Typhoon: a vortex-lattice code for assessing dynamic stability characteristics of hydrofoil crafts.

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Abstract— **In this paper an open-source implementation of the vortex-lattice method to perform a dynamic stability analysis for hydrofoil crafts is discussed. It gives a brief background to all the concepts used, followed by a short theoretical explanation of the vortex-lattice method. The second part of this paper focuses on a practical example of how this code can be used and what the possibilities are.**

Keywords—**foiling, vortex-lattice method, free-surface, dynamic stability**

I. Introduction

Hydrofoiling has been around since the early 20^{th} century, but has become much more prevalent over the past few years on sailing vessels. The use of hydrofoils comes with some obvious advantages: a possibility for more efficient travel, higher achievable speeds, a less pronounced wave-signature... Examples of applications of hydrofoils are widespread: ferries, crew-transfer vessels, high-performance sail-racing vessels, surf-boards, pleasure crafts... An example of a hydrofoiling sailboat is given in fig. 1. The increased speed and the radically different way of sailing has however imposed new risks. The completely different dynamic behaviour of a vessel while airborne on foils in comparison to its buoyant state prompts a better understanding of the dynamic behaviour of these vessels. This understanding is necessary to optimise the dynamic stability of these vessels and provide the necessary safety. Masuyama [4] describes how a static description of the motions of a vessel can overestimate its top speed by quite some margin. This overestimation is due to a theoretical top-speed which is at a static equilibrium but is however dynamically unstable. This means that the vessel would accelerate but once it comes in the dynamically unstable region it would inevitably crash off its foils with possibly dangerous consequences. The combination of the higher speeds with possible crashing should be a sufficient argument for a proper analysis of the dynamic behaviour of hydrofoiling vessels.

Fig. 1. The Goodall Design Foiling Viper.

A better understanding of the dynamic behaviour can be established through a so-called dynamic stability analysis (DSA). In present day designs of hydrofoil crafts, the assessment of the dynamic stability is often lacking whereas in aeroplanes it is common practice. The working principles of a hydrofoil craft are nonetheless very similar to those of an aeroplane, with the exception of the added complexity of the free-surface. This means a lot of existing knowledge on aeroplane theory can be extended to hydrofoil crafts. The DSA is typically performed by linearizing the dynamic and kinematic equations, and substituting the forces by their first-order Taylor expansions with force derivatives for all the different motion variables. A more profound explanation of the DSA for aircrafts and the linearization of the system can be found in the work by Drela [2]. The DSA especially for hydrofoil crafts is explained in the work by Masuyama [4] or more recently by Bagué et al. [1] where a framework is laid out to perform this DSA.

The reason why the assessment of the dynamic stability in hydrofoil crafts is often lacking can be attributed to the lack of widely available and easy-to-use tools which are available for aeroplanes. If you were to attempt to perform such a DSA for the design of a hydrofoil craft today, you should turn to Computational Fluid Dynamics (CFD) and would have to run a multitude of costly flow calculations. In contrast, for aeroplanes there exists a variety of different potential-flow codes which allows professionals and amateurs alike to perform swift flow calculations and dynamic stability analyses. Some of many examples are Athena Vortex Lattice (AVL) by Drela and Youngren [7] written in Fortran or Tornado by Tomas Melin [5] implemented in Matlab. These programs allow to define a certain aeroplane geometry and perform various flow calculations or a DSA for this geometry. Both these programs are available under the GNU General Public License.

This paper discusses the implementation and possibilities of such a code specifically for performing flow calculations and performing the DSA of hydrofoil crafts. This code should be an easy-to-use tool which can perform fast dynamic stability analyses to compare different designs or design options. After comparing Prandtl's lifting-line method and the vortex-lattice method, it was concluded that the vortex-lattice method was better suited for the problem at hand as it did not need any preexisting knowledge on lift- and drag-coefficients, such as is the case for Prandtl's lifting-line method. The code, which is named Typhoon, is implemented in Matlab and uses Tornado as its basis. The choice to use the open source code Tornado as a starting point is because it has an existing framework to define a geometry and uses a vortex-lattice method to do flow calculations. Typhoon will use and extend this vortex-lattice method by adding an additional boundary condition to include the free-surface effect. The goal is that this code will accelerate the research in the field of dynamic stability of hydrofoil vessels and at the same time help to make better design decisions from a stability standpoint. The code is therefore made available to all to become an open-source project.

