UNE METHODE DE TRANCHES POUR LA TENUE A LA MER DES YACHTS – TRAITEMENT DES AILERONS

A STRIP METHOD FOR SAILING YACHT SEAKEEPING - FIN TREATMENT

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Résumé

Une méthode des tranches pour l'analyse de la tenue à la mer des yachts est actuellement en cours de développement dans le domaine public. Pour ce type de structure, il est indispensable de modéliser les ailerons. La théorie pour prendre les ailerons en compte de façon semi-analytique est présentée et une application démontre l'influence des ailerons.

Summary

A public-domain strip method under development intends to analyze the seakeeping of sailing yachts. As a major feature, the large fins of sailing yachts need to be modeled. The theory to consider fins in a semi-empirical way is described and one application shows the influence of the fins.

I. INTRODUCTION

The standard design tools for seakeeping are

- Green Function Method for offshore structures of zero (or very low) speed
- Strip method for slender ships of low to moderate speed

Strip methods date back to *Korvin-Kroukowski and Jacobs (1957)*. The basic idea of the strip method is to convert a 3-d problem into several (independent) 2-d problems, Fig.1, which reduces the effort for grid generation and computation significantly. While strip methods are well established in industry to evaluate the seakeeping of 'normal' displacement ships, the seakeeping analysis of sailing yachts introduces several complications not addressed by regular strip methods:

- Non-symmetric cross sections: Due to yaw and heel, sailing yachts have typically non-symmetric cross sections. Extension of modern close-fit methods for the 2-d module to non-symmetric cross sections is straight-forward.
- Speed influence: The classical strip method approach considers the geometry of the

ship up to the waterline at zero speed. The submerged waterline of sailing yachts changes significantly with forward speed, changing the stiffness matrix (waterline area and metacentric heights) as well as added mass, damping and exciting forces.

- Lifting surfaces: Sailing yachts have often relatively large lifting surfaces (keel sword and rudder). These require special treatment in a strip method, either by introducing lifting elements (dipoles, vortices) or by empirical models. The lifting surfaces affect added mass, damping and exciting forces.
- Sails: The large sails add considerable 'external' roll damping

In late 2005, a research project between FH Kiel and ENSIETA started to develop a seakeeping module to be added to a Velocity Prediction Program (VPP) for competitive sailing yachts. The long-term aim is to have a versatile, public-domain strip method for teaching, research and industry, *Bertram et al (2006a,b)*, *Palladino et al. (2006).* As a major component for sailing yachts, we focus here on the treatment of fixed fins. *Graf et al. (2007)* give additional theoretical background, particularly for the computation of added resistance of sailing yachts.

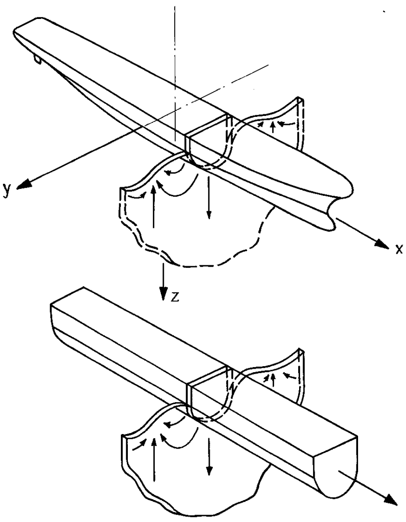

Fig.1: Basic principle of strip method, *Bertram (2000)*

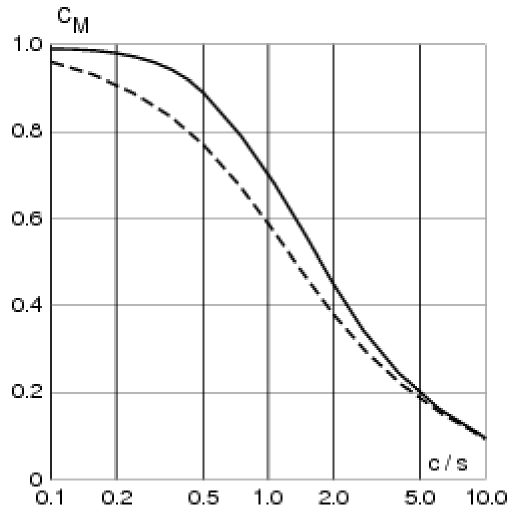

Fig.2: Added mass coefficient c_M vs. $1/\Lambda$; elliptical (full line), rectangular planform (dotted line), *Meyerhoff (1968)*

