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Experimental investigation of a fast catamaran in head waves

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ABSTRACT

The present work is about the seakeeping behavior of a fast catamaran advancing in head sea. To this aim seakeeping tests with transient, regular and irregular waves are performed in the rectilinear water tank of CNR-INSEAN. Seakeeping transient tests are used to provide the response amplitude operator for a wide range of wave lengths and several speeds of advancement. These tests allow identifying the Froude number at which the maximum vertical response occurs and an analysis of natural heave and pitch frequencies. A comparison with theoretical predictions is provided. Regular wave tests are used to assess nonlinear effects on the hull motions, as well as the added resistance generated by the increasing steepness and dependency on both the Froude number and wave lengths: therefore several ship speeds, several steepness and wave lengths of the incident wave system are considered. For a similar Froude number range, irregular wave tests are also pursued to investigate the seakeeping properties of the vessel in real scenarios. The estimation of added resistance in wave, its dependency on the Froude number, the investigation of nonlinear effects and the analysis of increased resistance in a real scenario are addressed as well. To make sure the present experimental campaign is valid, it is checked with repeatability analysis and matched with ad hoc experimental data collected at TU Delft. The whole set of measurements is a valuable database for both hydrodynamic studies of high speed catamarans and CFD validation.

1. Introduction

With the main goal of increasing the cruise speed of the ships, designers have proposed a wide variety of arrangements. In most of them, the weight of the vessel can be supported by submerged hulls, hydrofoils, air cushion effects, or combinations of them. Mono-hulls and catamarans are the two different geometries commonly used. The main feature requested to a fast ship operating in developed sea conditions is to keep a behavior that allows it to operate correctly and to ensure its safety. In this perspective all the possible arrangements have some pros and cons.

A mono-hull has lower wave induced vertical accelerations than a similarly sized (i.e. same displacement) catamaran, because its larger length is beneficial from this point of view. However the roll motion of mono-hulls needs special attention and might alter ship stability. Among multi-hull ships, Small Waterplane Area Twin Hull (SWATH) has higher heave and pitch natural periods and generally lower vertical excitation loads than a similarly sized catamaran. Therefore its seakeeping behavior is better when operating in head-sea conditions. However, beyond a threshold Froude number the SWATH becomes dynamically unstable in the vertical plane if fins or control surfaces are not introduced, and, therefore, it might not be satisfactory in severe seas. Among other types of multi-hull fast ships, the Surface Effect Ship (SES) deserves to be mentioned; this type of vessel uses an air cushion mechanism in order to obtain the desired cruise speed and performances. The excess pressure in the air cushion between the two SES hulls lifts the vessel and carries about 80% of its weight. The total calm water resistance is smaller than the one of a catamaran of similar dimensions; however, it can dump drop more speed in waves than a catamaran (see for example Faltinsen (2005)).

For all these reasons, the catamaran is still considered a good choice for fast ships; as a matter of fact a large number of research works have been carried out. Nevertheless, several hydrodynamic aspects are still under investigations.

The first experimental studies on the hydrodynamics of multi-hull vessels can be traced to Everest (1968) and to Turner and Taplin (1968). Since then, several researchers have performed theoretical, numerical and experimental studies of fast vessels in calm water conditions. Insel and Molland (1992) highlighted experimentally and numerically some hydrodynamic features of catamarans; they focused on the effects on the overall resistance performance varying the main demi-hull dimension and separation length. A similar analysis, applied to a broader set of hull

