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Simulating Biomimetic Propulsors under spring loading and/or active control for the pitching motion of the wings

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ABSTRACT

New rules but also economy, demand ever higher efficiency but also require a high level of safety and comfort onboard a vessel. The area of biomimetics has been sought after in the past with arguable success, but was abandoned, as the 70's energy crisis receded and technical issues made it unprofitable to pursue. Nevertheless, the interest is being reheated, as experimental data and simulations promise high efficiencies, outstanding maneuverability and seakeeping qualities, while technical obstacles are being overcome. The problem of a spring loaded and/or controlled pitching motion of the wing is the natural sequel to the fully prescribed motions if a compromise of propulsive power and reduction of ship motions is the objective function for propulsor design, for the ship operating in a wavy environment.

In this paper the numerical solution of a heaving wing pitching either passively (spring loaded) or actively (properly determined by the user) is set and discussed. Towards this end the 3D boundary element solver with free wake UBEM (Politis 2011) is coupled with a data generation code capable to handle the complex motions resulting for the case of a spring loaded and/or actively pitched wing. Moreover for the spring loaded case the one DOF hydroelastic ordinary second order differential equation in time has been integrated numerically using different time integration schemes (central difference, Crank Nikolson, Newmark -linear and non linear-), while for the active pitch control, an evolution of the existing active pitch control method (Politis and Politis 2014) is presented. Some results are presented for the developed time dependent thrust as well as for the mean thrust coefficient for different selections regarding heaving motion and pitch control of the wing. Comparisons are also presented between spring loaded, controlled and prescribed motion wings operating in complex environments.

Keywords

Biomimetics, Flapping foil propulsion; Spring loaded wing dynamics; Active pitch control; Boundary element method; Incompressible non-viscous unsteady lifting flows; Unsteady wake rollup.

1 INTRODUCTION

Demand for low costs, regulations on emissions, and unstable markets, make an ever growing demand for lower consumptions, which lead to a serious decrease in the powering of vessels. On the other hand, the increased demand on safety and the rougher seas observed lately, dictate an increase of installed power and improvement of seakeeping characteristics. Under the light of the latest developments both in numerical investigations (Belibassakis and Politis 2013, Politis and Politis 2014, Politis and Tsarsitalidis 2014) and experimental (Bøckmann and Steen 2014), Biomimetic Propulsion systems prove to have the potential of surpassing the aforementioned stalemate.

The modern history of biomimetics starts in 1935 with Gray's paradox, and theoretical developments start with the works of Sir James Lighthill (1969), T.Y. Wu (1971). A thorough review of those theories can be found in Sparenberg (2002). Extensive reviews of computational and experimental work in biomimetics can be found in the papers of Shyy (2010) regarding aerodynamics and aeroelasticity; of M. Triantafyllou (1991, 2004) regarding experimental developments and of Rozhdestvensky (2003) regarding all types of applications, even full scale, with additional care given to the work done by eastern scientists (i.e. Russians and Japanese). Interesting information is also included in the books by: (Shyy, Aono et al. 2010) and Taylor et al. (2011). Marine biomimetic propulsors are also discussed in the book of Bose (2010).

The ability of an oscillating wing to absorb energy from wave induced ship motions and transform it to propulsive power gave rise to the idea for combined use of this system both as an energy saving device and as a control system for ship motions. As also reported in the extended review by Rozhdestvensky & Ryzhov (2003), the Norwegian Fishing Industry Institute of Technology carried out full-scale tests of a passive propulsor, comprising two wings with elastic links, installed at the bow of a 180ton research fishing ship.

The tests showed that the efficiency of such a propulsor reached up to 95% and it was demonstrated that it could be combined with a conventional screw propeller. At a speed of 15kn in waves up to 3m height, a significant part (25%) of the thrust was provided by the wing propulsors. Using only the wing propulsor the ship was able to travel at speed up to 8kn. Furthermore, full-scale tests of a 174ton Russian research fishing vessel equipped with a wing device for extracting sea wave energy (see, e.g., (Nikolaev, Savitskiy et al. 1995)), showed that such a device could increase the delivered power up to 50-80% and reduce the ship motions by at least a factor of 2. Also, Japanese researchers used a suspended engine to oscillate a flapping wing system, (Isshiki 1994). Two different arrangements of the wing elements of the flapping propulsor have been considered. The first consists of two vertically mounted wings, operating in opposite phase, and the second of a horizontal wing, operating below a stationary plate. This engine-propulsor system was tested and the measured data show that it provides the same efficiency as a screw propeller, for an extended range of operating conditions. The above full-scale experiments confirm that the flapping wing, in some modes of operation, could be found to be equally effective as the typical marine propeller. However, by operating at lower frequency it has the advantage to excite less noise and vibration. Apparently, there is already strong evidence about the good performance and capabilities of the proposed system, permitting the development of tools for technological design and innovation.