II. Dynamic stability analysis

To get a better understanding of what the power of Typhoon is, one should be familiar with the concepts in a dynamic stability analysis. A DSA provides the user with numbers to quantitatively understand how well the design behaves dynamically. It gives an idea how well the vessel manoeuvres, how it will react on disturbances like waves or gusts and, when comparing different situations, it can also give an idea on how certain parameters influence this behaviour.
A vessel, under the influences of all forces and moments interacting, will always tend to move to a situation where both the sum of all forces and the sum of all moments are zero. When these force and moment balances are satisfied the vessel is said to be in a static equilibrium. It is in this equilibrium situation that we are interested in the stability characteristics of the vessel. There are two distinct but very important notions regarding stability: there is a static stability and a dynamic stability. Static stability means that there is always an opposing force or moment for any movement. Any excursion away from the static equilibrium will thus be counteracted by a force or moment and therefore the vessel will have a tendency to move back to the static equilibrium. This does however not mean that the vessel will manage to re-achieve this static equilibrium as the vessel is a dynamic system. That is why there is a second notion to stability, namely the dynamic stability. A statically stable system can still be dynamically unstable which means that because of a small disturbance the system will diverge away from the static equilibrium due to an oscillation with increasing amplitude.

A. *Static equilibrium*

The first step in performing the DSA consists in finding the static equilibrium where all force and moment balances are satisfied. Depending on the dimensions which are taken into account in the analysis, every included force and moment balance should be satisfied by changing the position and orientation of the vessel relative to the water. To illustrate this fig. 2 shows the vertical force and moment around the y-axis on a vessel as a function of both the draft of the vessel and the trim angle. The two black iso-lines show where either the total moment or force are zero. The intersection of those two lines thus represents the static equilibrium point in which both vertical forces and the moments around the y-axis are balanced and zero.

B. *Static stability*

Fig. 2 also leads to the conclusion that the vessel is statically stable: increasing the relative draft increases the force experienced thus returning the system to its equilibrium point. Increasing the trim angle results in a more negative moment, therefore again returning the system to its equilibrium state. This plot however does not lead to any conclusions about the dynamic stability.

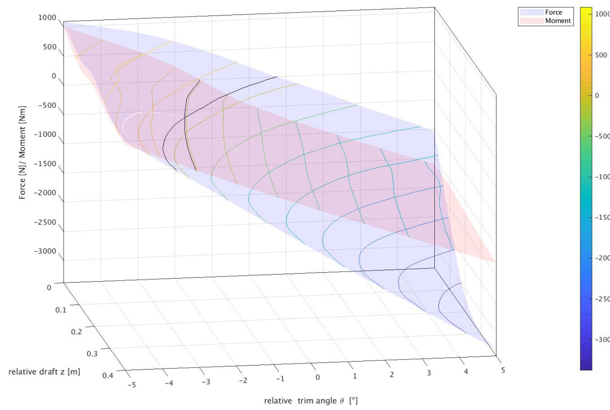

Fig. 2. A surface plot of the of the force and moment of the Viper as a function of the relative draft z and the relative trim angle θ. [1]

C. *Dynamic stability*

The determination of the static equilibrium and checking the static stability in this equilibrium is the first step in analysing dynamic stability as they are a prerequisite for having dynamic stability. The dynamic stability can be examined by setting up the stability matrix. The stability matrix is a handy way of writing the linearized equations of motion where the forces and moments are substituted by their first-order Taylor expansion. This introduces derivatives of the forces and moments to the different motions in the equation. For the longitudinal case this then leads to eq. 1 and eq. 2. This longitudinal stability matrix handles all pitch and heave motions. For a more thorough background on this particular case we refer to Bagué et al. [1] and for a more general background to the dynamic stability analysis (of aeroplanes) we refer to Drela [2]. Apart from the mass and the mass-moment of inertia the stability matrix gets influenced by the so-called force and moment derivatives. The calculation of these derivatives will be one of the key purposes of Typhoon. These will be calculated by using finite-differencing.

$$\frac{d}{dt}\begin{bmatrix}\Delta u\\ \Delta z\\ \Delta\theta\\ \Delta w\\ \Delta q\end{bmatrix} = [A]\cdot\begin{bmatrix}\Delta u\\ \Delta z\\ \Delta\theta\\ \Delta w\\ \Delta q\end{bmatrix} \tag{1}$$

$$[A] = \begin{bmatrix} -\frac{1}{m}\frac{\partial X}{\partial u} & -\frac{1}{m}\frac{\partial X}{\partial z} & -\frac{1}{m}\frac{\partial X}{\partial \theta} & -\frac{1}{m}\frac{\partial X}{\partial w} & -\frac{1}{m}\frac{\partial X}{\partial q}\\ 0 & 0 & 0 & -1 & 0\\ 0 & 0 & 0 & 0 & 1\\ -\frac{1}{m}\frac{\partial Z}{\partial u} & -\frac{1}{m}\frac{\partial Z}{\partial z} & -\frac{1}{m}\frac{\partial Z}{\partial \theta} & -\frac{1}{m}\frac{\partial Z}{\partial w} & -\frac{1}{m}\frac{\partial Z}{\partial q}\\ \frac{1}{I_{yy}}\frac{\partial M}{\partial u} & \frac{1}{I_{yy}}\frac{\partial M}{\partial z} & \frac{1}{I_{yy}}\frac{\partial M}{\partial \theta} & \frac{1}{I_{yy}}\frac{\partial M}{\partial w} & \frac{1}{I_{yy}}\frac{\partial M}{\partial q} \end{bmatrix} \tag{2}$$

