Biomimetic Propulsion using twin oscillating wings

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ABSTRACT

The ever growing demand for less emissions and higher efficiency, lead the scientists to investigate alternative methods of propulsion. The area of biomimetics is a very promising one, as all experimental data and simulations show high efficiencies, outstanding maneuverability and seakeeping qualities. Yet, the area has not received big acceptance, due to mistrust to the estimations and/or difficulties in constructing such systems. The problem of a twin oscillating wing configuration has attracted the scientific interest many years ago, since it provides a balance to the significant lateral forces produced by a single biomimetic wing propulsor.

In this paper we take the initiative to present systematic open water results for twin oscillating wing configurations. Towards this end we have produce a data generation code for the creation of the required geometry and motion data of twin oscillating wings. The data generation code has then been used to feed the boundary element code UBEM. The effect of the unsteady trailing vortex sheets emanating from the twin wing system is taken exactly into consideration in UBEM by satisfying the vorticity transport equation in a step by step time base. With the proper filtering of induced velocities which introduces artificial viscosity to our model, beautiful roll-up patterns emerge, indicating the main vortex structures by which the twin wings interact by themselves and develop forces.

The calculated open water performance of the twin oscillating wings has then been used to design such a system for a real ship. Comparisons are presented with the same ship propelled by either a twin wing configuration, a single biomimetic wing and a conventional propeller. It is shown that the twin wing propulsor is very efficient without having the disadvantage of serious transverse forces of a single biomimetic wing.

Keywords

Biomimetic Propulsion, Twin oscillating wing propulsion; Boundary element method; Unsteady wake rollup;

1. INTRODUCTION

As it was very well expressed by Rozhdestvensky (2003), it is evident that the interest in biomimetic devices is justified because such systems:

- can be viewed as “ecologically” pure,
- are relatively low-frequency systems,
- possess sufficiently high efficiency,
- are multi-functional in the sense of being capable of operating in different regimes of motion,
- can combine the function of propulsor, control device and stabilizer,
- can provide static thrust,
- can provide high maneuverability,
- possess more acceptable cavitation characteristics than conventional propellers,
- have relatively low aerodynamic drag in the “switched-off” position,
- allow the use of modern controls, MEMS, piezoelectric, reciprocating chemical muscles (RCM), and other technologies.

The modern history of biomimetics starts in 1935 with Gray's paradox, and theoretical developments start with the works of Sir James Lighthill (1969) and (1973) and 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 et al. (2010) and Taylor et al. (2011). Marine biomimetic propulsors are also discussed in the book of Bose (2010).

The scope of the present work is: (a) to provide the designer with insight in the physical mechanisms of a twin oscillating wing configuration, (b) to propose a complete methodology for choosing an optimal twin wing propulsor. To this end, a limited extend systematic series
has been produced, using the code UBEM (Unsteady Boundary Element Modeling), which has already been tested for grid independence and consistency, Politis (2004, 2011). An experimental validation of the UBEM code for biomimetic wings is also included in the present work, using the experimental results of Prof. Triantafyllou and his team, Triantafyllou et al. (1996), Read et al. (2003).

In some past research work the authors have used the UBEM code to investigate a number of biomimetic flows as follows: flapping wings, Politis & Tsarsitalidis (2009), bird flight, Politis & Tsarsitalidis (2010) and the Flexible Oscillating Duct in Politis & Tsarsitalidis (2012). In this paper the twin wing configuration geometry is systematically examined. Hydrodynamic performance simulations are undertaken using UBEM for a limited in extent systematic series of twin oscillating wings and the calculated mean thrust and power are plotted in diagrams, appropriate for the propulsor design. Systematic runs include variation of Strouhal number and pitch angle amplitude for the pre-selected twin wing geometry. A design method, that employs the produced charts, is presented and used to calculate the powering performance of a passenger/car ferry equipped with the twin wing propulsor. Powering performance calculations have also been made for the same ship equipped with either a single flapping wing or a conventional propeller. The comparison shows that the twin configuration can produce high efficiencies superior to that obtained with either a single flapping wing or a conventional propeller.