The scope of the present work is to propose ‘pitch setting’ strategies for biomimetic wings, aiming at considerable thrust production in connection with reduction of ship motions, in real environments where complexity of heaving motion is the rule. To this end the unsteady boundary element code with free wake UBEM (Politis 2011) has been coupled with a 1-DOF hydro-elastic model of a spring driven wing, to dynamically calculate its pitch in time. In addition a new APC (Adaptive Pitch Control) algorithm has been proposed on the basis of the (known) random heaving history of the wing, following the lines of thought in Politis and Politis (2014). Presented results indicate that biomimetic wings with either APC or spring loaded can have substantial abilities as ship propulsors and energy saving devices.

2 FORMULATION

2.1. Wing geometry, motion and panel generation.

For the general case of a flapping wing configuration, the independent variables which define the state of the system can be decomposed in two groups. The ‘geometric’ variables and the ‘motion related’ variables. For the selection of wing geometry the flapping wing series described in (Politis and Tsarsitalidis 2014) has been used. More specifically we have chosen a wing with s/c=4 where s denotes span and c the chord length. The outline and meshing of the wing is presented in Figure 1. A NACA0012 profile throughout the span is used for all cases. Finally to the geometric variables we have to add the pitching axis position. This is the subject of section 2.4.

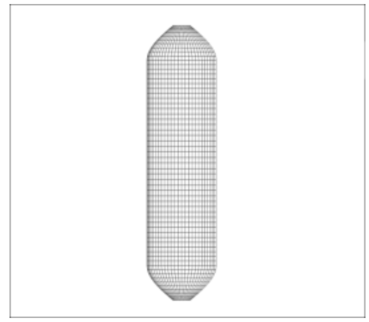

Figure 1 Geometry of a straight wing of s/c=4.0

Regarding description of wing motion, for the cases considered in this paper, they can be decomposed in a translational part with velocity of advance U , a heaving part with instantaneous heaving amplitude $h(t)$ and a pitching motion with instantaneous pitch angle $\theta(t)$. For the simplest ‘prescribed motion’ case, heaving and pitching can be independently selected harmonic (sinusoidal) functions of frequency f with amplitudes h_0, θ_0 and some phase angle ψ between them (in the current paper $\psi = 90^0$). For the most advanced cases considered in this work, i.e. the spring loaded and the actively pitched wing, the pitching motion is dependent from the heaving motion in general in a complex way. More specifically for the spring loaded case instantaneous pitch results from the equilibrium of moments, equation (4), and the properties of the spring/damper system (elastic constant K and damping factor C) acting as parameters for the calculation of instantaneous pitch. For the actively pitched wing, instantaneous pitch is selected as a function of the time rate of heave and the velocity of advance (Politis&Politis 2014).

With the motion parameters known, the instantaneous angle of attack $a(t)$ of each wing (wing is assumed untwisted) with respect to the undisturbed flow is given by:

$$a(t) = \theta(t) - \tan^{-1}\left(\frac{dh(t)/dt}{U}\right) \qquad (1)$$

Additionally, as in previous works, Str denotes the Strouhal number defined by:

$$Str = \frac{f \cdot h}{U}, h = 2h_0 \qquad (2)$$

where h denotes the heave height. Finally the Thrust coefficient is defined by:

$$C_T = \frac{T}{0.5\rho U^2 S} \tag{3}$$

where T is the calculated mean thrust and S the swept area covered by the wing in motion, given by $S = s \cdot 2h$.

2.2 Spring loaded wing simulations

In order to find the pitching angle at each time t, the following differential equation has to be solved for $\theta(t)$:

$$M_{ext}(t) = I\ddot{\theta}(\mathrm{t}) + C\dot{\theta}(\mathrm{t}) + K\theta(\mathrm{t}) \tag{4}$$

where M_{ext} is the external moment (in the specific case, the hydrodynamic moment), *I* the moment of inertia about pitch axis, *C* the damping factor and *K* the spring stiffness.

The solution of the coupled problem is done in an explicit scheme, where the hydrodynamic moment $M_{ext}(t)$ calculated at each step is used in order to find the pitch angle for the next time step. As long as the time step is small enough and pitch angle variations are also small, this scheme is expected to be robust and accurate, as long as time integrations (solution of (4) for constant $M_{ext}(t)$ and given time step) are made with care. For the time integration of (4) a Newmark -β scheme is applied. (Chopra 2007). Alternative methods, such as Crank Nicholson, have been tested, but in highly unsteady cases do not provide reliable results, unless the time step is too small.

Regarding wing geometry and properties we have worked as follows: For the wing, the geometry is selected as discussed in section 2.1 (figure 1, s/c=4.0) and a uniform mass distribution, with density that of solid aluminum of the same shape, was assumed. Then, the mass, center of mass and moment of inertia can be calculated by employing a CAD software using either numerical integrations or empirical rules (found in textbooks). For the wing of Figure 1 with: c=1.0m and s=4.0m the calculated useful data are: -Surface area= 7.5818m^2, -Volume = 0.2823m^3, -Volume moment of inertia about pitch axis I=0.02704m^5.