Once all the force and moment derivatives are calculated, the stability matrix can be evaluated and the eigenmodes determined. The eigenmodes will give a clear indication on what the dominant motions will be and how the vessel will react to disturbances. An eigenmode consists of the eigenvalue and the eigenvector. An eigenmode will either have a real eigenvalue or a complex eigenvalue. If the eigenvalue is real the response to a disturbance will be exponentially increasing or decreasing. If the eigenvalue is a complex number there exists a complex conjugated value and the response will be sinusoidally oscillating. The dynamic stability will be determined by the sign of the real part of the eigenvalue: when the real part is negative then the mode is stable since all disturbances will be dampened out, if the real part is positive then it is unstable since any disturbance will be amplified and the vessel would diverge away from the equilibrium state. The corresponding eigenvector will determine the dominant motions of the mode. This could for example be a coupled motion between heave and pitch or between roll and drift. These eigenmodes are the results of interest of this dynamic stability analysis and enable the user to compare different designs and to understand how design parameters influence the dynamic behaviour.

III. TYPHOON

As mentioned in the previous sections, the goal is that the code should be able to handle the dynamic stability analysis of different types of hydrofoil designs. It is primarily focused on being a tool to be used in a preliminary design stage to get a better understanding on how design parameters influence the dynamic stability. Through the use of the vortex-lattice method some accuracy is compromised in favour of a lower calculation cost. This loss in accuracy is mostly due to the non-existing viscous effects in potential-flow theory. This however enables to swiftly compare the dynamic behaviour of different designs at different conditions. As such this tool can be used by industry leaders and by amateurs alike. The code allows to define the geometry of the appendages which form the supporting structure in the air-borne mode. Only these appendages need to be defined as most components above the water (e.g. hull) do not contribute to dynamic behaviour directly as long as the vessel is in air-borne mode. External forces from engines or sails can be defined and included in the calculations. Along with the definition of the (foil) geometry there is also a possibility to define the conditions like speed, trim, draft (or foil submergence)... This again is an important feature as it allows to understand how a vessel can be optimised for different sailing conditions (e.g. high-peed vs low-speed).

A. Theoretical background

Typhoon makes use of the vortex-lattice method (VLM) to calculate the lift and drag generated by the foils. The VLM uses the theory of potential flow and by making a couple of assumptions the flow-field becomes the subject of superposition. This principle enables to look at different influencing effects by treating them separately and adding up their contributions. As such the flow in one point is affected separately by the free-stream velocity, the presence of a hydrofoil, the free-surface and so on. In the next few paragraphs a short introduction to this theory is given but for a more thorough background we can refer to [2].
The basic idea behind the VLM is that every wing/foil gets discretized into different panels. This discretization happens in both the span and chord wise direction. To every panel, a horseshoe vortex with a constant circulation strength Γ_i is assigned. Every vortex is comprised of three straight segments: two trailing legs extending to infinity and one shorter leg connecting the two other legs completing the "horseshoe". This connecting segment is located at the one-quarter chordwise position of the panel. An overview of this can be found in Fig. 3.

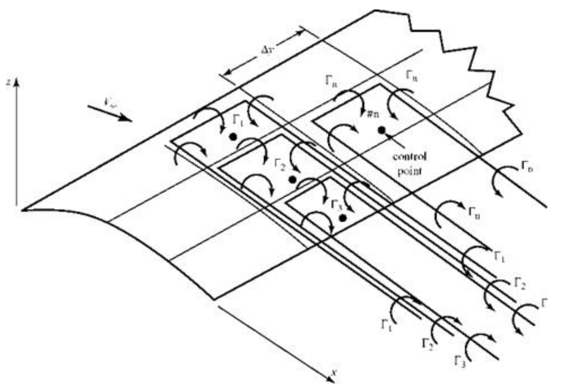

Fig. 3. A representation of the discretization of a foil and of the horseshoe vortices. [3]

The contribution $\overrightarrow{V}'$ of a complete horseshoe vortex to the total velocity field can be found by solving the Biot-Savart line integral as shown in Eq. 3. The integral runs over the entire horseshoe vortex, which consist of three parts: the two trailing vortices and the connecting segment.