2. Wing geometry, motion and panel generation.

For the case of a twin wing configuration, the independent variables which define the state of our system can be decomposed in two groups. Group A contains the geometric variables and group B contains the motion related variables.

**Group A:** Assuming zero skewback and twist the wing outline is fully described by its span-wise chord distribution \( c(s) \), where \(-\text{span}/2 < s < \text{span}/2\). For the current paper the span-wise chord distribution has been selected according to figure 1, where wing tips are tapered and rounded for a better hydrodynamic performance. For a quantitative description of the tip geometry, a cubic spline has been used, which extends span-wisely from tip to \( c/2 \), with the following boundary conditions: At wing-tip: wing chord is \( c/4 \) and \( d^2 c/ds^2 = 5 \). At \( c/2 \) (from wing-tip), the chord is \( c \) and \( dc/ds = 0 \). An additional geometric variable for our twin wing system is the chord-wise position of the pitching axis \( b \), which is the same for each wing (twins wings are symmetric around a plane parallel to the flow at infinity). Furthermore for a twin wing configuration a geometric parameter defining the distance between the mean positions of the two wings, has to be introduced. Since our aim is the development of a systematic series, the selection of this parameter should be done with care. More specifically from our experience with extended twin wing simulations, a better variable characterizing the transverse position (measured along the heaving direction) of the wings, is the ‘minimum distance’ \( h_{min} \) between wing surface points, during a full cycle of wing oscillation. The appropriateness of this variable has to do with the following: (a) it is related to the mirroring flow effect produced by the twin wing configuration, and (b) it is the proper variable which controls/avoids the collisions of points of the twin oscillating wings in a direct manner. Thus we decide to use this minimum distance \( h_{min} \) (and not the distance between the mean positions of the wings) as the geometric parameter describing the ‘distance’ between our twin wing configurations. This selection introduces some complexity in the geometric description of our system, which shall be discussed after the introduction of the motion parameters.

**Figure 1. Wing outline (s/c= 6).**

Group B: Propulsor motion is defined by: (a) the amplitude \( h_n \) of a sinusoidal heaving motion normal to the velocity of advance \( U \), (b) the amplitude \( \theta_n \) of a sinusoidal pitching motion, (c) the frequency \( n \) (common for both heaving and pitching motions) and (d) the phase angle \( \psi \) between heaving and pitching motions.

Thus the state of the twin system is completely defined by the variables: \( (U, n, \psi, h_n, b, \theta_n, h_{min}) \). The previous parameters define uniquely the instantaneous angle of attack \( a(t) \) of each wing with respect to the undisturbed flow through the equation:

\[
a(t) = \theta_n \sin(2\pi n \cdot t + \psi) - \tan^{-1}(h_n 2\pi n \cdot \cos(2\pi n \cdot t) / U)
\]

or in non-dimensional form:

\[
a(t) = \theta_n \sin(2\pi n \cdot t + \psi) - \tan^{-1}(\pi \cdot St \cdot \cos(2\pi n \cdot t))
\]

where \( St \) denotes the Strouhal number defined by:

\[
St = \frac{n \cdot h}{U}, h = 2h_n
\]

and \( h \) denotes the heave height.