Regarding selection of the damping factor we worked as follows: As it is known from the dynamics of harmonic oscillators:

$$\zeta = \frac{C}{2\sqrt{IK}} \tag{5}$$

is called the 'damping ratio'. The value of the damping ratio ζ critically determines the behavior of the system. A damped harmonic oscillator can be *Overdamped* (ζ>1, *Critically damped* (ζ =1) or *Underdamped* (ζ<1). It is desirable that the system is not allowed to resonate with the excitation, but also that it does not delay to respond. Thus, $\zeta=1$ was chosen for the initial explorations. Thus damping factor *C* becomes a function of K, and the differential equation (4) depends solely on K and the inertia properties of the wing system.

2.3 Active Pitch Control

Active pitch control has introduced originally in Politis and Politis 2014 (paper has been accepted since 2012 but there was a delay in publication in the corresponding issue of Journal of Fluids and Structures). In this paper a simple open loop algorithm has been presented capable of producing significant thrust under random heaving conditions. In a later paper Belibassakis and Politis (2013) present application of adaptive pitch control to the coupled wing-ship problem in waves. In the current paper we extend the previous developments, presenting a new algorithm for pitch adaptation with better performance regarding avoidance of unsteady wing flow separation and corresponding stall. More specifically, from the original of (Politis and Politis 2014), the pitch angle at each time step is defined as:

$$\theta(t) = w \tan^{-1}\left((dh/dt)/U\right) \tag{6}$$

where w is a control parameter ranging from zero to one that is set beforehand. Knowing the expected heave amplitude, frequency and speed of advance, and knowing that:

$$a(t) = (1-w)\tan^{-1}\left((dh/dt)/U\right) \tag{7}$$

the parameter w can be set to a number that the maximum angle of attack does not exceed a defined value.

Closer examination of (7), leads to the realization that $\tan^{-1}\left((dh/dt)/U\right)$ gives the angle of the undisturbed flow and that decrease in the value of w, increases the angle of attack. If the constant parameter w is substituted with a variable $w(t)$ and keeping in mind the objective of keeping the angle of attack below a given value, a new law for $w(t)$ can be obtained by finding the lowest $w(t)$ satisfying the inequality:

$$A \geq \left(1-w(t)\right)\tan^{-1}\left(dh/dt/U\right), A = A_{\max} \tag{8}$$

The value found, is then substituted in (6), to give the pitching angle. This gives at a minimal addition of computational cost, a different, non- harmonic profile of pitching motion, where the angle of attack is kept below the given value $A_{\max}$, but also equal to it for a longer time. It should be noted, that when the angle of the undisturbed flow is smaller than the desired angle of attack (and when it changes from the positive to negative –one side of foil to the other-) it is better to keep the foil at a zero pitch angle, something that this algorithm follows very well, as shown in the sequel (Figure 6).

2.4 Selection of Pitching Axis Position

For the selection of the pitching axis position the requirement of stable motion patterns leads to select it in front of the center of pressures. From linear, steady 2D wing theory it is known that the center of pressures coincides with the one quarter chord point from the leading edge. In our case the wing performs large nonlinear motions and thus a preliminary investigation is required to confirm (or not) the results from linear theory. By analyzing the results from existing prescribed motion simulations (Politis & Tsarsitalidis 2014) and applying $d(\mathrm{t}) = M_z(\mathrm{t}) / F_y(t)$ ($M_z(\mathrm{t})$ is the hydrodynamic moment around the selected pitch axis of the wing, $F_y(t)$ is the hydrodynamic force) the time dependent position of the aerodynamic center from the selected pitch axis of the wing $d(\mathrm{t})$ can be found. In Figure 2, results of these calculations are shown for a multitude of different prescribed motion simulations, as taken from previous works (one linetype for each simulation) for the pitching axis positioned at 0.3c from the leading edge. The peaks of the lines should be disregarded, as they are the result of very small F_y at the upper and lower points of the heaving oscillation. From the main part of the curves, it can be concluded that the hydrodynamic center resides slightly ahead of 0.3c for most of the time for all cases. Similar calculations (not included here) for the pitching axis positioned at 0.2c from the leading edge, confirm this result and additionally indicate that the position of the pitching axis has a secondary effect on the position of the center of pressures. After this analysis we have chosen the pitching axis at 0.25c from leading edge, for both minimization of moments as well as stability considerations. It should be noted that a position much closer to the le, could mean large moments, which could lead to strong responses and instabilities, difficult to be controlled with either a spring loaded or a actively pitched wing.

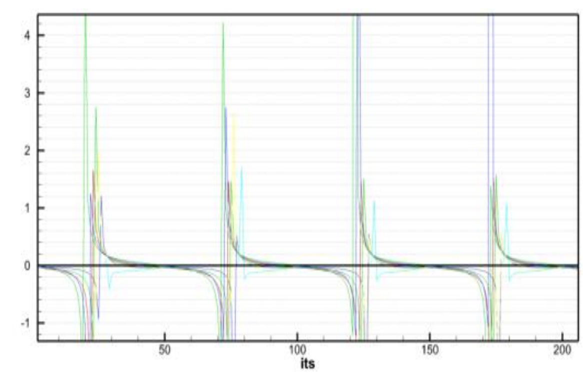

Figure 2 Histories of position of the hydrodynamic center, relative to the pitching axis, for pitch axis at 0.3c from le. (negative is for forward).