$$\overrightarrow{V}'(\overrightarrow{r}) = \frac{\Gamma_i}{4\pi} \int \frac{\overrightarrow{dl_i}' \times (\overrightarrow{r} - \overrightarrow{r_i}')}{|\overrightarrow{r} - \overrightarrow{r_i}'|^3} \tag{3}$$

In this equation every term is known except for the circulation strength Γ_i, and this is the case for every panel which has its own horse-shoe vortex. This circulation strength is calculated by imposing a boundary condition on the so-called collocation points. Each panel has such a collocation point and this boundary condition says that no flow can go trough this point in the normal direction to the panel. Physically this means that there can be no flow trough the wing. This boundary condition is known as the Dirichlet boundary condition and is shown in Eq. 4. This condition relates every panel to every other panel in a way that the geometry of the foil will determine the circulation strength for every panel.

$$\begin{aligned} \frac{\partial \phi}{\partial n} &= \overrightarrow{V}(\overrightarrow{r}^c_j) \cdot \overrightarrow{n}_j = 0 \\ &\leftrightarrow (\sum_{i=1}^{N} \Gamma_i \hat{V}_i(\overrightarrow{r}^c_j) - (\overrightarrow{U} + \overrightarrow{\Omega} \times \overrightarrow{r}^c_j)) \cdot \overrightarrow{n}_j = 0 \end{aligned} \tag{4}$$

Up to this point, this is still the standard VLM. It is perfectly suited to do a DSA for an airplane, but for a hydrofoil vessel the rather important effect of the free-surface would not be included. Therefore an additional boundary condition needs to be included which alters the relation every panel has to every other panel. This additional boundary condition results from the linearized free-surface boundary condition:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{g}{U^2}\frac{\partial \phi}{\partial y} = \frac{\partial^2 \phi}{\partial x^2} + \kappa_0 \frac{\partial \phi}{\partial y} = 0 \qquad \text{at } z = \zeta \approx 0 \tag{5}$$

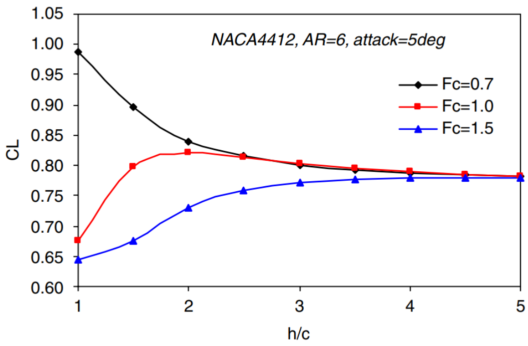

Fig. 4. Results by Xie and Vassalos[6]

which when solving leads to the following potential, which is called the wave-making potential ϕ_w.

$$\begin{aligned} d\phi_w =& \frac{\Gamma}{2\pi} Re \left[\int_{-\pi/2}^{\pi/2} (tan(\nu) d\zeta - isec(\nu) d\eta) \right. \\ & \left(-i\kappa_\nu exp[\kappa_\nu(z+\zeta) + i\kappa_\nu \omega] \right. \\ & \left. \left. + \frac{1}{\pi} \int_0^\infty \frac{\kappa}{\kappa_\nu - \kappa} exp[\kappa(z+\zeta) + i\kappa\omega] d\kappa \right) d\nu \right] \end{aligned} \tag{6}$$

This wave-making potential together with the potential from Eq. 4 and the free-stream potential results in the total flow which in turn enables us to calculate the lift and drag of the entire foil. The reason why this wave-making potential is so important is because it makes the lift coefficient not only a function of the submergence (draft) but also of the speed. This dependency is displayed in Fig. 4. This figure show the lift coefficient for different non dimensional forward speeds (Froude numbers Fr_c) as a function of the submergence h/c. Without the wave-making contribution the lift generated by the foils would be equal to the value at an infinite depth and it would not be influenced by speed. As hydrofoils are mostly operated around the air water interface, this effect cannot be neglected.

B. Principle

The code Typhoon will be made freely available, so that everyone can use it and also continue to develop it to his or her needs. The code also has a graphic user-interface (GUI) which deliberately has a limited functionality to keep it relatively easy to use. This way everyone with a little background can start using Typhoon and gain understanding of the dynamic behaviour of any designed vessel. The functionality of the text user-interface (TUI) is far more extensive and can also be expanded. This TUI is therefore more aimed at experienced users with more background on the subject. This TUI also allows to adapt the code to the needs of the user and perform batch calculations.