The selection of \( h_{min} \) as the ‘distance’ parameter for the twin wing configuration, introduces a problem regarding calculation of the distance between the mean positions of
the two wings. This distance is needed to define the thrust and power coefficients later on. For a resolution to this problem we observe that for: (a) a symmetric wing outline around the mid-chord (span-wise) axis with a zero twist, (b) with the pitch axis in front of the mid-chord point and (c) with \( h_{\text{min}} \) greater than a multiple of the maximum thickness of the wing, the dangerous point for collision is the trailing edge of the wings. Furthermore, under the same conditions, the mid-span wing section is a representative of the whole wing. Taking those considerations into account, the distance of the wing trailing edge from the mean wing position, as a function of time, is given by the formula:

\[
H(t) = h_0 \sin 2\pi nt + (c - b) \sin(\theta_0 \sin(2\pi nt + \psi))
\]

This is a nonlinear equation in \( t \). Therefore, the maximum distance of the wing trailing edge from the mean wing position, can be found either numerically (i.e. by evaluating formula (4) in the range: \( 0 < t < T, T = 1/n \) and taking the maximum, \( T \) is the period of oscillation) or analytically. For the analytic prediction, we use the substitution:\( 2\pi nt = \pi / 2 + \epsilon \) together with the selection \( \psi = \pi / 2 \). A 3rd order series expansion in \( \epsilon \) of formula (4) has then been derived and the value of \( \epsilon \) which maximizes \( H \) has analytically evaluated. The resulting equations are as follows:

\[
\epsilon = \frac{-h_0 + \sqrt{h_0^2 + 2((c - b)\theta_0)^2 + 2(c - b)^2 \theta_0^4}}{(c - b)\theta_0(1 + \theta_0^2)}
\]

\[
H_{\text{max}} = h_0 - (c - b)\theta_0\epsilon = \frac{h_0}{2}(c - b)\theta_0^2 + \frac{(c - b)\theta_0^4}{6}(1 + \theta_0^2)\epsilon^3
\]

Using \( H_{\text{max}} \), the distance of the mean wing position to the symmetry plane, of the twin wing system, is given by:

\[
h_t = H_{\text{max}} + h_{\text{min}}
\]

Comparisons of analytical with numerical predictions for \( h_t(m) \) vs \( \theta_0(\text{deg}) \) (horizontal axis) are shown in figure 2, together with a least square approximation for the analytic expression for \( h_t \).

Having introduced the analytical description of both geometry and motion of our wings, the creation of a surface panel distribution describing the systems at consecutive time steps is straight forward.

Figure 3 shows the time instances of the twin wing mid-span section, evenly distributed in two periods. With the flapping wing paneling in time known, the code UBEM can be applied to calculate the resulting unsteady forces, energy requirements and free shear layer evolution.

![Figure 3. Sequential positions of the twin wings for \( h_0/c=1.5, \text{Str}=0.35, \theta_0=23.6, h_{\text{min}}/c=0.1 \)](image)

### 3. Calculation of forces, moments, power and efficiency.

In the case of an arbitrary body (rigid or flexible), energy is transferred through flexibility in a point-wise manner. UBEM code uses a specialized procedure for the calculation of the power provided to the twin wing configuration, termed DHP (Delivered Horse Power) and the useful power developed by the system to propel the ship, termed EHP (Effective Horse Power). The corresponding methodology has already been presented in Politis & Tsarsitalidis (2011).

### 4. Theoretical formulation and solution of the twin wing propulsor design problem.

Propulsor design problem consists in finding the propulsor geometric and motion characteristics by which it can propel a given ship with a given ship speed. Among all possible design solutions, satisfying the constraint of a given ship speed; there is an optimum, which requires a minimum delivered power. Although the optimum propulsor problem is a problem of mutual propulsor/stern optimization, in most cases, the propulsor is optimized with the assumption of a given hull/stern geometry. The design methodology for a biomimetic propulsor (more specifically the FOD – Flexible Oscillating Duct), has already been presented in Politis & Tsarsitalidis (2012). In the same context, a well-posed propulsion problem for a twin oscillating wing configuration, can be set as follows:
Calculate the time dependent open water performance using the UBEM code for a range of the parameters \((\theta_0, \text{Str})\) assuming given \((h_s/c, s/c, b/c, h_{\text{min}}/c)\) (in the sequel \(s\) denotes the swept surface). Calculate then the period-mean values for thrust and delivered power and denote them by: \(T\) and \(DHP\) respectively. Twin wing performance can then be expressed by the following non-dimensional (mean) thrust and (delivered) power coefficients:

\[
C_t = \frac{T}{0.5 \rho U^2 S} = C_t(\theta_0, \text{Str}, h_s/c, s/c, b/c, h_{\text{min}}/c) \tag{8}
\]

\[
C_p = \frac{DHP}{0.5 \rho U^3 S} = C_p(\theta_0, \text{Str}, h_s/c, s/c, b/c, h_{\text{min}}/c) \tag{9}
\]

where \(S\) denotes the swept surface \((= s \cdot 2(h_s + H_{\text{max}}))\). Since in our formulation we hold the \(h_{\text{min}}\) constant, the surface \(S\) is a function of the pitch angle \(\theta_0\) according to equations (5),(6) and (7). 

In self-propulsion conditions we assume that a Taylor wake fraction \(w\) is defined by:

\[
U = V(1 - w) \tag{10}
\]

where \(V\) is the ship speed. Furthermore a relative rotative efficiency \(\eta_h\) is defined by:

\[
\eta_h = \frac{DHP}{DHP_g} \tag{11}
\]

where \(DHP\) denotes the (period-mean) power delivered to the flapping wing in self-propulsion conditions. Assuming further that a ‘thrust equalization method’ has been used for the determination of propulsor-hull interaction coefficients \(w, t, \eta_h\) (where \(t\) denotes the thrust deduction factor), the flapping wing thrust and power, in the self-propulsion conditions becomes:

\[
T_g = T = 0.5 \rho V(1 - w)^2 S \cdot C_t(\theta_0, h_s/c, h_{\text{min}}/c, V(1-w)c) \tag{12}
\]

For a self-propelled ship, moving with velocity \(V\), the surrounding fluid interacts with the hull developing a resistance force: \(R_0(V)/(1-t)\), where \(R_0(V)\) denotes the hull towing resistance. A hull can also pull an object with a force \(F\) (case of a tug-boat or a trawler). Then the thrust, under self-propulsion conditions, is given by:

\[
T_g = R_0(V)/(1-t) + F \tag{14}
\]

Assuming that \(V, \theta_0, c, s, h_s, b, h_{\text{min}}, w, t, \eta_h\) are known parameters, equations (12), (13) and (14) become a non-linear system of three algebraic equations with three unknowns: \((T, DHP_g, n)\). This system can be solved for a range of ship speeds: \(V \in (V_1, V_2)\) and pitch angles: \(\theta_0 \in (\theta_{0,1}, \theta_{0,2})\). Thus, the totality of design solutions for the given ship is obtained:

\[
DHP_g(V, \theta_0), n(V, \theta_0) \leftrightarrow \{\text{ship, c, s, h_s, h_{\text{min}}, w, t, \eta_h}\} \tag{15}
\]

The content of Equation (15) can be represented in a 2-D \(DHP_g - n\) diagram in the form of parametric curves of constant \(V\) and constant \(\theta_0\). Notice that this presentation is similar to that used in conventional propellers, where the propeller pitch ratio \(P/D\) is taking the place of \(\theta_0\). Using this presentation, we can finally extract the required optimum flapping wing by selecting the characteristics (geometric and motion) which require the minimum \(DHP_g\) for the given ship speed \(V\).

5. Decisions regarding Geometric and Flow/motion variables for the proposed twin wing series.

To proceed to a series based design process for a twin configuration, decisions have to be taken, on the corresponding geometric and flow related parameters. For the needs of the current paper which can be considered as a pilot work on the subject, the series is limited in extent and consist of only one twin system geometry (span-wise chord distribution is discussed in previous paragraph 2) with \(s/c = 6\), \(h_s/c = 1.5\), \(b/c = 0.33\), \(\psi = \pi/2\) and \(h_{\text{min}}/c = 0.1\). The Strouhal number has been selected in the range: \(Str = 0.1 - 0.7\). Using our previous experience, this selection is expected to contain the region of maximum hydrodynamic efficiency. Finally the range of the pitch angle \(\theta_0\) has been selected from 5 deg to a maximum value, which depends on the Strouhal number. This maximum value of the pitch angle has been properly selected to include the full range of thrust producing wing motions.