II. DESCRIPTION OF THE STRIP METHOD

II.1. GLOBAL ASPECTS

For harmonic motions $\mathbf{u}=\hat{\mathbf{u}}e^{i\omega t}$ in six degrees of freedom $\mathbf{u}=\{u_1,u_2,u_3,u_4, u_5,u_6\}^T$ (surge u_1, sway u_2, heave u_3, roll u_4, pitch u_5, yaw u_6) the fundamental equation of motions can be derived, *Bertram (2000):*

$$(-\omega_e M - B + S)\hat{\mathbf{u}} = \hat{\mathbf{F}}_e \tag{1}$$

Here $\omega_e = \omega - kv\cos\mu$ is the encounter frequency. $k = 2\pi/\lambda$ is the wave number, ω the wave frequency, v the ship speed and μ the wave direction. The ^ symbol indicates generally a complex amplitude, bold face a vector. M is the real mass matrix of the ship, S is the real matrix due to hydrostatics, B is the complex matrix due to ship motions (added mass and damping) and $\hat{\mathbf{F}}_e$ are the excitation forces due to the incident wave and its diffraction. In general B is calculated from 2D hydrodynamic forces exerted from the water on a sectional strip moving periodically, *Bertram et al. (2006a).* The 3-component motion amplitude vector of the strip $\hat{\mathbf{u}}_x = \{\hat{u}_2, \hat{u}_3, \hat{u}_4\}^T$ is related to the respective force vector $\hat{\mathbf{f}}_x = \{\hat{f}_2, \hat{f}_3, \hat{f}_4\}^T$ by:

$$\hat{\mathbf{f}}_x = \begin{bmatrix} \overline{m}_{22} & \overline{m}_{23} & \overline{m}_{24} \\ \overline{m}_{32} & \overline{m}_{33} & \overline{m}_{34} \\ \overline{m}_{42} & \overline{m}_{43} & \overline{m}_{44} \end{bmatrix} \omega_e^2 \hat{\mathbf{u}}_x \tag{2}$$

The elements of the complex added mass matrix in (2) can be interpreted as real value added masses m_{ij} and damping n_{ij}:

$$\overline{m}_{ij} = m_{ij} + \frac{n_{ij}}{i\omega_e} \tag{3}$$

Rewriting (2) as time derivative of momentum allows to take into account forward ship speed by introducing substantial derivatives for partial time derivatives. Proper transformation of the 3-component strip velocity and forces into the global ship motion coordinate system and integration over ship length allows to calculate B. A similar approach is used for the excitation forces, the forces acting on the fixed hull generated by an incident wave. These forces consist of the Froude-Krilov part (due to the pressure in the undisturbed wave) and the diffraction part (due to the pressure from the diffraction of the wave due to the ship hull). For surge motion a different approach has to be used since strip theory is not capable to predict added mass for surge. Here an empirical formula for the added mass of a strip is used and introduced into the matrix B.

II.2. FIXED FINS

Sailing yachts frequently have fins (keels, rudders). We consider here only fixed fins. The shape of a fin is characterized by a mean chord length c (in x direction) and a span s measured in the y,z-plane. Fins having an aspect ratio $\Lambda = s/c << 1$, and fins which continue the hull to the rear (like skegs or rudders) may be treated as parts of the hull.