3 RESULTS AND DISCUSSION

3.1 Spring Loaded Wing Systematic Simulations

Figure 3 presents the calculated response pitch angle histories (denoted as 'rot' in the figure) for a straight wing for varying K at given Strouhal number $Str = 0.3$. The seven colored lines starting from the lower correspond to $K = 20kNm/rad, 1kNm/rad (3.16kNm/rad)$. The dashed line denotes the history of heaving motion. As expected, the increase of stiffness produces decreased responses. A small difference of the phase of the responses is also observed. Systematic simulations were also made for Str ranging from 0.2 to 0.7 and K/ρ from 5 to 40 (ρ denotes the fluid density in kg/m^3). The calculated thrust coefficient C_T against K/ρ is shown in Fig. 4 in a parametric form with parameters the Strouhal number (thicker lines) and the efficiency (thinner lines). The C_T against pitch angle 'theta' chart, with the same parametric lines, produced for the same wing under fully prescribed motion (with phase angle between heave and pitch equal to 90deg), is given in Figure 5 for comparison. Notice that for the spring loaded case, C is calculated by enforcing ζ=1. Thus the only free parameter in equation (4) for the determination of time dependent pitch $\theta(t)$ is K. Thus K is the 'proper replacement' for 'theta' in C_T plots for the case of a spring loaded wing. From figure 4 it is shown that the spring loaded wing produces substantial thrust, but the maximum efficiency is smaller and for a narrower area of parameters compared to a prescribed motion wing. Thus the spring loaded wing irrespective of its simplicity does not seem to be an efficient main propulsor device (i.e. when energy for heaving motion is provided by us using a main engine) compared to the prescribed motion wing. On the other hand when the spring loaded wing is used as an energy saving device (i.e. heaving energy is taken from ship motions reducing them) the efficiency of the system redefined as the useful propulsive power divided by the power given by us, which is zero in this case, becomes infinite. Notice that even in this case the conventional efficiency contained in figure 4 characterize how efficient the spring loaded wing transforms heaving motions to thrust and thus the problem of efficiency optimization of the spring properties in connection with the solution of the coupled wing-ship problem (e.g. Belibasakis&Politis 2013) is the correct design setup for a spring loaded wing propulsor. Closing this section it should be noted that the effect of parameters such as pitching axis position, damper settings, different wing shapes and possible non- linear springs and dampers have to be investigated, but the existing knowledge, that spring loaded wings operate well in limited conditions, is confirmed.

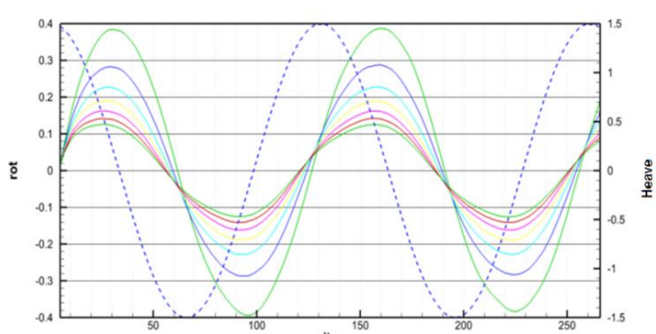

Figure 3 Pitch angle responses (rot) in radians, for varying

$K = 20 \div 1\, kNm/rad$ for straight wing s/c=4 at Str=0.3, h/c=1.5 Dashed line denotes history of heaving motion over chord length.

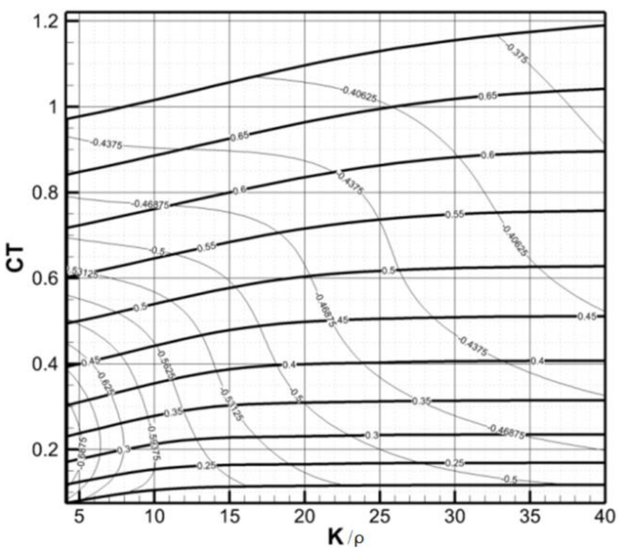

Figure 4 $C_T - K/\rho$ chart for a straight wing s/c=4, h/c=1.5, under simple harmonic motion. Thicker lines are for Strouhal number and thinner, are for efficiency.

