented:

- **To record microstrains on the extrados and on the intrados at maximum section thickness** (see Figure 29): having the data both on the extrados and the intrados at the same developed length enables to check for the neutral axis position compared to the one calculated by the model and adjust mechanical properties such as inertia. Positioning sensors where the foil thickness is maximum enables to record maximum microstrains and thus maximum normal stresses that occur in the Uni Directional fibres of the stacking which are the one computed by Sofia.
- **To add a measuring point before the lower bearing** (see Figure 29): this would enable to calculate properly the maximum bending moment that occurs at the lower bearing. Of course, the more measuring points there is, the better. However, there are practical limitations to increasing the number of measuring points like the
cost, the setup time or maximum wavelength range per sensor which limit the number of measuring points that can be recorded.

- **To locate accurately the measuring points regarding the discretization of the Sofia model:** the Sofia model is discretized into nodes at different developed length and mechanical properties (inertia, neutral axis position, thickness...) are calculated on those nodes. In the studied case for this Master Thesis, the location of the measuring points was not in coincidence with the nodes in the Sofia Model. As a result, mechanical properties were interpolated linearly between the two nodes of the Sofia model located before and after each measuring point. This linear interpolation leads to approximations on mechanical properties which affect the calculated bending moment from measured strains. One way to limit those approximations is then to have a Sofia model whose nodes coincides with the measuring points.

![Figure 29: Recommendations on measuring point location for future foil instrumentation](image-url)
Conclusion

This Master Thesis work enabled to set the first steps in the analysis of recorded data on foils. With the growing development of foils on racing sailing yachts but also in pleasure yachts, being able to design foils regarding lifetime is getting more and more important. To do so, analysing and being able to tell what loads the foil will actually see during its lifetime is necessary. The work performed during this Master Thesis on recorded strains on a racing foiling catamaran enabled to highlight what were the points to focus on such as the post processing of recorded data and the setup of a representative numerical model of the foil in terms of geometry and mechanical properties. These focus points enabled to build one representative load case in terms of Side and Up forces using the automatic model adjustment script developed in this Master Thesis. Calculation times remain an important issue to be able to run the automatic model adjustment script on a large dataset. It implies that future work on data processing or optimisation improvements will constitute the next steps developed by GSea Design to be able to set up a foil design in terms of lifetime.

From a personal point of view, this internship gave me the opportunity to work in a small French company where rigor and professionalism are very important. I discovered the main issues in composite structure calculation for racing sailing boats and more specifically on foil design. I could experiment research and development in a company which is quite different from research in universities. Indeed, research work in company can be directly applied to projects under development. For instance, I was able at the end of the Master Thesis to formulate recommendations on foil instrumentation and these recommendations were considered for next foils designed by GSea Design.
References

[10] Anath Ranganathan, The Levenberg-Marquardt Algorithm, 8th June 2004
Appendix A. Variation of \([F_y; F_z]\) around the optimum

Figure 30: Manual variation of \([F_y; F_z]\) around optimum value: variation of \(F_y\) while \(F_z\) is fixed

Table 3: Manual variation of \([F_y; F_z]\) around optimum value: variation of \(F_y\) while \(F_z\) is fixed

<table>
<thead>
<tr>
<th>Variation</th>
<th>(F_y) (T)</th>
<th>(F_z) (T)</th>
<th>Sum of least squared differences</th>
<th>Relative difference between measured (M_x) and calculated (M_x) at S1_EXT (lower bearing)</th>
<th>Relative difference between measured (M_x) and calculated (M_x) at S4_EXT (elbow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum</td>
<td>-1.07</td>
<td>2.98</td>
<td>3.57E+11</td>
<td>-1.2%</td>
<td>-1.0%</td>
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<tr>
<td>(F_y +0.1T)</td>
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Figure 31: Manual variation of \([Fy;Fz]\) around optimum value: variation of \(Fz\) while \(Fy\) is fixed

Table 4: Manual variation of \([Fy;Fz]\) around optimum value: variation of \(Fz\) while \(Fy\) is fixed

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<th>Relative difference between measured (M_x) and calculated (M_x) at (S_4) (elbow)</th>
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<td>(7.69E+12)</td>
<td>-4.3%</td>
<td>-6.8%</td>
</tr>
<tr>
<td>Fz +0.3T</td>
<td>-1.07</td>
<td>2.68</td>
<td>(1.57E+13)</td>
<td>-5.8%</td>
<td>-10.0%</td>
</tr>
<tr>
<td>Fz -0.1T</td>
<td>-1.07</td>
<td>3.08</td>
<td>(2.19E+12)</td>
<td>2.5%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Fz -0.2T</td>
<td>-1.07</td>
<td>3.18</td>
<td>(7.08E+12)</td>
<td>4.3%</td>
<td>6.5%</td>
</tr>
<tr>
<td>Fz -0.3T</td>
<td>-1.07</td>
<td>3.28</td>
<td>(1.68E+13)</td>
<td>6.5%</td>
<td>10.0%</td>
</tr>
</tbody>
</table>
Figure 32: Manual variation of \([F_y;F_z]\) around optimum value: variation of \(F_y\) and \(F_z\) together

Table 5: Manual variation of \([F_y;F_z]\) around optimum values: variation of \(F_y\) and \(F_z\) together

<table>
<thead>
<tr>
<th>Variation</th>
<th>(F_y) (T)</th>
<th>(F_z) (T)</th>
<th>Sum of least squared differences</th>
<th>Relative difference between measured (M_x) and calculated (M_x) at (S1_EXT) (lower bearing)</th>
<th>Relative difference between measured (M_x) and calculated (M_x) at (S4_EXT) (elbow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum</td>
<td>-1.07</td>
<td>2.98</td>
<td>3.57E+11</td>
<td>-1.2%</td>
<td>-1.0%</td>
</tr>
<tr>
<td>(</td>
<td>F_y</td>
<td>+0.1T) (F_z-0.1T)</td>
<td>-0.97</td>
<td>3.08</td>
<td>1.57E+12</td>
</tr>
<tr>
<td>(</td>
<td>F_y</td>
<td>+0.2T) (F_z-0.2T)</td>
<td>-0.87</td>
<td>3.18</td>
<td>8.23E+12</td>
</tr>
<tr>
<td>(</td>
<td>F_y</td>
<td>-0.1T) (F_z+0.1T)</td>
<td>-1.17</td>
<td>2.88</td>
<td>1.70E+12</td>
</tr>
<tr>
<td>(</td>
<td>F_y</td>
<td>-0.2T) (F_z+0.2T)</td>
<td>-1.27</td>
<td>2.78</td>
<td>8.34E+12</td>
</tr>
</tbody>
</table>