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List of symbols

A_{33}	heave added mass
A_{55}	pitch added inertia
$A(\omega)$	wave amplitude
Ak	wave steepness
A_W	water plane area
b	beam of the demi-hull
B	overall beam
C_B	block coefficient
CFD	Computational Fluid Dynamics
CG	center of gravity
C_{IT}	coefficient of inertia of the water plane area about y axis
C_{WP}	water plane coefficient
Δ	displacement
EFD	Experimental Fluid Dynamics
f_e	ship encounter frequency ($f_e=\sqrt{(g/2\pi\lambda)}+(U/\lambda)$)
f_{n3}	heave natural frequency
f_{n5}	pitch natural frequency
f_n	ship natural frequency
f_{p3}	measured encountered frequencies for the heave peak
$f_{p5}{}^1$	measured encountered frequencies for the first pitch peak
$f_{p5}{}^2$	measured encountered frequencies for the second pitch peak
Fr	Froude number ($Fr=U/\sqrt{gL_{pp}}$)
$(Fr_{max})_3$	Froude of maximum heave response
$(Fr_{max})_5$	Froude of maximum pitch response
g	gravity constant (9.81 m/s^2)
h	Distance between center of the hulls
H	wave height ($H=2A$)
$H_{1/3}$	significant wave height
H_s	significant height (used for heave or pitch)
I_{55}	mass moment of inertia respect to y axis
I_T	moment of inertia of water plane
KG	vertical center gravity
k_{yy}	pitch radius of gyration
LCG	Longitudinal Center of Gravity
L_{pp}	length between perpendicular
m	mass of the catamaran
m_n	spectral moment (nth order)
PSD	Power Spectral Density
R_{AW}	added resistance
R_{CW}	calm water resistance
R_{total}	resistance in waves (mean value)
s	separation distance
SES	Surface Effect Ships
S_{ii}	density spectrum for the ith ship motion
S_η	sea density spectrum
SS	Sea State
SWATH	Small Waterplane Area Twin Hull
t	time
T	model draft
T_1	mean period
T_0	peak wave period
T_z	zero crossing period
PIV	Particle Image Velocimetry
RAO	Response Amplitude Operator
U	speed of advancement
$\xi_i(x,t)$	generic ship degree of freedom
k	wave number ($k=2\pi/\lambda$)
λ	wave length ($\lambda=2\pi/k$)
λ_g	model scale
$\eta(x,t)$	wave elevation
$\varphi_i(\omega)$	phase of the generic ship degree of freedom
$\varphi(\omega)$	wave phase
ρ	water density
σ	standard deviation of ship motion
ω	pulsation ($\omega=2\pi f$)
$\zeta_i(\omega)$	amplitude of the generic ship degree of freedom
(x,y,z)	non-inertial ship-fixed coordinates

forms, was conducted by Molland et al. (1996). Hull separation length effects were also studied by Bruzzone and Ferrando (1995) by using a boundary element method. A large experimental campaign on a systematic series was provided by Muller-Graf et al. (2002); investigation was focused on several length-to-beam ratios, midship deadrises, hull-forms and propulsion configurations. Several aspects on the hydrodynamics of fast catamarans were reported by Welnicki (1994, 1997). In particular he analyzed the influence of varying length-to-beam ratios on the resistance both in calm water and in waves, and for several transom depths (due to different type of propulsion devices). The influence of viscosity on the hydrodynamic behavior of a catamaran was studied in Doctors (2003) by using a theoretical approach; whereas, Armstrong (2003) focused his effort on identifying the different resistance components. An investigation of hull clearance was also experimentally and theoretically carried out by Molland et al. (2004) and Millward (1992); whereas, a pure experimental analysis was proposed by Souto-Iglesias et al. (2007) and Souto-Iglesias et al. (2012). Hull clearance effects on resistance, trim and sinkage, including a detailed longitudinal wave cuts measurements, were studied by Broglia et al. (2011) on the catamaran object of this paper.

Seakeeping analysis of catamarans is a relatively recent topic; the first theoretical study of catamarans and their interactions with waves can be found in 1971 in Kogan (1971). Lee (1973) conducted a combined theoretical and experimental study of motions and loads on a catamaran in head waves; the pioneering experimental works by Wahab et al. (1971) and Belenky et al. (1979) are also worth mentioning. In 1991, together with the creation of a conference dedicated to fast vessels, the first study of fast catamaran in waves and the associated added resistance was presented by Faltinsen et al. (1991), immediately followed by Faltinsen et al. (1992). Numerical and experimental studies of a fast catamaran in waves, focused on motions, were successively done by Wellicome et al. (1995), Chang (1995), Fang et al. (1996), Centeno et al. (2000), Colagrossi et al. (2001) and Van't Veer (1998b), among others. Centeno et al. (2001) provided an interesting study on the hull distance effects on wave induced motion for a hard-chine catamaran in head sea. Lugni et al. (2004) underlined the role of the nonlinear effects for extreme sea conditions, motivating the present research work. The use of RANSE based solvers for the analysis of the seakeeping of catamarans is rather rare, making the work done by Castiglione et al. (2011) on the catamaran model under investigation here worth mentioning.

The geometry chosen for this study is the Delft 372 catamaran, which is a typical high-speed multi-hull model (see Van't Veer, 1998a; Van't Veer, 1998b). The wide interest in this catamaran model is shown by the large number of recent EFD and CFD activities in the framework of several international research projects. Indeed this type of hull calls for studies in widespread topics, such as interference (He et al., 2011; Zaghi et al., 2011),