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Influence of viscous effects on numerical prediction of motions of SWATH vessels in waves

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Abstract. The accurate prediction of motion in waves of a marine vehicle is essential to assess the maximum sea state vs. operational requirements. This is particularly true for small crafts, such as Autonomous Surface Vessels (ASV). Two different numerical methods to predict motions of a SWATH-ASV are considered: an inviscid strip theory initially developed at MIT for catamarans and then adapted for SWATHs and new a hybrid strip theory, based on the numerical solution of the radiation forces by an unsteady viscous, non-linear free surface flow solver. Motion predictions obtained by the viscous flow method are critically discussed against those obtained by potential flow strip theory. Effects of viscosity are analyzed by comparison of sectional added mass and damping calculated at different frequencies and for different sections, RAOs and motions response in irregular waves at zero speed. Some relevant conclusions can be drawn from this study: influence of viscosity is definitely non negligible for SWATH vessels like the one presented: amplitude of the pitch and heave motions predicted at the resonance frequency differ of 20% respectively and 50%; in this respect, the hybrid method with fully non-linear, viscous free surface calculation of the radiation forces turns out to be a very valuable tool to improve the accuracy of traditional strip theories, without the burden of long computational times requested by fully viscous time domain three dimensional simulations.

Keywords: seakeeping; SWATH; viscous effects; viscous added mass and damping; Navier-Stokes equations solver for oscillating floating bodies; Autonomous Surface Vessels

1. Introduction

A new family of Autonomous Surface Vehicles (ASVs) has been designed to achieve low motions in waves (enhance operability at sea) and reduced powering requirement at cruise speed to maximize endurance or achieve high speeds (Brizzolara and Chryssostomidis 2013). The family is based on an unconventional SWATH hull which has been optimized with respect to these two objectives resulting in a twin canted struts arrangement and a particular underwater hull shape having two maximum area sections and an intermediate minimum area section, opportunely positioned along the length to minimize the drag.

A design example of the vehicle of the family is presented in Fig. 1: it is a small (7 m long) Unmanned Surface Vehicle (USV) designed (Brizzolara *et al*. 2011) to serve a network of

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A series of unsteady free surface viscous simulations models already tested and validated on simple section shapes (Bonfiglio *et al*. 2012) also in catamaran configurations (Bonfiglio and Brizzolara 2013). More details about the numerical model can be found in the cited papers.

Once the time history of the radiation force component (in the selected direction) is obtained from each simulation, at each given oscillation frequency (and degree of freedom: heave in this case), the results are projected from time domain to frequency domain applying the Fourier analysis which is used to calculate the real and the imaginary part of the force for the k^{th} harmonic

$$Re\,F_{33}(k\omega_k) = \int_{t_0}^{t_1} F_{33}(t)\cos(2\pi k\bar{\omega}t)dt$$
$$Im\,F_{33}(k\omega_k) = \int_{t_0}^{t_1} F_{33}(t)\sin(2\pi k\bar{\omega}t)dt \tag{34}$$

in which $\bar{\omega}$ represents the forced oscillation frequency.

According linear seakeeping theory the added mass and damping coefficient are obtained from the 1st harmonic obtained by the Fourier analysis, i.e., the force component characterized by the same frequency of the motion. Considering the sinusoidal motion amplitude of ξ_k imposed in the transient simulation, sectional added mass and damping coefficient are expressed as follow

$$a_{33}(\omega_k) = -\frac{Re\,F_{33}(\omega_k)}{\omega_k^2\xi_3} \qquad b_{33}(\omega_k) = \frac{Im\,F_{33}(\omega_k)}{\omega_k\zeta_3} \tag{35}$$