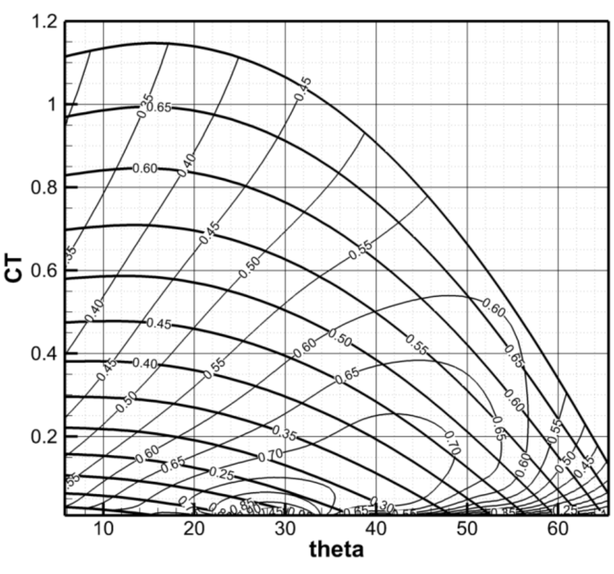

Figure 5 $C_T - \theta_0$ chart for a straight wing of s/c=4, h/c=1.5. Thin contour lines are for Efficiency and thick ones are for Strouhal Number, theta denotes the pitch angle in degrees (from Politis & Tsarsitalides (2014))

3.2 Active Pitch Control Systematic Simulations

The APC relation (8) has been applied for a harmonically heaved wing for a range of strouhal numbers and maximum angles of attack A_{max} . Figure 6 shows the obtained time series of various parameters for a harmonically heaved wing under APC at $Str = 0.4$ and target $A_{max} = 17^0$. More specifically Figure 6 contains representative histories of the pitch angle (rot), the local attack angle (local_attack), the (time dependent) pitch control parameter (ww), the heaving position (heave) and finally the thrust force Fx/ρ (denoted as fx in figure, notice that negative thrust is propulsive thrust according to our selection of coordinate systems). As shown in Figure 6 flatter angle of attack profiles are observed. Thus the wing operates at the desirable (below stall) angle of attack for longer part of the period, which means larger and always positive thrust, with good efficiency. This is also visible in the systematic $C_T - A_{max}$ diagram (Figure 7) where high efficiency and thrust coefficient is observed for a broad region of A_{max}. Concluding, an actively pitch controlled wing seems a very good selection if both propulsive efficiency and energy extraction from ship motions is the design target.

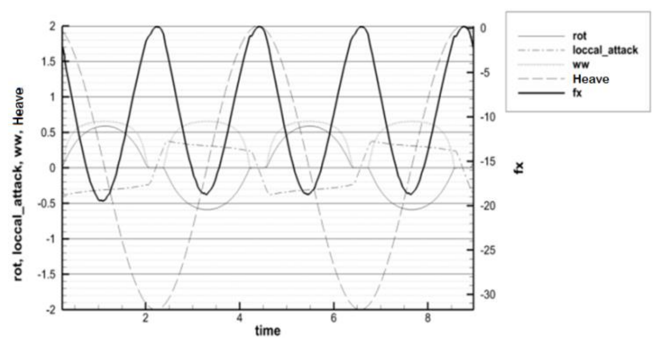

Figure 6 Time series of simulation of an APC foil of s/c=4 at Str=0.4 and Target A_{max}=17°.

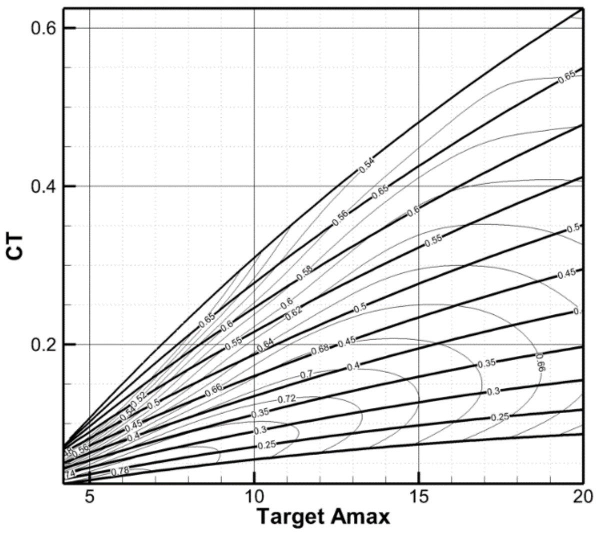

Figure 7 $C_T - A_{max}$ chart for a straight foil s/c=4, h_0/c=2, under simple harmonic heaving motion and APC. Thicker lines are for Strouhal number and thinner, are for efficiency.