6. Transient twin wing performance and selection of simulation period.

The main difference between a traditional propeller and a flapping wing is that the latter produces a period mean thrust as a result of a highly unsteady instantaneous thrust. The simulation method in hand can predict this time dependent thrust but, since it is a time stepping method, initial conditions on motion have to be imposed. A burst starting twin wing is used as the starting condition. In this case a transient phenomenon occurs. Thus the mean period values for thrust or power have to be calculated after the passage of this initial transient phenomenon. To take care for this, time domain simulations have been performed for three periods and for several cases. Indicatively, Figures 4, 5 are presented the unsteady thrust or power for two cases.

From these figures it can be concluded that, for the representative selected parameters, the transient phenomenon is limited to the few initial time steps after the burst start. Thus it is safe to use the 2nd period of
simulation, to calculate the mean thrust and power to be used in the design charts.

**Figure 4. Time evolution of thrust for (s/c =6, h₀/c=1.5, hₘᵦ/c=0.1, Str=0.34, Theta=20.6)**

**Figure 5. Time evolution of thrust for (s/c =6, h₀/c=1.5, hₘᵦ/c=0.1, Str=0.46, Theta=44.5)**

7. Open water performance diagrams and comparison with single wing systems.

Systematic unsteady BEM simulations have been performed with the selected flapping wing series described in section 5. In all simulations a chord of \( c = 1.0m \) has been selected. Furthermore in all simulations we have used a twin system with:

\[
\frac{s}{c} = 6, \quad \frac{h_0}{c} = 1.5, \quad \frac{h_{\text{min}}}{c} = 0.1, \quad \frac{b}{c} = \frac{1}{3}, \quad \psi = 90^\circ
\]

Variation of Strouhal number has been achieved by changing the frequency of the flapping wing oscillation while the corresponding translational velocity has been held constant and equal to \( U = 2.3m/s \). This results to a constant Reynolds number equal to \( 0.202 \times 10^7 \), based on translational velocity (\( \text{Re} = U \cdot c / \nu \)). Corresponding Reynolds numbers based on the maximum undisturbed flow velocity are Strouhal dependent, according to the relation:

\[
\text{Re}_{\text{Str}} = \frac{U \cdot c}{\nu \sqrt{1 + (\pi \cdot \text{Str})^2}}. \text{Thus Re}_{\text{Str}} = 0.22 \times 10^7
\]

at \( \text{Str} = 0.10 \) and \( \text{Re}_{\text{Str}} = 0.51 \times 10^7 \) at \( \text{Str} = 0.7 \) (kinematic viscosity: \( \nu = 1.139 \times 10^{-4} \text{m}^2 / \text{s} \)). Mean thrust and power have then been calculated by running the BEM code for two time periods and calculating the mean values of the unsteady forces over the second period. The results are presented in the form of \( C_T - \theta_0 \) diagrams (where \( \theta_0 \rightarrow \text{theta} \) in diagrams), \( C_p - \theta_0 \) diagrams, and \( C_p - \theta_0 \) with parameter the Strouhal number (thick line in the diagrams), figures 6,7 and 8. \( C_p \) denotes the energy required for the pitching of the wing, given by:

\[
C_p = \frac{0.5 \rho U^2}{S}
\]

\[
= \frac{1}{0.5 \rho U^2 S} \int_{-\tau}^{\tau} M_p(t) \cdot \omega_p(t) \, dt
\]

where \( M_p(t) \) is the instantaneous moment around the pitching axis and \( \omega_p(t) \) is the instantaneous rotational velocity around the pitching axis. \( C_T - \theta_0 \) diagrams contain additionally in parametric form the open water efficiency \( \eta \) of the system (thin lines):

\[
\eta = \frac{T \cdot U}{DHP} = \frac{C_T}{C_p}
\]

\[\text{(17)}\]