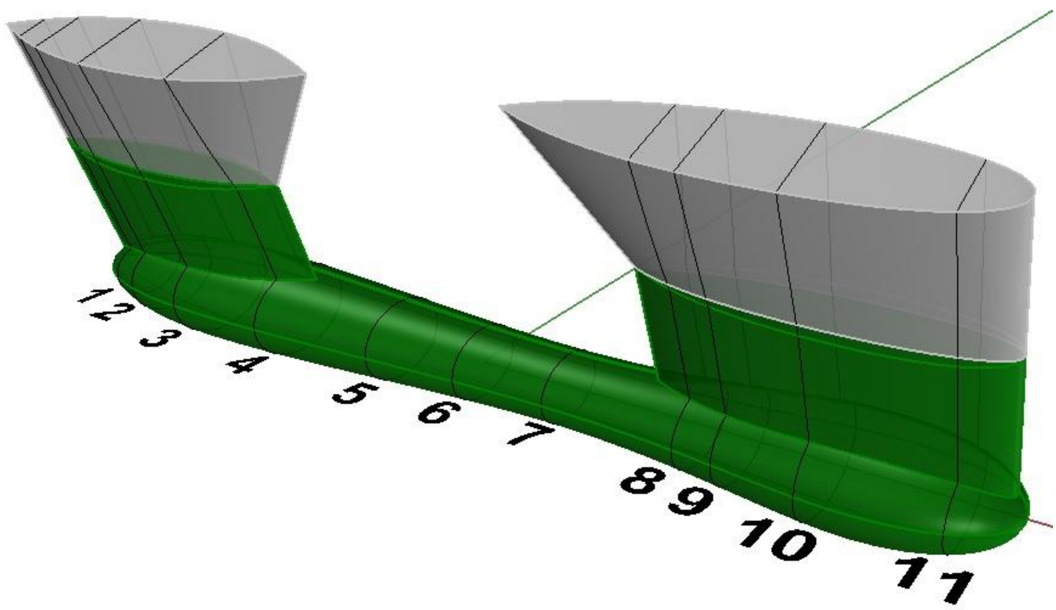

Fig. 3 Geometry of a SWATH demi-hull with position of the 11 sections (from stern to bow) considered to calculate the viscous added mass and damping (reference system origin is at LCG

4. Results

Following the strip theory approach, the 3D geometry of the SWATH has been represented with 11 sections along the length that are presented and numbered in Fig. 3. The sections have been selected considering a non-uniform spacing to minimize their number without compromising accuracy (sensitivity analysis tests were done).

As anticipated, radiation forces have been estimated at each section with the two different approaches: potential flow (Frank's close fit method with 50 points along the section) and the viscous method based on the solution of the transient N-S equation for the oscillating sections in calm water. The numerical simulations have been performed for a model in scale 1:6 to the actual vessel (i.e., submerged hull length L=1m). The amplitude of the vertical oscillatory motion for the viscous calculations has been set to 2.5%·L ≡ 0.0127·T, where T=draft.

Only vertical plane motions are discussed in this paper, i.e., only heave and pitch motions related coefficients. This means that only the problem of the 11 vertical oscillating sections has been considered and solved with the viscous free surface N-S solver. For SWATH vessels in general and in particular for the twin canted struts version considered in this study, viscous effects are important not only for the transverse motions but also for heave and pitch. In fact, for these last motions, wave damping is relatively low or comparable to the viscous forces when far from the resonant frequencies (piston effect).

The nature of viscous effects can be evinced from the snapshots of Fig. 4 that presents the vorticity field for three stations along the hull length having different typologies: a thin strut (st.1), a larger strut (st.4) and a fully submerged section (st.6). Vorticity generated by separation of the flow along the struts due to the vertical oscillating motion or in the alternate wake of the elliptic section are noted and principally contribute to the viscous damping and added mass which is neglected by the presented potential flow based method. In case of the first two sections a frequency close to the resonance of the piston effect has been chosen to highlight the complex interaction between vorticity and free surface: vortexes shed by the struts are convected to the free surface and interact with wave induced flow field, enhancing or reducing their intensities. Especially in the case of section 4, a strong non-linear effect on the generated wave created by the strut portion above the design waterline is noted: this effect is again neglected by traditional linearized seakeeping methods. Obviously the relative importance of these non-linear effects (both generation of the inner wave and vortex shedding) is somehow enhanced by the two dimensional approach adopted. Future studies on how the three-dimensionality of the flow can affect these are under development.

The importance of viscosity is quite evident when the sectional added mass and damping calculated by the two different methods are compared. To this scope the series of graphs of Fig. 5 have been prepared. They present the calculated values of added mass and damping coefficients along the length of the vessel for three different frequencies, among those considered in the study: low, medium and high.

As expected, the added mass of sections without strut is not influenced by viscous effects: the predicted value of a_{33} for the three midship sections is the same for the two methods. Instead, for the sections with struts (four at bow and four at stern), a_{33} increases at relatively low circular frequencies (wave lengths $\lambda \geq 3L$), while it decreases at relatively high circular frequencies ($\lambda \leq 2L$).