3.3 More complex heaving motions

In this part of the paper we have attempted a harmonic series heaving motion, produced systematically for a range of Strouhal numbers. The harmonic series for heave has been obtained using the Bretschneider's spectrum as follows: The modal amplitude of the Bretschneider's spectrum has been selected constant and equal to h with $h/c = 2$ ($c = 1m$). The modal frequency f has been selected variable in order for the Strouhal number to vary from 0.2 to 0.7. Eight terms (heaving amplitudes) have been used in the harmonic series for heave, scanning the support of the Bretschneider's spectrum. To this heave harmonic series, our wing either adapts the pitch according to relation 8 or works as a spring loaded wing. Figure 8 shows the time dependent pitch angle of our wing operating in the given heaving (solid line) employing either APC (dotted line), or operated as a spring loaded system (dash dot). It can be observed, that the spring loaded wing produces slower and smaller response which result in higher angles of attack (beyond deep stall), as shown in Figure 9. On the other hand, APC produces larger and quicker responses, which result in angles of attack that slightly exceed the target, figure 9. Systematic $C_T - A_{max}$ diagrams for this complex heaving motion are shown in figure 10. As in the previous section, high efficiencies and thrust coefficients are observed for a broad region of A_{max}, concluding that an actively pitch controlled wing seems to be a very good selection in complex environments where energy is provided through random motions such as ship motions in a wavy sea.

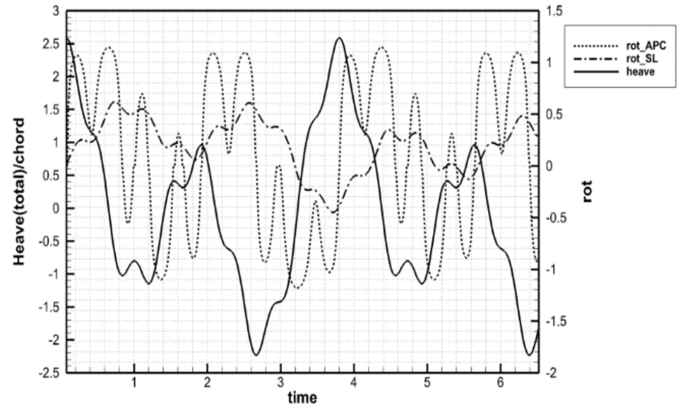

Figure 8 Pitch angle $\theta(t)$ (in rad) of a Spring Loaded wing (K=5kNm/rad , ζ=1) and a wing with APC (Target A_{max}=10deg) for the same heaving motion. Dotted line is for APC, Dash-Dot for Spring Loaded and the solid line is the heave motion.

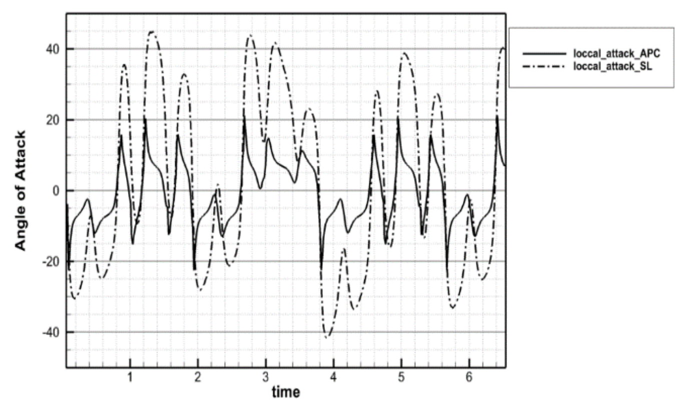

Figure 9 Angle of attack (in degrees) on the wing of a Spring Loaded wing (K=5kNm/rad , ζ=1) and a wing with APC (Target A_{max}=10deg) for the same heaving motion. Dotted line is for APC, Dash-Dot for Spring Loaded.

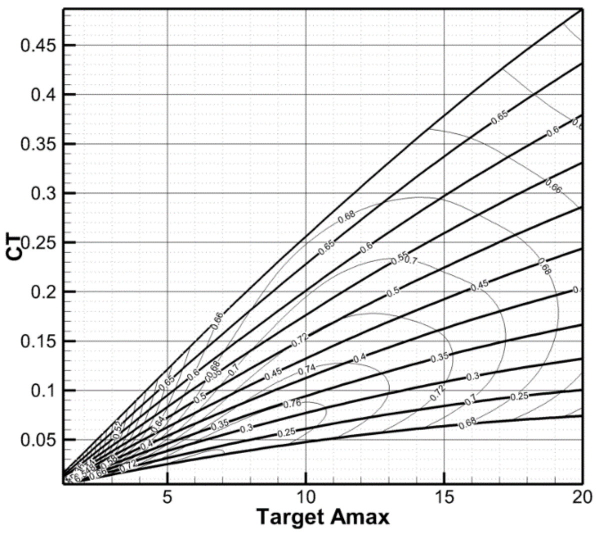

Figure 10 $C_T - A_{\max}$ chart for a straight wing s/c=4 under harmonic series for heaving motion. Thicker lines are for Strouhal number and thinner, are for efficiency.

