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Exploration of seakeeping and drag performance of planing craft with active control systems

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ABSTRACT

Most available planing craft design tools and guidelines were not envisioned to be used with vessels that have Active Control Systems (ACS). Consequently, vessels with ACS are conventionally designed as “add-ons” in a sequential manner: first the geometry of the vessel is designed using traditional guidelines, and then the ACS is implemented. However, sequential design is not always optimal for systems whose dynamics are affected by control systems. This research explores the design space of a planing craft with an ACS, and performs an exhaustive search in the coupled design space of vessel geometry and ACS parameters using a time-domain simulation program in sea states (SS) 2 and 3. The vessel is assumed to be prismatic, and the controller is a linear quadratic regulator (LQR) whose outputs are forces on the vessel. The results suggest that if the ACS is designed along with the planing craft, the seaway drag could be reduced in some cases by 30% in SS 2, and 10% in SS 3. The seakeeping also shows significant improvements, with 20% reductions in the ISO 2631-5 metric D_z for SS 2, and 50% in SS 3. Thus, it is recommended that if a vessel is expected to have an ACS, co-design should be pursued by considering the vessel's geometry and its controller simultaneously.

1. Introduction

The design of planing craft is commonly based on semi-empirical methods and guidelines which can provide quick conceptual designs of the vessel's geometry. While the rich knowledge and history of semi-empirical methods represent a great success in the advancement of conventional planing craft design, little is known about their appropriateness for designing vessels with Active Control Systems (ACSs). Consequently, it has been customary to first design a planing boat following the conventional approach and then adapt an ACS to the vessel — i.e., sequentially designing the vessel geometry and the ACS. But a first sign of caution is that the existing semi-empirical methods are based on experimental results of vessels without ACSs; consequently, they do not exploit any coupling that might exist between the vessel geometry and its ACS.

In this paper, we build from our previous calm-water co-design results which showed that the calm-water and seaway drag could be improved if the vessel was allowed to be open-loop[1] unstable (OLU) (Castro-Feliciano et al., 2016) and be stabilized by an ACS. Here, we explore the seakeeping and seaway drag behavior to further understand and characterize the differences in the sequential design and co-design approaches when applied to a planing craft and its ACS. We accomplish this by performing an exhaustive search in the vessel geometry and control parameter spaces using POWERSEA (Akers, 1999), a strip-theory planing boat simulation program.

The results of this paper suggest the following:

- Co-designed vessels surpassed the sequentially designed vessels both in seakeeping and transport efficiency. Results suggest reductions in seaway drag of 30% for sea state 2 and 10% in sea state 3; and reductions in the seakeeping metric D_z (an ISO definition to be discussed in Section 3.2) of 20% in sea state 2 and 50% in sea state 3.
- For the two metrics considered, namely average seaway drag R_T^S and D_z, co-designed optimal vessels at the Pareto front are in general not the same as those resulting from the Pareto front of sequential design.
- A vessel with an ACS has an optimal average seaway trim angle for seakeeping, i.e., the vessel's seakeeping does not monotonically deteriorate with increasing average seaway trim angle. As a result, the vessel can operate in more drag efficient trim angles in a seaway without a serious penalty in seakeeping.

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[1] Open-loop and closed-loop refers to the behavior of the craft without ACS and with ACS, respectively.

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Nomenclature

C_Δ	load coefficient $= \Delta/(\gamma b^3)$
C_v	speed coefficient $= V/\sqrt{gb}$
D_z	acceleration dose from ISO 2631–5, m/s^2
F_1	ACS's body-fixed vertical force at the stern, N
F_2	ACS's body-fixed vertical force LOA/3 forward from the stern, N
F_z	lift, total vertical force, N
L/D	lift-to-drag ratio
L_C	chine wetted length, m
L_K	keel wetted length, m
R_T^C	calm-water drag, total horizontal calm-water resistance, N
R_T^S	seaway drag, total horizontal seaway resistance, N
R_g	pitch radius of gyration, m
V	forward velocity of vessel, m/s
Δ	displacement, N
β	deadrise angle, degrees
η_3	vertical displacement of the center of gravity relative to z_{wl}, m
η_5	rotation of the body relative to the calm-water τ, degrees
γ	specific weight of water, $10.06 kN/m^3$
τ	trim angle, degrees
b	beam of planing vessel, m
g	gravitational acceleration, $9.807 m/s^2$
lcg	longitudinal distance of center of gravity from transom, m
vcg	vertical distance of center of gravity from keel, m
z_{wl}	vertical distance of center of gravity to the calm-water line, m
ACS	active control system
LOA	length overall, m
OLS	open-loop stable
OLU	open-loop unstable

2. Background

Planing craft geometry design was mostly based on experience and rule of thumb up until the 1960's, where research in high-speed craft became a popular research subject throughout the 60's and early 70's. The most common planing craft concept design tools used today come from this period of research — where the use of ACSs was essentially nonexistent.