The damping coefficients calculated with the viscous flow solver show the same trend of the inviscid ones, but they are generally higher both for sections without strut, as generally expected, and also for the sections with struts. This is not always the case when the strut is vertical, while the present canted strut design does create additional damping. Around the resonant frequency of the piston mode effect (ω =5.03), the non-linear effects related to the amplified standing wave in between the two hulls, drastically increase the damping force on the strut sections by about a factor 4 with respect to subcritical or supercritical frequencies: this is evident comparing the end scale of the three graphs for damping.

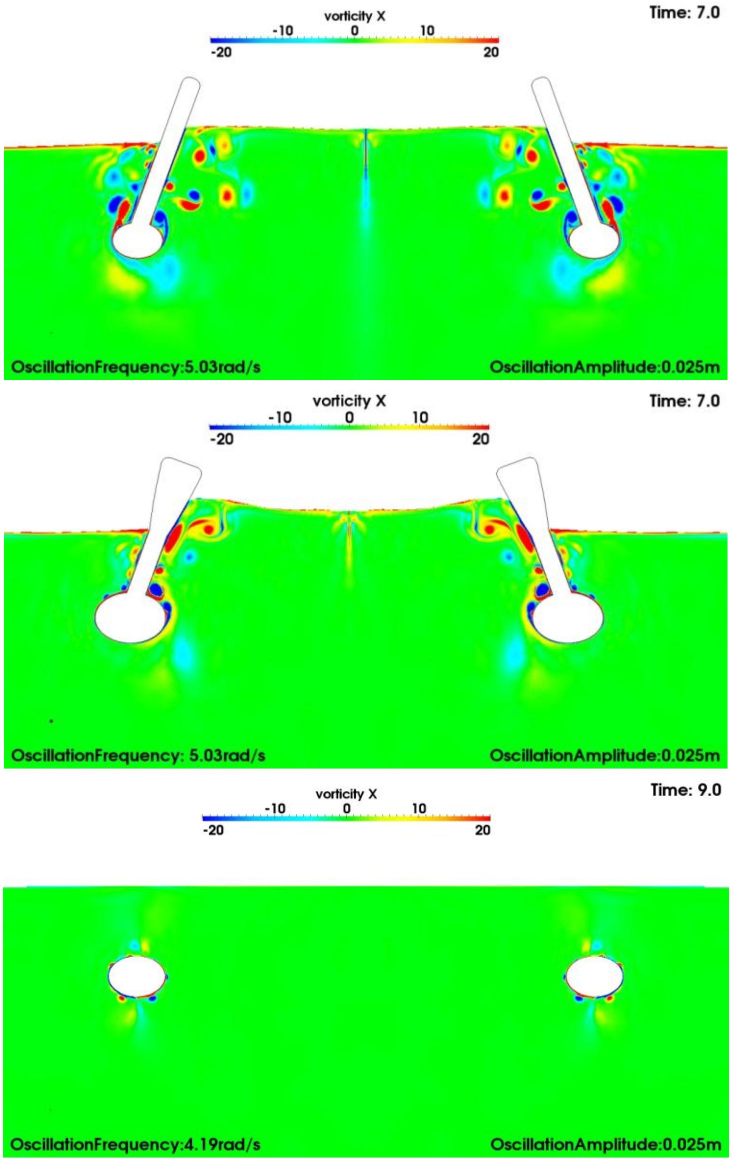

Fig. 4 Snapshot of the predicted viscous flow field (vorticity) for station 1, 4 and 6 respectively for the heave radiation problem