4 CONCLUSIONS AND FUTURE WORK

An initial exploration of the potential of wings with passive (spring loaded) and active pitch control has been presented. Both systems seem promising, with the actively controlled wing being more flexible in complex environmental conditions, but with the spring loaded independent of electronics and capable of custom-made design in cases of one design point ship operation. Before any verdict is made, further investigations have to be made. For the case of spring loaded wings, a wider systematic variation of parameters is needed, while also investigating the effect of the pitch axis position and the damping factor. The effects of different shapes are another interesting issue, while the use of springs of nonlinear stiffness may show a great potential. Almost the same apply for the case of actively controlled wings. Variation of the position of pitching axis is to be investigated, but also it is interesting to see its performance for different wing shapes. Different methods of control need to be applied, as well as more sophisticated systems that would use the data from extensive simulations for system recognition that would lead to the creation of a state-space controller for thrust production in random motions (Wen et.al 2010).

Horizontal wings used for energy extraction from heaving and pitching motions, while the vertical for extraction of energy from rolling motions, are absolutely feasible and beneficial, especially for fast ships and ships that suffer from excessive motions, such as containerships, Ro-Ro vessels and passenger ships. From the mechanical engineering part, the ability to make the systems retractable is necessary as well as sizing, positioning and mounting of actuator motors have to be defined, solved and offered in a cost effective manner, in order to turn the concept into an actual device.

Proposed designs both for ships using the oscillating wing as a propulsor or only as energy saving system, as retrofits with minimal alterations to conventional hulls are displayed in Figure 11 and Figure 12.

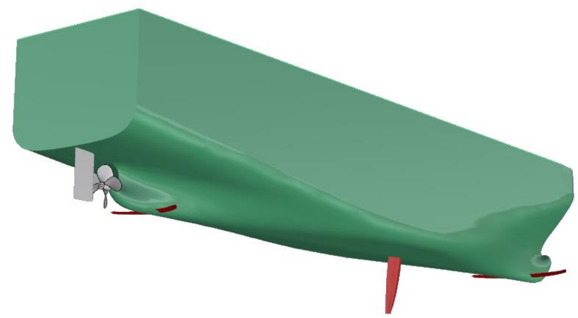

Figure 11 Conventional ship equipped with wings working as energy saving

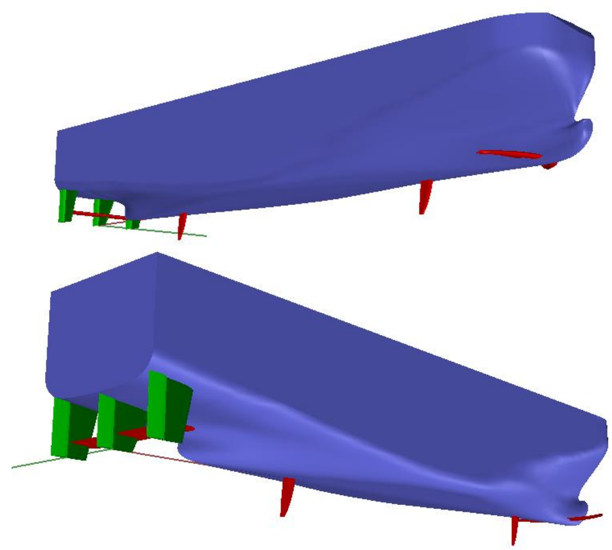

Figure 12 Ship equipped with flapping wing propulsors as main drive, along with energy saving bow and bottom wings

ACKNOWLEDGMENTS

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REFERENCES

Belibassakis, K. A. and G. K. Politis (2013). "Hydrodynamic performance of flapping wings for augmenting ship propulsion in waves." Ocean Engineering **72**: 227-240.

Bøckmann, E. and S. Steen (2014). "Experiments with actively pitch-controlled and spring-loaded oscillating foils." Applied Ocean Research **48**: 227-235.

Bose, N., (2008). Marine Powering Prediction and Propulsors. The Society of Naval Architects and Marine Engineers.

Chopra, A. K. (2007). Structural Dynamics.

Isshiki, H. (1994). Wave energy utilization into ship propulsion by fins attached to a ship. Proceedings of the International Offshore and Polar Engineering Conference.

Lighthill, M.J., 1969. Hydromechanics of aquatic propulsion: a survey. Annual Review of Fluid Mechanics 1, 413–446.

Nikolaev, M. N., A. I. Savitskiy and Y. U. F. Senkin (1995). "Basics of calculation of the efficiency of a ship was propulsor of the wing type." Sudostroenie **4**: 7-10.

Politis, G. and K. Politis (2014). "Biomimetic propulsion under random heaving conditions, using active pitch control." Journal of Fluids and Structures **47**: 139-149.