**Figure 6. Ct-theta chart for twin system. Thicker lines are for Strouhal number and thinner, are for efficiency.**

**Figure 7. CP-theta chart for twin system. Thicker lines are for strouhal number and thinner, are for maximum angle of attack.**
Also, $C_p-\theta_b$ diagrams contain additionally in parametric form the $a_{\text{max}}$ angle (thin lines) defined as the maximum value of $a(t)$, relation (2), over one period. This last information is very useful for the designer in order to avoid maximum angles with a potential danger for separating flow (e.g. greater than 20deg), phenomenon which is not modeled by the used version of UBEM. For illustrative reasons, diagrams 8, 9 and 10 contain similar results for a single wing with:

$$s = \frac{h}{c} = 6, \frac{h_s}{c} = 1.5, \frac{b}{c} = \frac{1}{3}, \psi = 90^\circ$$

so that comparisons are made easy.

Assume that a ship is given, with a design speed of $V$ knots. The problem of designing a $s/c=6$, $h/c=1.5$ twin wing (i.e., select its optimum geometry with the corresponding revolutions and required DHP) can be solved as follows: (a) with the design speed known, the ship resistance and, from equation (14), the propeller thrust and $C_T$ can be calculated; (b) with this $C_T$ draw a horizontal line on Figure 6 and find the intersection of this horizontal line with the various constant Strouhal lines, let $(\theta_b, \text{Str})$, $i = 1, n_w$, denote the $n_w$ intersection points; (c) from each Strouhal number the frequency of the propulsor motion can be found: $n_i = \text{Str} \cdot V / (2 \cdot h_s)$; (d) use Figure 7 to find $C_{P,i}$ for the points $(\theta_b, \text{Str})$, $i = 1, n_w$, from the $C_{P,i}$ find the required open water power and use (11) to find $DHP_{b,i}$; (e) from the calculated $DHP_{b,i}$, $i = 1, n_w$, select that with minimum required $DHP_b$. Finally use figure 8 to estimate the required power for the pitch mechanism.

Interesting conclusions drawn from those figures are the following: (a) There is a relatively wide region of maximum hydrodynamic efficiency which is achieved at a maximum angle of attack less than 15degrees i.e. at the region of flow without expected separation, (b) The order of magnitude of the power required for pitching is approximately 1% of the corresponding total delivered power. It should be also noted that systematic inspections of the calculated pressure distributions gave no indication of local pressure less than the corresponding vapor pressure in the region around optimum performance. As a result no cavitation is expected at that region. For the comparison between the single wing and the twin wing system, it can be told, that the ground effect between the two wings seems to cause a very small difference in the resulting $C_T, C_p$ values. After further examination of the efficiency curves, though, it can be seen, that the contours are narrower in the sense of theta, but slightly wider in the sense of $C_T$ and Strouhal number. This difference will affect positively the design results produced later on. Commenting finally on the values of the power required for the pitch setting (Figure 8 and Figure 11), we observe that in the whole range of the pitch setting are small with a trend to approach zero for smaller Strouhal numbers.

These charts can be used to select an optimum twin wing configuration for a given ship very easily as follows:
8. Experimental evidence regarding predictability of biomimetic system performance using UBEM