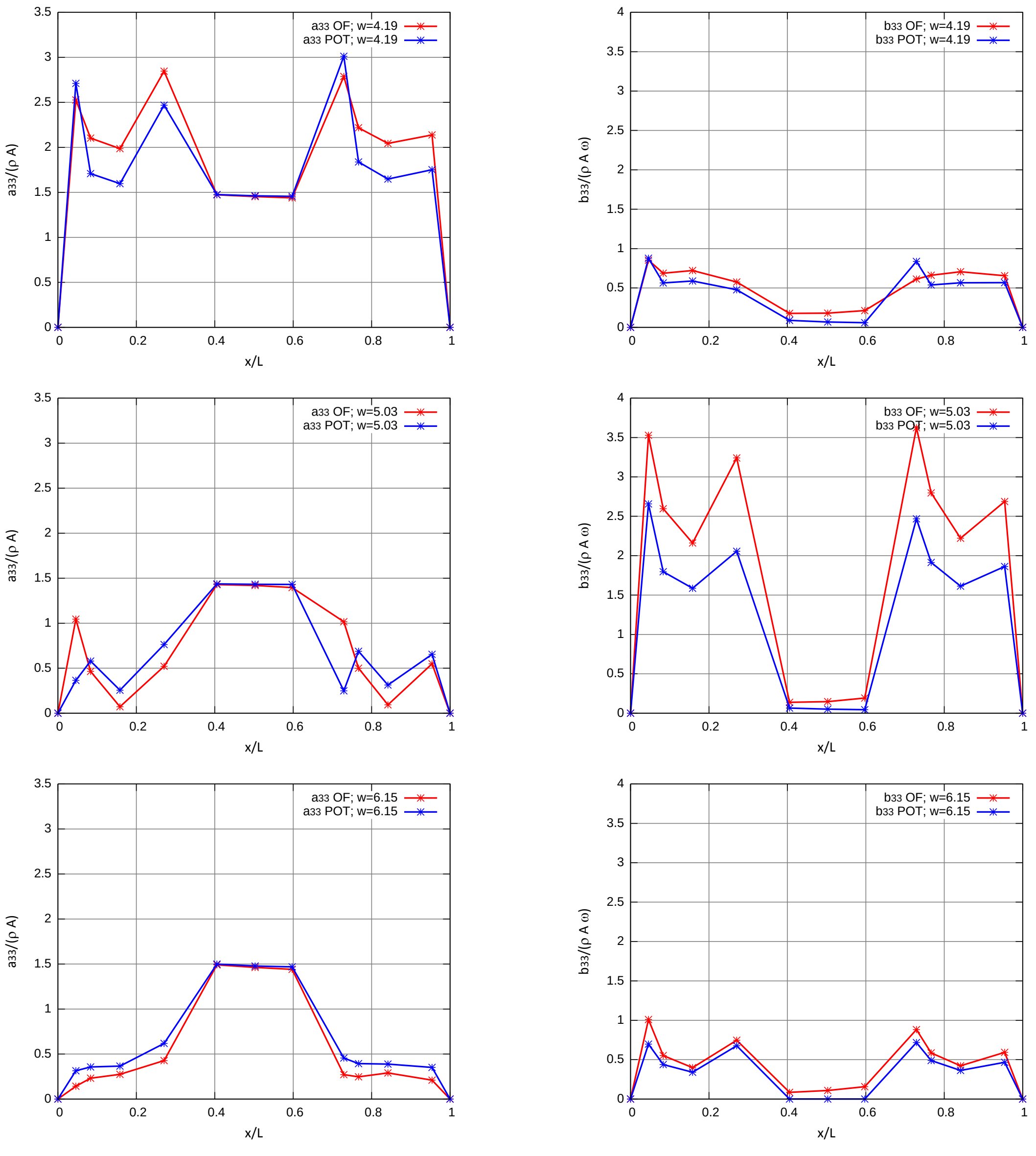

Fig. 5 Sectional heave added mass (a_{33}) and damping (b_{33}) calculated with inviscid (POT) and viscous (OF) methods at three different oscillation frequencies plot along ship length