Geometry definition

A first, very important feature of Typhoon is the ability to define and alter almost any geometry. These geometries can have different foils with different partitions. Each of these partitions can have varying foilshape, twist, sweep, chord length, taper, radius of curvature... This geometry definition will then be used to form an adequate model of the design with the desired number of panels. An example of the Viper displayed in fig. 1 is shown in fig. 5. As can be seen only the appendages are moulded in Typhoon as these dominate the dynamic behaviour while foiling.

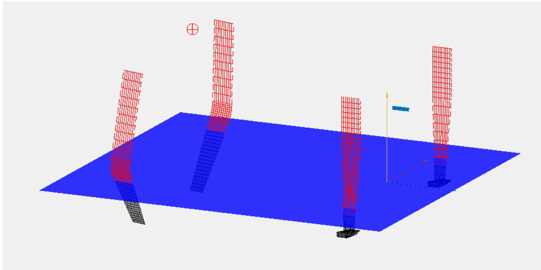

Fig. 5. The viper as represented in Typhoon.

State definition

Another important feature is the ability to model different states or conditions. This state allows you to change the position and orientation of the vessel relative to the water surface, change the speed and also change the external forces and moments interacting with the vessel. The defined geometry and state combined lead to the mesh from fig. 5.

Simple calculation

Once the geometry and the state are defined, and the mesh is generated, Typhoon will have all input to be able to calculate the circulation strength from sec. III-A and consequently lift and drag for every panel. This enables us to make predictions about the expected performance of the design.

Static equilibrium

Once there is the possibility to calculate the forces and moments resulting from the flow and having defined the external forces and moments acting on the vessel via the state definition, it is now possible to determine the static equilibrium of the vessel, if it exists. At this equilibrium point, all force and moment balances need to be satisfied. However, this cannot be calculated analytically as the forces are a function of the flow field. Therefore Typhoon is provided with a Newton-Rhapson algorithm which alters the position and orientation of the vessel iteratively and provided a good initial guess will end up in an approximate equilibrium point. This algorithm to find the static equilibrium is mostly important for vessels which have a passive stability. The earlier mentioned viper for example has a passive stability as it does not need any external feedback for achieving this equilibrium. The International Moth on the contrary makes us of a “wand” system which delivers active feedback to respond to waves and other disturbances. For such designs this algorithm is of no use (in its present version), but the stability matrix can still be evaluated at a predetermined position and orientation and can still provide important insights in the dynamic behaviour. Fig. 6 shows a visual representation for a longitudinal example where the algorithm changes both the sinkage and the trim of the vessel to find a situation where both total force and moment are

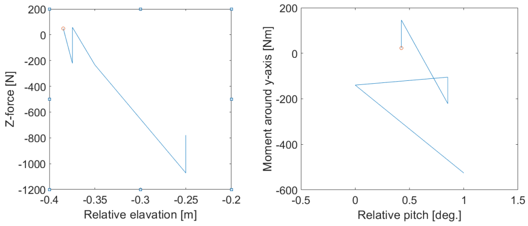

Fig. 6. A visual representation of the Newton-Rhapson algorithm.

(almost) zero. The algorithm determines the best next step by taking into account the current forces/moments and determining the force and moment derivatives of the current state. It then determines how to change the sinkage and/or trim.

Dynamic stability matrix

The last step in the DSA is the evaluation of the dynamic stability matrix. Below the matrix is shown for the Viper case discussed above as calculated with Typhoon.

$$[A] = \begin{bmatrix} -0.065 & 0.16 & -4.13 & 0.50 & -0.15 \\ 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -1.99 & 19.8 & -117.9 & -12.8 & -12.3 \\ 0.01 & -8.29 & -38.9 & -4.11 & -16.6 \end{bmatrix}$$

The eigenvalues and eigenvectors of this matrix are determined and visualised using Typhoon. The eigenvalues determine the general behaviour of each mode, and the eigenvectors determine the amplitude and phase of each variable. The eigenvalues are visualised in Fig. 7 and the eigenvectors are visualised in Figs. 8, 9, 10 and 11. From the eigenvalues λ and eigenvectors v, the eigenmodes can be constructed:

$$\Delta x_i = v_i e^{\lambda_i t} \qquad \text{with } i = 1, ..., 5 \tag{7}$$

From the eigenvalues some interesting conclusions can be drawn. They either exist as a purely real eigenvalue or exist as a complex conjugated pair. The sign of the real part of the eigenvalue determines whether or not the mode will be stable. A positive real value means that the mode will cause a divergence from the equilibrium state, hence being an unstable mode. A negative real value means that the mode will converge back to the equilibrium state, hence being a stable mode. The value of the real part also determines how hard a mode will be damped, a higher value means the resulting motion will disappear quite quickly. This can be expressed using the half-life $t_{\frac{1}{2}}$. The half-life is an interesting measure to compare different modes.