To verify the predictive capability of UBEM, experimental data concerning a single oscillating wing with parameter \( s = 6, \frac{h_0}{c} = 1, \frac{b}{c} = \frac{1}{3}, \psi = 90^\circ \) was taken from the works of Prof. Triantafyllou and his team (Read, Hover et al. 2003), (Schouveiler, Hover et al. 2005) and plotted over the corresponding charts for the single wing case produced by UBEM, Figure 12. Notice that in figure 12 the presented results refer to our definition of \( C_T, C_p \) which uses the ‘nominal swept surface’ in the denominator, equations (8), (9). This definition is different from that used by Prof. Triantafyllou and his team. Thus we have properly pre-process the results of Prof. Triantafyllou and his team in order to produce Figure 12. From Figure 12 we show that there is a good coincidence of experimental results with that obtained using UBEM, in the area of high efficiency \( \theta_s = 30^\circ - 60^\circ \) and \( Str \leq 0.45 \). For smaller maximum angles of attack (i.e. less than 30deg) there is a trend for UBEM to underestimate the experiments. This is due to the endplates used in the experimental setup. For smaller theta (higher maximum angles of attack) UBEM overestimates the thrust, as leading edge separation has not been modeled in the version of UBEM used for this simulation. Notice that 3D leading edge separation has been recently added to UBEM and we plan to repeat and publish the corresponding comparisons in the near future.

9. Wake visualizations – Understanding how the twin wing configuration produces thrust.

For a better understanding of the underlying physical mechanisms of thrust production, the free shear layer produced by the twin wing system \( \left( s = 6, \frac{h_0}{c} = 1.5, \frac{h_{\text{min}}}{c} = 0.1, \frac{b}{c} = \frac{1}{3}, \psi = 90^\circ \right) \) is plotted, figures 13a,b. The wing surface and the free vortex sheet surface on those figures have been colored according to their surface dipole distribution intensity. Notice that constant dipole lines coincide with surface vortex lines. By using either the last property or the deformation patterns of the free vortex sheets, a number of strong ring vortices in the wake of the wing are made recognizable. Those ring vortices produce series of oblique jet flows by which the flapping wing produces thrust. Figure 13 also contains artistic add-ons, showing the train of ring vortices (curved arrows) and corresponding jets (straight arrows) by which the flapping wing feeds with momentum the wake and produces thrust. More specifically the straight arrows are the results of the induced velocities produced by the ring vortices.

10. Application of a twin wing for the propulsion of a ship – Optimum design example.

A passenger ferry is used in a feasibility study for the application of a twin wing, a single wing and a traditional propellers as alternative propulsors. The passenger ferry is a twin screw vessel with displacement of 8917.66 tns and a maximum allowed propeller diameter of 4.1 meters. The bare hull resistance curve of the ship, taken from the database of the NTUA towing tank, is given in table 1.
Figure 13. Wake of a Flapping wing of s/c=6, h₀/c=1.5, hₘᵣ₉/c=0.1, Str=0.46, θ₀=44.5. Colors are for dipole potential. Artistic add-ons showing the train of ring vortices and corresponding jets by which the wing produces thrust.

With the bare hull resistance given, the system of algebraic equations (12), (13) and (14) can be solved for a range of ship speeds \( V \) and \( θ₀ \), and the totality of design solutions can be presented in a diagram as dictated by Equation (15). For the need of the comparison, it has been assumed that in all cases: \( w = 0.0, t = 0.0, \etaₚ \approx 1.0 \). This is a reasonable assumption for a twin screw vessel which has small propulsor-hull interactions. The use of the same hull-interaction coefficients for the flapping wing systems and the propeller can be considered reasonable since interaction coefficients are (for the same stern geometry) mainly functions of propulsor diameter and the developed thrust. Harvald (1983). No inclined axis corrections were made for the conventional propellers. No correction of the bare hull resistance for appendages has been made. A shaft efficiency equal to 1 has been used in the calculations. No corrections for full scale Reynolds number have been introduced for the propulsors.

Totality of design solutions in the form of Constant-V, constant-\( θ₀ \) grids for flapping wings and Constant-V, constant-P/D grids for propellers are illustrated for comparison in figures 14, 15 and 16. The comparison of the optimum flapping wings (twin, single) vs the optimum B-screw, for a ship speed equal to 23 knots can be summarized in table 2.

### Table 1. Resistance curve

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<th>( V ) (m/s)</th>
<th>( R ) (kp)</th>
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### Table 2. Comparison of propulsors.