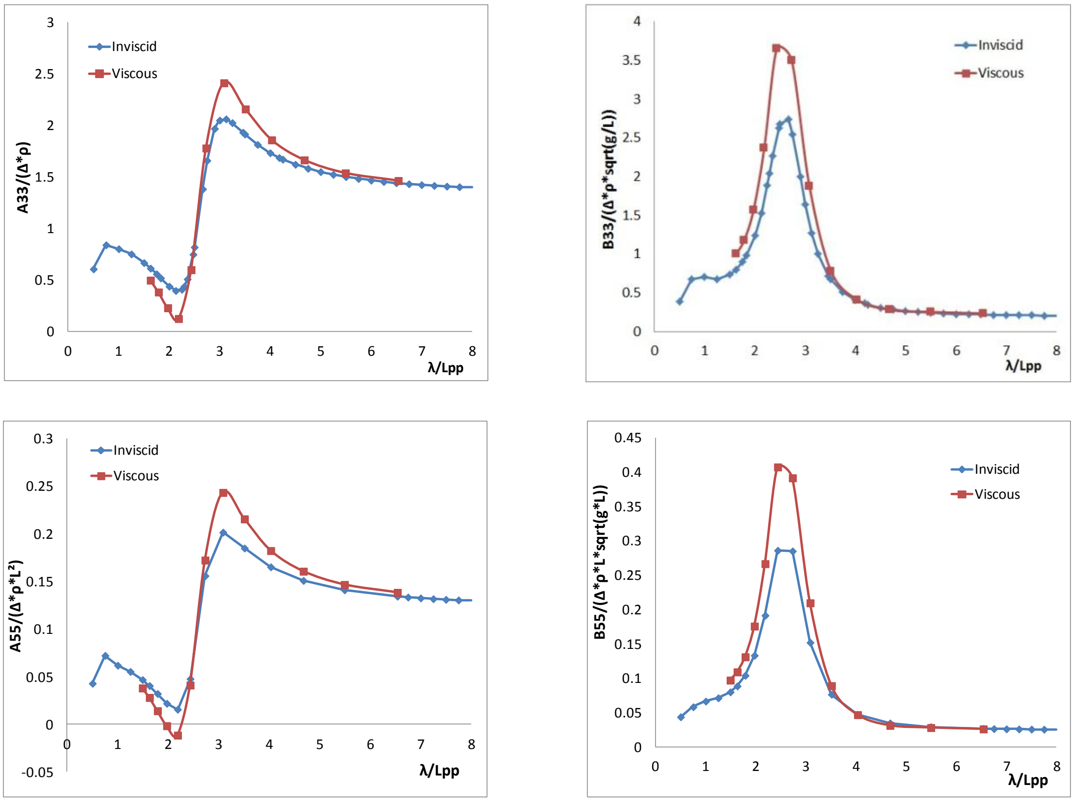

Fig. 6 Three dimensional (global) added mass and damping for heave (A33, B33) and pitch (A55, B55) calculated with Frank close fit and with Viscous (N-S) flow solver

When integrated along the length, according to formulae in Table 1, the effects just commented for the individual transverse sections become even more evident, as captured in Fig. 6 : the heave added mass of the whole hull increases at lower frequencies (λ≥3L) and decreases at higher frequencies (λ≤2L); the relative difference at the peaks amounts to more than 20%.

Simultaneously, the damping is generally increased with relative a difference of about 35÷50% around the peak.

The relevance of viscous and non-linear free surface effects in terms of motion response is given in Fig. 6, where the R.A.O. of heave and pitch are presented. At higher frequencies (low λ/L values), the predicted vertical motions amplitudes show the correct monotonic trend to zero.

Two different peaks are evident in the heave and pitch RAOs: the first, at λ≈2.7L, is due to the resonance frequency of the wave generated inside the two hulls (piston mode effect) which in turn depends on the separation and shape of the two hulls and in fact corresponds with the peak of the damping in Fig. 6 , while the second peak noted at higher wave lengths is due to the effect of the wave exciting forces.