Fins having a span s which is in the same size range or larger than the distance between fin center and the `roll axis' (approximately parallel to the $x$ axis through the center of gravity of ship's mass) will be treated more accurately if they are subdivided into two or more `part fins' so that the sum of their spans s is equal to that of the total fin. In this case, the lift gradient $dC_L/d\alpha$ of the part fins has to be determined using the aspect ratio Λ of the total fin, not that of the part fins. For fins attached to the hull (like the keel), the aspect ratio should be doubled.

The program takes account only of the oscillating forces normal to the (average) center plane of the fin; in linear approximation, this force is the lift. Resistance forces and lift forces depending nonlinearly on the angle of attack are neglected. Especially, the stall angle is not taken into account.

A fin generates waves and vortices. Their influence on other fins (e.g. a rudder behind the keel fin of a sailing yacht) is neglected.

The position of a fin is characterized by its pressure center $\mathbf{x_F} = \{x_F, y_F, z_F\}^T$. Normally a good guess of the pressure center is: at half span, ¼ c behind the leading edge. The local flow velocity (needed e.g. to determine the average angle of attack) is calculated at $\mathbf{x_{F1}}$ located normally ½ c behind $\mathbf{x_F}$. To determine the angle of attack, ship and wave orbital motions are taken into account, but radiation and diffraction waves are neglected. The direction of the axis of a movable fin is characterized by a unit vector $\mathbf{a_F}$. E.g. a vertical keel fin for a sailing yacht without heel has $\mathbf{a_F}$={0,0,1}. Let $\mathbf{n_F}$ be a unit vector, in the y,z-plane, and normal to the fin center plane, i.e. $\mathbf{n_F} = \{1,0,0\} \times \mathbf{a_F}) = \{0,n_{F2},n_{F3}\}$. For a rudder, this gives $\mathbf{n_F} = \{0,-1,0\}$. The amplitude of flow speed in the direction of $\mathbf{n_F}$ induced by the incident wave of complex amplitude $\hat{\zeta}$ and water depth D is:

$$\hat{v}_{FW}\hat{\zeta} = r\frac{\omega\hat{\zeta}}{\sinh(kD)}e^{i(-kx_{F1}\cos\mu+ky_{F1}\sin\mu)}.\mathbf{n}_F\begin{Bmatrix}0\\ \sin\mu\cosh(k(z_F-z_B))\\ -i\sinh(k(z_F-z_B))\end{Bmatrix} \quad (4)$$

z_B is the vertical coordinate of the water bottom. $z_B=D$ is the origin is in the calm water plane. r is a user provided reduction factor taking into account the presence of the canoe body in the vicinity of the fin. $r \approx 1$ for fins at a sufficient distance from the hull; $r > 1$ for fins attached to the hull and pointing to the sides or downward, and $r \approx 0$ for rudders (or all fins attached at the aft end of the hull, if they do not reach out of the hull's wake).

The complex amplitude v_{FS} of the fin velocity in direction $\mathbf{n_F}$ relative to the inertial coordinate system follows from the ship motions:

$$\hat{v}_{FS} = i\omega_e \cdot \mathrm{W_F} \cdot \hat{\mathbf{u}} \quad (5)$$

with $\mathrm{W_F} = \{0,n_{F2},n_{F3},-n_{F2}z_F+n_{F3}y_F,-n_{F3}x_{F1}, n_{F2}x_{F1}\}$.

The added mass of a fin for accelerations in direction $\mathbf{n_F}$ is determined as

$$m_F = c_M \cdot ¼\, \pi \rho c^2 s \quad (4)$$

ρ is the density of water. c_M is a user-specified input. $c_M \approx 1$ for $s/c >> 1$, $c_M \approx \Lambda$ for $s/c >> 1$. Λ is to be doubled if the fin is attached to the hull without gap for water to flow through (like a keel fin). For intermediate ratios s/c Fig.2 can be used to estimate c_M, where the abscissa is $1/\Lambda$. The added mass force due to the waves is then:

$$\hat{F}_{FW} = m_F\, i\omega r\hat{v}_{FW}\,\hat{\zeta} \quad (5)$$

$$\hat{F}_{FS} = m_F\,\omega_e^2\, rW_F\hat{u} \quad (6)$$

An acceleration due to ship motion in direction x results in a force on the fin in direction $-x$, hence the sign in F_{FS}. Beside the added mass forces additional periodic forces are generated due to the time varying angle of attack of the fin $\hat{\alpha}$. The complex amplitude of this force $\hat{L}$ acting in direction $\mathrm{n_F}$ is calculated from the lift of the fin:

$$\hat{L} = \frac{\rho}{2}v^2 s\, c\frac{dc_L}{d\alpha}\hat{\alpha} \quad (7)$$

The lift coefficient gradient for fins in free flow can be approximated as, *Bertram (2000):*

$$\frac{d\boldsymbol{C}_L}{d\boldsymbol{\alpha}} = 2\boldsymbol{\pi}\frac{\Lambda(\Lambda+0.7)}{(\Lambda+1.7)^2} \tag{8}$$

In reality, the lift coefficient gradient may be influenced substantially by various effects:
- ship's wake, to be taken into account by the ratio (inflow speed to the fin /v)^2.
- boundary layer along the hull
- non-viscous interaction between hull and fin increasing the lift gradient.
- gaps between different parts of the fin decreasing the lift.
- boundary layer at the fin (effective only for small fins in model tests; decreases the lift)

These effects may be estimated by an expert and/or calibrated against measurements.

The complex amplitude of the angle of attack $\hat{\alpha}$ is the sum of the following contributions:

- Due to the wave, for ship speed $v > 0$:

$$\hat{\alpha}_W = r\frac{\hat{v}_{FW}}{v}\hat{\zeta} \tag{9}$$

For ship speed $v=0$ the expression is not evaluated because $L=0$ then.

- Due to the fin moving with the ship in direction $\mathbf{n_F}$:

$$\hat{\alpha}_{S1} = -r\frac{\hat{v}_{FS}}{v} = -i\omega_e\, r\frac{W_F}{v}\hat{u} \tag{10}$$

- Due to the rotation of the fin with the ship:

$$\hat{\boldsymbol{\alpha}}_{S2} = r \cdot \{0,0,0,0,-n_{F3},n_{F2}\} \cdot \hat{\mathbf{u}} \tag{11}$$

Fin forces from (9), (10) and (11) are combined into a single expression. The arising total complex amplitude of the fin forces consists of terms being linearly dependent on ship motion, which contribute to the complex matrix B in (1) and of terms depending linearly on wave amplitude, which contribute to the excitation forces.

II.3. NATURAL SEAWAYS

For the description of natural seaways a modified formulation of the JONSWAP spectrum is used:

$$\boldsymbol{S}_\zeta(\boldsymbol{\omega},\boldsymbol{\mu}) = \boldsymbol{H}_{1/3}^2\boldsymbol{T}_1\frac{177.5-6.52\boldsymbol{\gamma}}{(\boldsymbol{T}_1\boldsymbol{\omega})^5}\boldsymbol{e}^{-1.25(\boldsymbol{\omega}_M/\boldsymbol{\omega})^4}\boldsymbol{\gamma}^\Gamma \cdot \begin{Bmatrix} (\cos^{\boldsymbol{n}}(\boldsymbol{\mu}-\boldsymbol{\mu}_0))/\boldsymbol{f} & \text{for } |\boldsymbol{\mu}-\boldsymbol{\mu}_0| \le \boldsymbol{\pi}/2 \\ 0 & \text{otherwise} \end{Bmatrix} \tag{12}$$

with $\Gamma = e^{-(\omega-\omega_0)^2/\left(2\omega_M^2\begin{Bmatrix}0.07 & \text{for } \omega<\omega_M \\ 0.09 & \text{otherwise}\end{Bmatrix}^2\right)}$. $H_{1/3}$ is the significant wave height and T_1 is the significant period of the seaway at spectrums centroid. T_1 is linked to a significant wave length λ_1 with:

$$\lambda_1 = \frac{g\,T_1^2}{2\pi} \tag{13}$$

μ_0 is the main direction of waves. $\omega_M = (4.65+0.182\gamma)/\ T_1$ is the circular frequency of the maximum of the spectrum and γ is a peak enhancement factor. γ=1 gives the Pierson-Moskowitz spectrum while γ=3.3 gives an average JONSWAP spectrum.