One of the popular calm-water powering prediction methods is Savitsky's semi-empirical method (Savitsky, 1964). For seakeeping guidance, Savitsky's and Brown's empirical equations (Savitsky and Brown, 1976) based on Fridsma's model tests (Fridsma, 1971) have been used extensively. A summary of the research from this period can be found in (Savitsky, 1985; Doctors, 1985). With these two relatively simple methods, a designer can have a rough concept design of a planing craft and its estimated calm-water and seaway performance; the end result would be a traditionally sound concept design. However, these methods and guidelines were never envisioned to be used for vessels with ACSs. Therefore, if a vessel will have an ACS, the designer might be starting off with a concept design that unnecessarily inhibits the synergy between the planing craft and its ACS.

Take for example the success stories of co-designing a vehicle and its ACS in aerospace. Modern fighter aircraft, such as the F-16, may be inherently unstable (Nguyen et al., 1979) (known as “relaxed static stability” in aircraft design), and they are only capable of stable flight because of their ACS. In other words, if you turned off the ACS of the F-16 mid-flight, the plane would diverge from its path (possibly catastrophically) and not glide steadily. But not imposing open-loop stability allows the aircraft to be lighter, more efficient, and more maneuverable (AGARD, 1974). If the analogous design method was used from conventional planing craft design with ACS to fighter aircraft design, an aerospace designer would have never come up with the F-16.

Early in planing craft research, it was documented that planing vessels could suffer from instabilities (e.g., porpoising (Sun and Faltinsen, 2011; Celano, 1998) and chine walking (Katayama et al., 2007; Lewandowski, 1998)); and the first guidelines to prevent these were empirical (Savitsky, 1964), based on model test results conducted by Day and Haag (1952). An overview of planing craft instabilities can be found in (Faltinsen, 2005; Blount and Condega, 1992). Because the use of ACSs in planing craft is usually not considered at the design stage, instabilities are generally seen as undesirable; and the approach to correct or prevent any instabilities is to modify the vessel hull geometry, change the running trim angle, and/or restrict the operating speeds.

However, restricting the vessel to be open-loop stable (OLS) might prevent the vessel from operating at the optimal lift-to-drag ratio (Savitsky, 1964), where the disadvantage of operating in open-loop stable regimes increases as speed increases (Castro-Feliciano et al., 2016). Moreover, while the seakeeping of planing craft has improved significantly since the early designs (Savitsky, 1985), there is still a need for seakeeping improvement for vessels operating in rough sea conditions to protect people onboard — such as mariners of the Coast Guard, police, and navy. The rate of injury for this type of craft is known to be high; a survey of combatant craft crewmen reported that 65% of them had sustained at least one injury during service — with the harsh craft's motion being the primary subject (Ensign et al., 2000).

Consequently, recent research has explored the use of ACSs in planing craft in order to improve the vessel's seakeeping. This research has shown that a planing craft with an ACS is capable of superior seakeeping compared to those without (Wang, 1985; Savitsky, 2003; Shimozono and Kays, 2011; Engle et al., 2011; Rijkens, 2013). In addition, not only can an ACS improve the seakeeping of a planing craft, it can also stabilize it so that it can operate at its optimal lift-to-drag trim angle (Xi and Sun, 2006). All these promising results for incorporating ACS into planing craft are with vessels that were designed sequentially, i.e., the vessel geometry was first selected, and then the ACS was incorporated. But because the vessel geometry and ACS are coupled (both affect the vessel's dynamics), even better results are possible if both are co-designed and the hardware-control couplings are explored (Castro-Feliciano et al., 2016; Peters, 2010).

Co-design of vessel geometry and ACS requires effective tools to facilitate optimization, particularly the models that capture the sensitivity of key planing boat performance with respect to both geometry and ACS parameters. Recent research in the hydrodynamic optimization of a planing craft (Ayob et al., 2009, 2010) estimated the seaway drag and seakeeping performance by using empirical equations (Savitsky and Brown, 1976; Savitsky and Koelbel, 1993). As previously mentioned, the model tests used (Fridsma, 1971) did not have ACS, and therefore the empirical equations do not incorporate the effects of an ACS. Consequently, a time-domain simulation program is required to estimate the seakeeping performance of a planing craft with an ACS.

More specifically, the problem of designing a planing craft with an ACS is a multidisciplinary design optimization (MDO) problem — one discipline is the controls engineering, and the other is the naval architecture/hydrodynamics of the vessel and ACS's hardware. Aerospace is one of the most active fields in MDO; a summary of some MDO techniques used in aerospace is documented in (Sobieszczanski-Sobieski and Hafka, 1997). It is easy to see how an MDO problem could be made as complex as the designer would want. For example, we could also include structure design into the problem definition. Therefore, one of the challenges in MDO is choosing parameter spaces that have great