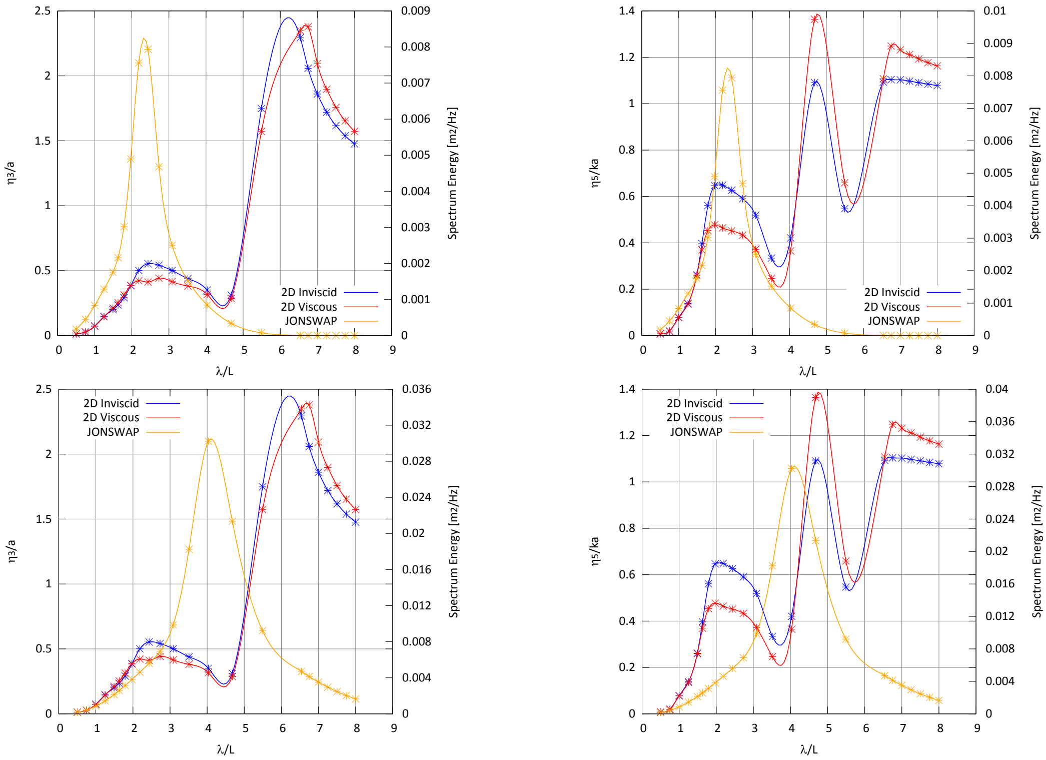

Fig. 7 Response Amplitude Operators of Heave (η_3) and Pitch (η_5) calculated by the two methods with JONSWAP

Around the first peak frequency, the heave motion amplitude predicted with the viscous method are about 15% lower than that predicted by the inviscid strip theory. The difference is even more relevant for the pitch angle: around the inner wave resonance frequency (λ≈2.7L) the value predicted by the viscous method is about one half (0.5!) of that predicted by the inviscid theory.

To predict the response of the vessel in a more realistic sea condition, spectral wave theory has been used with linear frequency domain seakeeping theory. Being the intended operation of for the considered autonomous vehicle concentrated in coastal areas, JONSWAP (JOint North Sea Wave Project) spectra have been chosen to characterize the most probable irregular sea state. For practical purpose we repeat here the mathematical description of JONSWAP spectra which defines a relation between the distribution of the energy and the frequency of each elementary component

$$S(\omega) = \frac{ag^2}{\omega^5} e - \beta \frac{\omega_p^4}{\omega^4} \gamma^a \tag{36}$$

Spectral peak sharpness is modeled through the peak enhancement parameter γ which ranges from 1 to 7 with the mean value of 3.3, that is the one chosen in the present analysis.

$$a = exp\left[-\frac{(\omega - \omega_p)^2}{2\omega_p^2\sigma^2} \right] \quad \text{and} \quad \sigma = \begin{cases} 0.07 & if\ \omega \leq \omega_p \\ 0.09 & if\ \omega \geq \omega_p \end{cases} \tag{37}$$

The shape of the distribution is mainly tuned by the parameter β, for which we selected a typical value is 1.25. The parameter α represents the intensity of the spectra and can be related to the wind speed, according the following empirical formula

$$\alpha = 5.061 * (\frac{\omega_p}{2\pi})^4 * (H_s^2) * (1 - 0.287 * \text{In}(\gamma)) \tag{38}$$

Fig. 7 shows the SWATH RAO with the irregular head sea energy spectra superimposed. This allows to better visual evaluation of the matching between the relative position of the peak of the wave spectrum relative to the RAO peak. Significant wave height and peak frequency chosen to define the wave spectra correspond to the most probable sea state conditions in the area of operation of the SWATH.