$$f = \int_{\mu_0-\pi/2}^{\mu_0+\pi/2} \cos^n(\mu-\mu_0)d\mu \quad (14)$$

is the integral over the angular spreading function. $H_{1/3}$, T_1 and μ_0 are user provided values, as well as n and γ.

The significant amplitude $r_{1/3}$ of a ship response follows from the variance m_0, $r_{1/3} = 2m_0^{1/2}$, where the variance m_0 of a ship response is calculated from the spectrum and the RAO:

$$m_0 = \int_0^{\infty}\int_0^{2\pi} S_\zeta(\omega,\mu)Y^2(\omega,\mu)\,d\mu\,d\omega \quad (15)$$

III. APPLICATION TO SAILING YACHT

III.1 TEST CASE GEOMETRY

The test case was a benchmark America's Cup (ACC) yacht, *Graf et al. (2007)*, Figs. 3 and 4. The main dimensions are beam B=3.6 m, length between girths is L_{BG}=20.18 m, displacement m_M=24 t for measurement flotation, m_S=26.65 t in sailing condition. Fig.3 shows a section line drawing of the yacht. From the line drawings an offset table was developed taking into account the canoe body and the ballast bulb, but not the foils. Fig.4 shows a simplified distribution of offset points on canoe body and bulb. For higher accuracy a denser distribution of strips is used for the following computations. ??? number of strips, number of points ???

As common for strip methods, the sectional strip contour ends at the waterline. Increased accuracy could be achieved by using the real dynamic water plane taking into account the generation of waves due to forward speed. However, this has not yet been done and results here are still for the zero-speed floating condition.