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<th>Case</th>
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<th>Power (PS)</th>
<th>Propulsive Efficiency (%)</th>
<th>Power Gain (%)</th>
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<tr>
<td>single</td>
<td>43.23</td>
<td>16289.72</td>
<td>75</td>
<td>4.75</td>
</tr>
<tr>
<td>B-screw</td>
<td>168.30</td>
<td>17103.40</td>
<td>72</td>
<td></td>
</tr>
</tbody>
</table>

It is observed that a gain in propulsive efficiency of 4.75% is obtained for the case of a single biomimetic wing in comparison to a conventional propeller. The corresponding gain for a twin wing configuration is 6.12%. It is also noticeable, that the optimum flapping wing revolutions are always lower compared to that of corresponding conventional optimum propeller. It should be stretched that the absolute values of power and overall efficiency, contained in table 2, are approximate to the extent of our uncertainty regarding values of propulsor-hull interaction factors. For the comparison between the single and twin wing, it is visible that the aforementioned small differences, has led to solutions with higher Strouhal numbers, meaning higher frequencies, but also an additional improvement in efficiency.

11. Closing remarks, Challenges and further Development

The code UBEM has been applied to investigate the open water performance of a twin wing propulsor. Systematic calculations were made and design charts were produced,
along with a design methodology, which has been explained thoroughly. Propulsive coefficients of the order of 0.77 have been calculated, which are higher than that observed in conventional propellers. After applying the design method to an actual ship, the twin wing configuration proves to be superior to conventional propellers with serious efficiency gains of practical interest. The box shaped swept area of the wing, allows taking advantage of the whole stern area, compared to a propeller, which can only utilize a disk area that fits under the ship. This fact alone indicates a serious advantage of the flapping wings over the propeller. Furthermore at the region of optimum efficiencies, no cavitation issues are expected. The twin wing, due to its shape and its non-rotational operation, seems to be friendlier to the environment and less catastrophic for aquatic animals. In addition to the above, the power required for the pitching motion of the wings, is shown low, which means that it is easy to control it with a small servomotor and shows the possibility of using the system for extracting energy from the waves and transforming it to useful thrust. Adding to the above, the fact that twin wings produce no lateral forces (due to symmetry), they get even more attractive. Expansion of the presented series of the twin oscillating wing configurations, is planned in the near future, a fact which will allow us to examine in more detail the effect of the kinematic and geometric parameters of the propulsor to its hydrodynamic performance.

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**REFERENCES**

APENDIX 1: Maneuverability; Lateral forces through biased pitching (added in response to reviewer’s request)

If demanded, the thruster can produce lateral forces, by simply biasing the pitching motion. The following figures present the resulting wakes and calculated forces for three indicative cases. Interesting wake patterns emerge and strong lateral forces are produced. As it can be seen, even though there is strong interaction between the wakes of the two foils, there was no issue of strong interaction between wake and foil, even in highly loaded cases. Extended exploration of this area is to be made in future publications.

Figure 1. Wake and resulting forces of a Flapping wing of s/c=6, h₀/c=1.5, hₘᵋn/c=0.1, Str=0.4, θ₀=30.7. Bias 20°. Colors are for dipole potential. Dashed lines are for Fₓ and solid for Fᵧ
Figure 2. Wake and resulting forces of a Flapping wing of $s/c=6$, $h_0/c=1.5$, $h_{min}/c=0.1$, $Str=0.4$, $\theta_0=56$, Bias 20°. Colors are for dipole potential. Dashed lines are for $F_x$ and solid for $F_y$.

Figure 3. Wake and resulting forces of a Flapping wing of $s/c=6$, $h_0/c=1.5$, $h_{min}/c=0.1$, $Str=0.4$, $\theta_0=56$, Bias 10°. Colors are for dipole potential. Dashed lines are for $F_x$ and solid for $F_y$. 