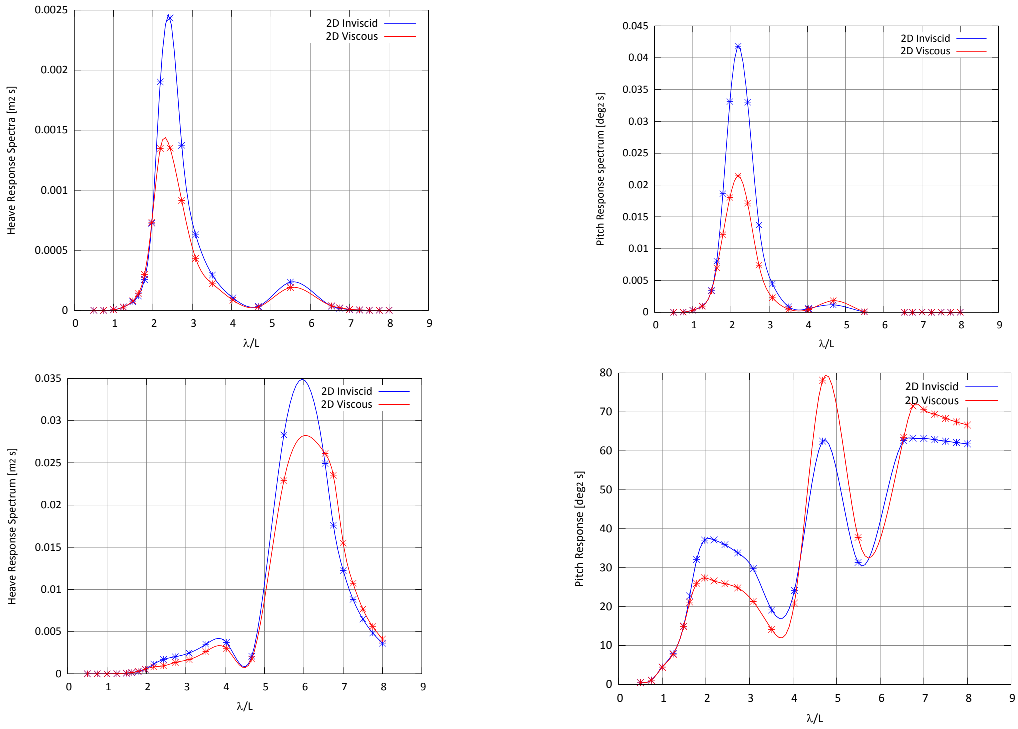

Fig. 8 Response spectra for Heave (η_3) and Pitch (η_5) amplitude for $h_{1/3}$=0.3 (top) and $h_{1/3}$=0.5 (bottom) irregular waves (see Table 2)

According linear seakeeping theory, the response spectrum of the vessel motion at zero speed has been calculated by

$$S_{\eta}(\omega)=\left|R.A.O.\right|_{\eta}^{2}*S(\omega) \qquad (39)$$

Assuming a narrow banded response spectrum, the significant value of the response amplitude is estimated from the zero order moment of the response spectra

$$Significant\ Response\ Amplitude=\eta_{i\ 1/3}=2\sqrt{\int_{-\infty}^{\infty} S_{\eta}(\omega)d\omega} \qquad (40)$$

The significant value of the heave and pitch amplitudes predicted by the two different methods for each considered sea state is reported in Table 2. The difference in the predicted response depends on the characteristics of the irregular sea condition and the motion RAO: the first spectrum has a shorter peak period and most of the energy of the irregular wave is concentrated in a wave length range (λ≈2.3L) where viscous effects significantly reduce the amplitude of the motions (with respect to potential flow predictions). The second irregular wave spectrum, instead, has the energy content shifted to higher wave lengths (λ≈4L). At wave lengths higher than the sea spectrum peak, the viscous RAO is higher than that predicted by the inviscid theory and hence the viscous response becomes also higher (3rd and 4th plots of Fig. 8). The reason of this overestimation of pitch and heave by the viscous method can be found in the different values of added mass and damping predicted by the two methods in the higher wave lengths range. In fact, as from Fig. 6, for λ>4L the viscous and inviscid damping are practically coincident while the viscous added mass is still higher; this difference in radiation forces translate into a higher response predicted by viscous method. This is true both for heave and pitch.

Table 2 Significant pitch and heave amplitudes calculated by the two methods (potential flow based POT and viscous OF) in two different irregular head waves

SPECTRUM	$h_{1/3}$	ω_P	$\eta_{heave\ 1/3\ POT}$	$\eta_{pitch\ 1/3\ POT}$	$\eta_{heave\ 1/3\ OF}$	$\eta_{pitch\ 1/3\ OF}$
[/]	[m]	[rad/s]	[m]	[deg]	[m]	[deg]
JONSWAP1	0.3	2.0944	0.062	2.08	0.052	1.60
JONSWAP2	0.5	1.5708	0.179	2.67	0.170	2.53

5. Conclusions

A hybrid strip theory method for calculating motions of SWATHs vessels in waves based on fully numerical predictions of viscous radiation forces has been outlined in its principal theoretical and numerical aspects. The method is based on a traditional strip theory developed at MIT for catamarans and SWATHs where the radiation problem is solved by an unsteady viscous fully non-linear free surface Navier-Stokes solver, built on OpenFoam libraries. Added mass and damping of the hull cross sections are obtained from the time history of the calculated viscous force acting on the oscillating sections by Fourier analysis and used inside the strip theory instead of the inviscid ones. The difference between the hydrodynamic radiation forces predicted by the viscous and the inviscid (Frank’s close fit) methods are very significant and commented in the paper.

The physical nature and relative importance of viscous effects is critically discussed through the analysis of the predicted viscous flow vorticity field around the different types of sections of the hull.

As a general results, viscosity effects are markedly non-negligible for the prediction of the motions in of the unconventional SWATH considered in this study: the difference in the predicted amplitudes of heave ad pitch motions around the characteristic piston mode resonance frequency of the SWATH is about -20% and -50% respectively (viscous against inviscid).