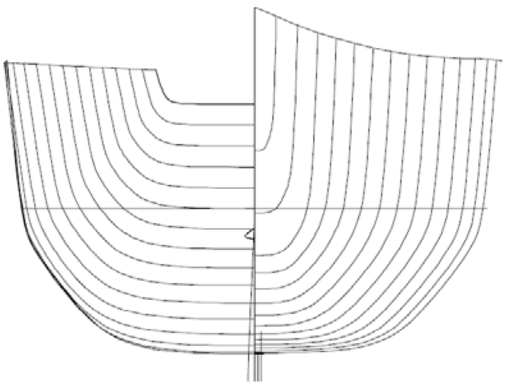

Fig.3: ACC yacht Benchmark at B=3.6 m

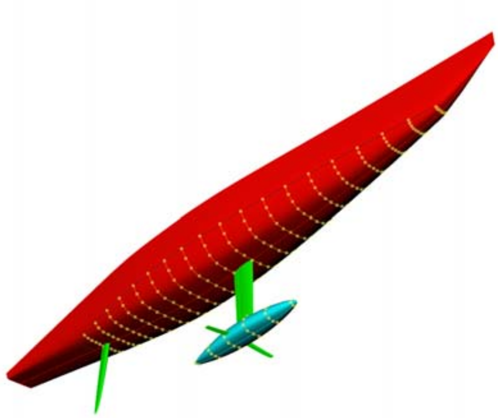

Fig.4: Offsets for canoe and ballast bulb

III.2 INFLUENCE OF FINS

The impact of foils is analysed using significant ship motions in natural seaways of a Pierson-Moskowitz spectrum with $H_{1/3}$=0.42 m, a mean wave direction of μ=145° and the heeled yacht at 10 knots, heel angle 27.5°. These are calculated from the response amplitude operator (RAO) of the respective ship motion, calculated in harmonic waves, and from the variance, Eq.(15). So far, no towing tank tests are available for validation, restricting us to a purely numerical study. We compared significant amplitudes for heave, pitch and roll for three different configurations: a) canoe body only, b) canoe body and ballast bulb, and c) canoe body, ballast bulb and fins. Fig.5 shows that heave amplitude is reduced primary by the fins. For very small and very large wave lengths the impact of foils vanishes. The pitch amplitude is reduced significantly by fins, Fig.6. The ballast bulb has an impact on pitch amplitude of same order of magnitude. For short waves differences between configurations vanish, but not for long waves. As expected, the roll amplitude is affected strongly by the fins, Fig.7. For the canoe body roll amplitudes of approximately 8° are generated. Including the ballast bulb increases the roll amplitudes further, maybe because excitation due to the bulb is stronger than the damping and hydrodynamic mass forces of bulb. Taking fins into account educes the roll amplitude drops by approximately 2/3. However, excitation due to fins can also be significant.

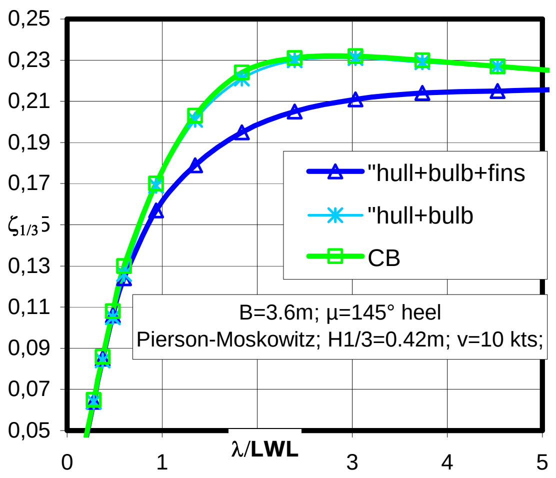

Fig.5: Significant heave amplitude

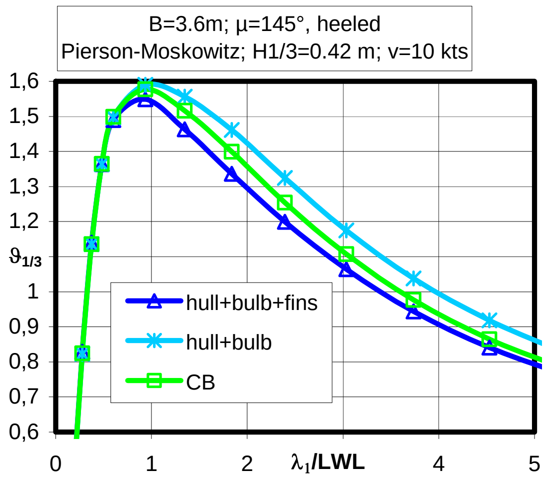

Fig.6: Significant pitch amplitude

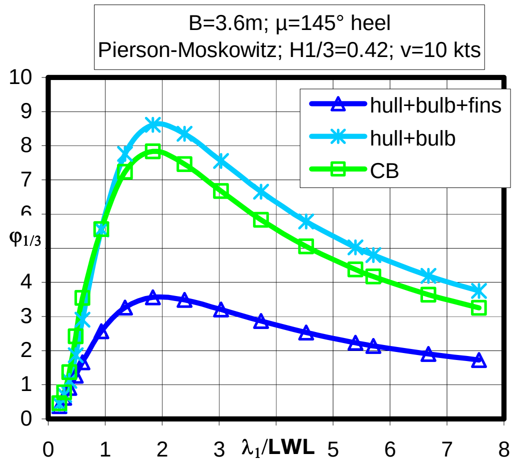

Fig.7: Significant roll amplitude

IV. CONCLUSION

??? validation needed ???

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