$$t_{\frac{1}{2},i} = \frac{ln(0.5)}{Re(\lambda_i)} \tag{8}$$

The significance of the real part of the eigenvalue is the same in a complex conjugated pair of eigenvalues. The fact that an eigenvalue is complex means that the resulting mode will have an oscillating motion rather that an exponentially increasing or decreasing motion resulting from a purely real eigenmode. The imaginary part of the eigenvalue will determine the period T of the oscillating motion.

$$T_i = \frac{2\pi}{Im(\lambda_i)} \tag{9}$$

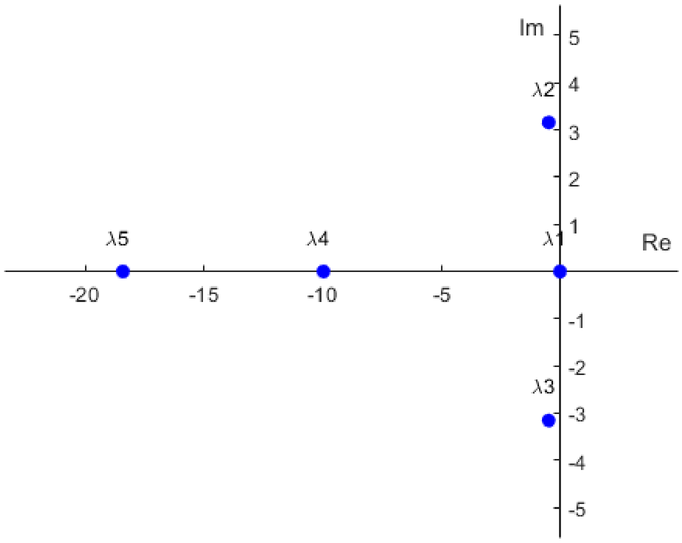

Fig. 7. The root locus diagram for the foiling Viper sailing at a speed of 10 m/s.

The eigenvalue with the smallest absolute value, λ_1, has a very small magnitude of -0.0293 which indicates that this mode is nearly neutral, meaning that the reaction to a disturbance of this mode will happen quite slow, if any. The corresponding eigenvector v_1, displayed in fig. 8, tells us more about the behaviour of this mode. This mode is a coupling between the forward velocity u and the sinkage/ride height/elevation of the vessel z. This behaviour could be expected as a decrease in speed will result in less lift which in turn results in the vessel to decrease its elevation. There will also be a slight increase in trim angle which will again increase the lift and will eventually decrease the sinkage.

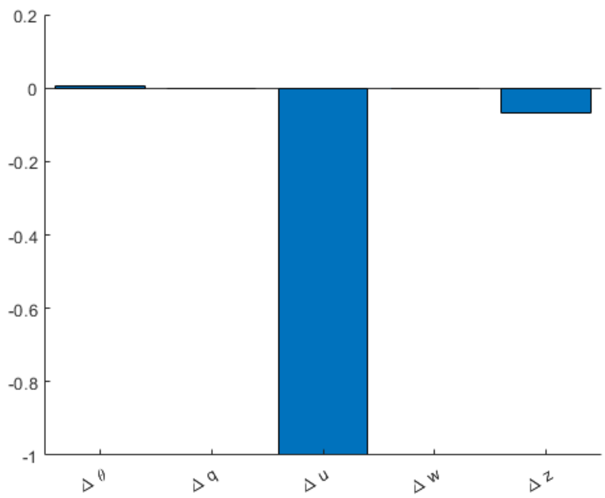

Fig. 8. A visualisation of the real eigenvector v_1.

The second and third eigenmodes are both complex conjugated pairs, meaning that the behaviour of these modes will result in an oscillating response. The resulting eigenvector for v_2

is displayed in fig. 9, eigenvector v_3 is the same but with opposite signs for the imaginary values. The visualisation of this eigenvector differs from the plot in fig. 8 as the eigenvector corresponding to a complex eigenvalue will be a complex eigenvector. This plot shows the phase angle between the different motions in this mode. For example, a vertical velocity disturbance Δw will be followed a quarter of a period T later by a change in longitudinal velocity Δu or in other words, there is a phase difference of approximately $90°$. This mode is dominated by the vertical and longitudinal velocities Δu and Δw together with the angular velocity Δq. This motion represents some kind of wobbling motions where the vessel moves up and down while speeding up and changing its trim angle.