Two different JONSWAP wave spectra has been used to predict SWATH behavior in irregular waves, these spectra are supposed to describe with the realistic sea state conditions that a coastal operating craft has to deal with. The response amplitude values show that neglecting viscous effect leads to an overestimation of vertical motion amplitudes that reaches 50% around the resonance peak, confirming the importance of properly considering improvement achievable even in a framework of a two dimensional analysis.

No empirical correction formulae exists or can be developed to accurately predict the effect of these complex non-linear phenomena above briefly described for a general SWATH geometry. From this point of view, the current hybrid (viscous/inviscid) strip theory method offers a unique opportunity to enhance the fidelity of the predicted motions in waves, without the burden of long computational times needed by fully 3D time domain viscous free surface solvers.

Future studies will continue the application, verification and validation of the viscous strip theory method with viscous time domain 3D solvers and with experiments on a model of the AUV-SWATH presented in this study, currently under construction at the MIT Innovative Ship (I-Ship) design lab.

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References

Bonfiglio, L. Brizzolara, S. and Chryssostomidis, C. (2012), “Added mass and damping of oscillating bodies: a fully viscous numerical approach”, *Proceedings of the 9th WSEAS International Conference on Fluid Mechanics (FLUIDS '12)*, Harvard, Cambridge, USA, 25-27 January.

Bonfiglio, L. Brizzolara, S. and Chryssostomidis, C. (2013), “Viscous free surface numerical simulations of oscillating SWATH ship sections”, *Proceedings of the 10th WSEAS International Conference on Fluid Mechanics. FLUIDS’13*, Milano, Italy, 9-11 January.

Bonfiglio, L. and Brizzolara, S. (2013), “Influence of viscosity on radiation forces: a comparison between monohull”, *Proceedings of the Catamaran and SWATH. ISOPE 2013, the 23rd International Ocean and Polar Engineering Conference*, Anchorage, Alaska, USA, 1-5 July.

Brizzolara, S., Curtin, T., Bovio, M. and Vernengo, G. (2011), “Concept design and hydrodynamic optimization of an innovative SWATH USV by CFD methods”, *Ocean Dynam.*, **61**, ISSN: 1616-7341, doi: 10.1007/s10236-011-0471-y.

Brizzolara, S. and Chryssostomidis, C. (2013), “The second generation of unmanned surface vehicles:

design features and performance predictions by numerical simulations", *Proceedings of the ASNE Day 2013*, Engineering America's Maritime Dominance, Arlington, VA, 21-22 Febuary.

Brizzolara, S. and Vernengo, G. (2011), "Automatic optimization computational method for unconventional S.W.A.T.H. ships resistance", *Int. J. Math. Model. Method. Appl. Sci*., **5**, 882-889.

Carrica, P.M., Wilson, R.V., Noack, R. and Stern, F. (2007), "Ship motions using single-phase level set with dynamic overset grids", *Comput. Fluids*, **36**, 1415-1433.

Centeno, R., Fonseca, N. and Guedes Soares, C. (2010), "Prediction of motions of catamarans accounting for viscous effects", *Int. Shipbuild. Progr*., **47**(451), 303-323.

Chryssostomidis, C. and Patrikalakis, N.M. (1986), *Seakeeping calculations for SWATH ships using a new modified version of 'CAT-5'*, MIT Sea Grant Report 86-7TN.

Fang, M.C. and Her, S.S. (1995), "Non-linear SWATH ship motions in large longitudinal waves", *lnt. Shipbuild. Progr*., **42**(431), 197-220.

Frank, W. (1967), *Oscillation of cylinders in or below the free surface of deep fluids,* NSRDC Report No. 2375.

Lee, C.M. and Curphey, R.M. (1977), "Prediction of motion stability and wave load of small-waterplane-area, Twin-Hull Ships", *SNAME Trans*., **85**, 94-130.

Mansour, A. and Choo, K.Y. (1973), *Motion and loads prediction of catamarans in random seas*, Report 73-6, MIT, Dept. of Ocean Engineering.

Mantzaris, D.A. (1998), *A rankine panel method as a tool for the hydrodynamic design of complex marine vehicles*, PhD Thesis, MIT Ocean Engineering Dept.

Rathje, H. and Schelling, T.E. (1996), "Dependence of SWATH ship response in waves on choice of viscous coefficients", *Proceedings of the 11th Int. Workshop On Water Waves And Floating Bodies*, Institut fur Schiffbau, Hamburg.