Politis, G. K. (2011). "Application of a BEM time stepping algorithm in understanding complex unsteady propulsion hydrodynamic phenomena." Ocean Engineering **38**(4): 699-711.

Politis, G. K. and V. T. Tsarsitalidis (2014). "Flapping wing propulsor design: An approach based on systematic 3D-BEM simulations." Ocean Engineering **84**: 98-123.

Rozhdestvensky, K. V. and V. A. Ryzhov (2003). "Aerohydrodynamics of flapping-wing propulsors." Progress in Aerospace Sciences **39**(8): 585-633.

Shyy, W., H. Aono, S. K. Chimakurthi, P. Trizila, C. K. Kang, C. E. S. Cesnik and H. Liu (2010). "Recent progress in flapping wing aerodynamics and aeroelasticity." Progress in Aerospace Sciences **46**(7): 284-327.

Sparenberg, J. A. (2002). "Survey of the mathematical theory of fish locomotion." Journal of Engineering Mathematics **44**(4): 395-448.

Taylor, G.K., Triantafyllou, M.S., Tropea, C. (Eds.), (2010). Animal Locomotion, Springer Verlag.

Triantafyllou, M. S., A. H. Techet and F. S. Hover (2004). "Review of experimental work in biomimetic foils." IEEE Journal of Oceanic Engineering **29**(3): 585-594.

Triantafyllou, M. S., G. S. Triantafyllou and R. Gopalkrishnan (1991). "Wake mechanics for thrust generation in oscillating foils." Physics of Fluids A **3**(12): 2835-2837.

Wen, L., Z. Fan, T. Wang and J. Liang (2010). "Fuzzy control of biomimetic propulsion using flapping foil." Jiqiren/Robot **32**(3): 306-313.

Wu, T. Y. (1971). "Hydromechanics of swimming propulsion. Part 1. Swimming of a two-dimensional flexible plate at variable forward speeds in an inviscid fluid." J. of Fluid Mechanics **46**: 337–355.

DISCUSSION

Question from Jacques Andre Astolfi

I am wondering about the non-viscous fluid model you used.

Generally, these devices are based on detachment of vortices, forming a Von Karman alley and the propulsion regime is attained as the Von Karman vortices are inversed, generating a jet-like behavior. All these phenomena are anticipated in viscous flows.

Authors' Closure

Thank you for your comment. We agree that detachment of vortices is a necessary prerequisite for the generation of an inverse Karman vortex configuration and the production of thrust. Panel methods for lifting flow modeling have very early recognized this fact, introducing in their modeling the well-known Joukouski hypothesis, according to which a potential flow model cannot include infinities or discontinuities in the derived flow field. This condition introduces artificially viscosity in a potential modeling of real viscous flows. In our implementation we use a pressure type Kutta (equalization of face and back pressure as we approach the trailing edge). This condition, together with the flow asymmetry between face and back, results in specific vorticity generation at the trailing edge, which is responsible for the production of free wake vorticity sheet and the creation of Karman street. A good old reference for the 2-D case, regrading Karman street formation after imposing a pressure type Kutta at trailing edge, is the paper by Basu and Hancock: 'The unsteady motion of a two-dimensional airfoil in incompressible inviscid flow', *J. Fluid Mech.* (1978), *val.* 87, *part* 1, *pp.* 159-178. Taking this opportunity, we add Figure 13 which illustrates the vortex formations for an indicative case under all discussed modes of pitch motion.

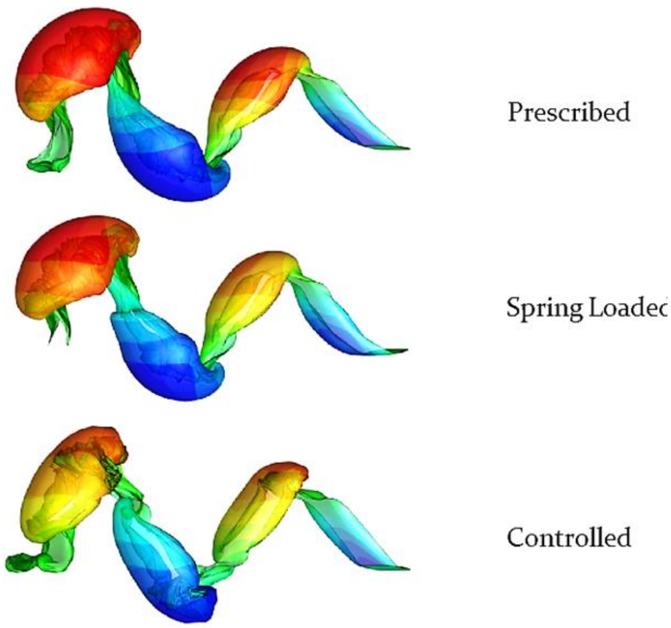

Figure 13 simulations for the same wing and same motion parameters $s/c = 4, h/c = 2, Str = 0.3$ with three different pitch motions. Prescribed: θ0=23.7deg, Spring Loaded: K=4Nm/Rad, Controlled: Amax=17deg