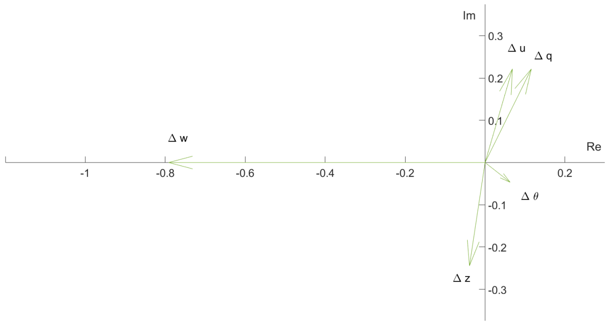

Fig. 9. A visualisation of the complex eigenvector v_2.

The two remaining eigenmodes, Δx_4 and Δx_5, each have a purely real eigenvalue, resulting in a dynamically stable mode which is a lot more damped than the previous real eigenmode as the absolute value is higher. This can be understood by calculating the half-life time of these eigenmodes using eq. 8. When looking at the visualisation of the eigenvectors, v_4 and v_5 in fig. 10 and fig. 11, it becomes apparent that they are really similar. It is a coupled motion dominated by a vertical velocity and a pitch velocity. The main difference between the two modes is the difference in sign of the vertical velocity. This means that when the boat would experience a change in pitch velocity, both modes would cause an opposing reaction and more or less cancel each other out.

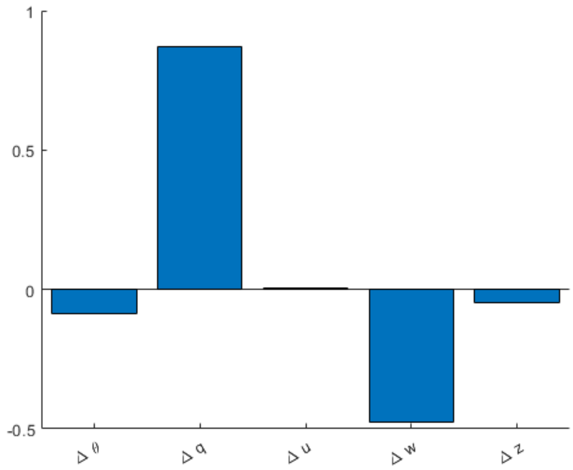

Fig. 10. A visualisation of real eigenvector v_4.

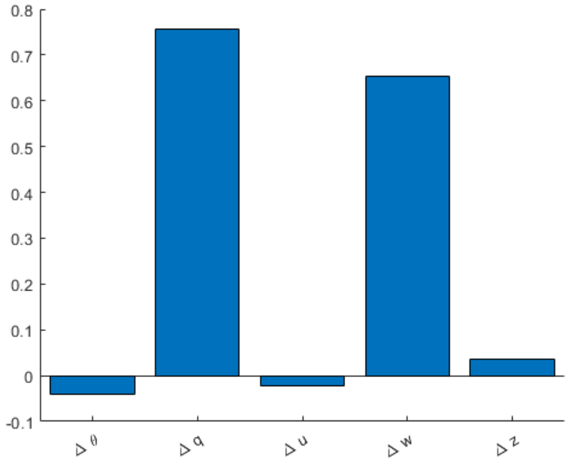

Fig. 11. A visualisation of the real eigenvector v_5.

The strength of Typhoon lies in its ability to easily compare the dynamic behaviour of two designs and examine how certain design parameters affect the dynamic stability of the vessel. Applying that to the Viper, the effect of the position of the rudder and stabiliser on the stability can be shown. In the new design the rudder and stabiliser are moved forward, which results in the design shown in fig. 12.

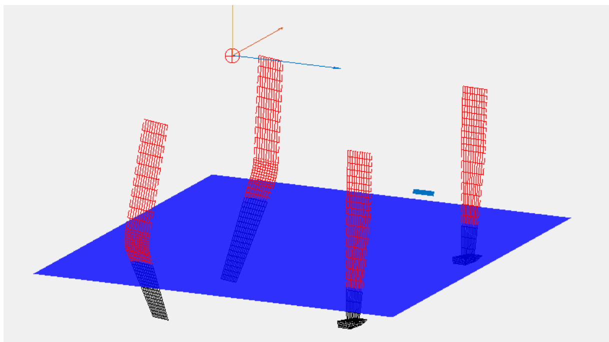

Fig. 12. Viper with rudder and stabiliser moved 0.5 m closer to foils.

Typhoon was used to calculate the new stability matrix and the corresponding eigenvalues and eigenvectors. Fig. 13 shows a root locus diagram with the eigenvalues of the old design and the new design where the rudder and stabiliser were moved closer to the centre of gravity. Immediately some interesting conclusions can be made: the new design is no longer dynamically stable as the complex conjugated pair of λ_2 and λ_3 now has a positive real value meaning that this mode will diverge away from the equilibrium. Eigenvalue λ_1 remains the same, still very small but negative, hence stable. The eigenvectors v_1, v_2 and v_3 have barely changed and still display the same behaviour as the eigenvectors plotted in fig. 8 and fig. 9 and will not be repeated here. Another interesting difference is the fact that λ_4 and λ_5 are no longer purely real and now form a complex conjugated pair. This means that the corresponding motion will now also be an oscillating motion. The eigenvector v_4 is displayed in fig. 14. It represents a motion again dominated by a vertical velocity with the pitch velocity just as was the case for the previous eigenvectors v_4 and v_5.

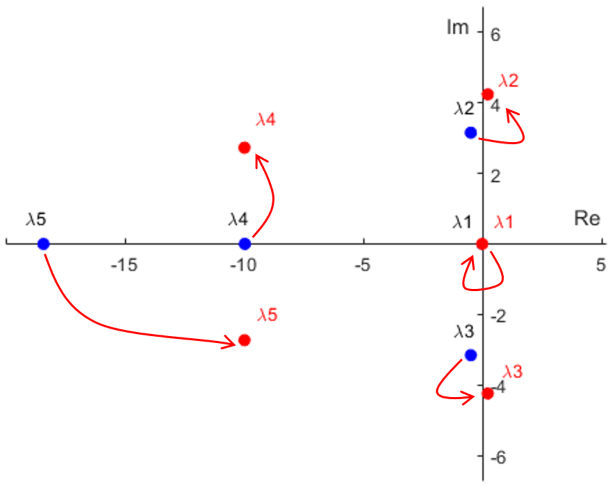

Fig. 13. A root locus plot displaying the old (blue) and new (red) eigenvalues.

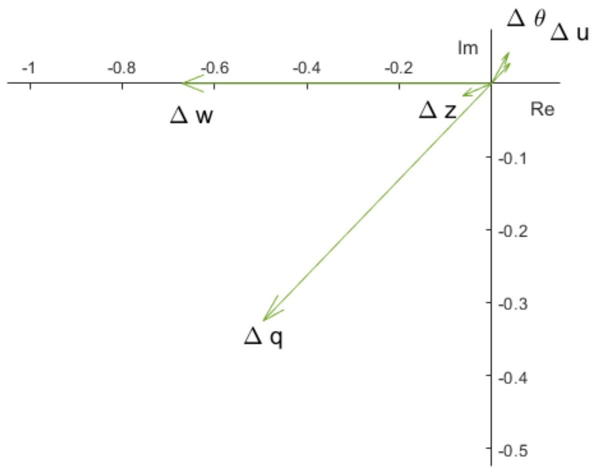

Fig. 14. The complex eigenvector of the second setup.

C. Discussion

The example laid out in the previous section demonstrates the strength of Typhoon which enables the user to create a design, calculate its stability characteristics, change the design and again calculate its stability characteristics to get a grasp on how design parameters alter the dynamic behaviour of the design. The example above was entirely done using the GUI version of Typhoon which deliberately has limited features to keep it relatively easy to use. But already with this simple version different conclusions can be drawn concerning the longitudinal stability behaviour of the vessel. The position of the stabiliser and rudder relative to the centre of gravity is known to be an important design parameter concerning the stability, and its importance was confirmed using Typhoon. Moving the rudder and stabiliser forward has a really adverse effect on the dynamic stability and should therefore be avoided.

IV. Conclusion

The possibility to easily define and change geometries enables to use this code for a wide range of applications which goes further than just sailboats. Other hydrofoil crafts like ferries and foilboards can also be examined using Typhoon. Typhoon will hopefully enable designers to make predictions about the stability performance early in the design cycle which in turn will increase safety of hydrofoil crafts. It gives the opportunity to try a whole bunch of design ideas at a very low cost as opposed to having to do very expensive CFD simulations. In a later stage the output of Typhoon can be used as input for CFD to have more accurate results which in turn can be used to validate the data coming from Typhoon.

There is however still a lot of untapped potential: the model as it is presented here only incorporates longitudinal motions but could also be expanded to include additional degrees of freedom like roll and drift (side slip). Another very realistic possibility for sailboats would be to simulate the sail in the same way the foils are simulated as the VLM is even more simple for airfoils. This way a full 6-DOF simulation is feasible and a full examination of all eigenmodes possible.

As it becomes more and more apparent that hydrofoils will play a roll in efficient shipping in the future, there is clear necessity to better understand the dynamic behaviour of these vessels and to consequently improve and assure its safety. With the development of Typhoon we hope to accelerate research in this matter. The project will become an open-source-like endeavour in which we aim to create a community around this subject and to continue to improve the understanding of the dynamic behaviour of hydrofoil vessels. Other interested parties like research facilities and boat builders can use the code and hopefully even improve parts of it.

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