Intersections Between Marine Hydrodynamics and Optimal Control Theory

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1 Background

The field of marine hydrodynamics has witnessed remarkable progress over the past 50 years both at the theoretical, experimental and computational fronts. Reliable analytical techniques and computer programs have been developed and are in routine use in practice for the modelling of steady and unsteady flows around ships and the interaction of surface waves with floating structures.

Optimal control theory, as a distinct discipline, has also witnessed progress over the same period towards the development of methods for the stabilization and control of a host of linear and nonlinear engineering systems. These methods are based on models which may be approximate or contain parameters which may be uncertain. For systems which are linear or weakly nonlinear, adaptive linear control theory has reached maturity. Significant advances have also been made towards the stabilization and adaptive control of strongly nonlinear systems.

Recently a number of applications spanning both disciplines have appeared. Problems that have been treated include the development of ship autopilots, the optimal maneuvering of ships in open or restricted waters, the motion control of ships and high-speed vessels in a sea state and the dynamic positioning of offshore vessels. The utility of methods from control theory presupposes the availability of *controls* - devices that are available for the control of the vessel performance and responses. In the case of ships, examples of such devices include the propeller revolutions and blade pitch angle, the rudder angle and lifting appendages. Recent developments and applications of control theory for marine vessels are discussed in [1].

The design of a control method is based on the availability of a hydrodynamic and motion response model for the *plant* - the vessel or floating structure. The complexity of the selected model depends upon the underlying physics, the properties of the controller and the desired performance of the controlled system. The more accurate the model the higher in principle the expected performance of the controlled system, assuming that a robust controller can be designed. In practice, the model may be possible to tune against the real time vessel performance and responses measured with instruments onboard the vessel. For example, the plant states and uncertain parameters in the model may be estimated in real time using the Kalman filer coupled with the techniques of adaptive control theory. Achieving a proper balance between model accuracy and controller effectiveness underlies the science and art of the controller design. Yet, the more accurate the model the higher the expected the performance of the controller. This is particularly true for the complex physical processes encountered in the field of marine hydrodynamics.

In what follows the treatment of two problems from marine hydrodynamics is discussed, involving the coupling of a reliable potential flow hydrodynamic model with the theory of Linear Quadratic (LQ) controllers. The first problem treats the motion regulation of a ship advancing next to a vertical wall while maintaining a prescribed separation distance. The second involves the heave and pitch motion control of a twin-hull vessel equipped with bow and stern hydrofoils while advancing in head random waves. The hydrodynamic model used in both problems is the state-of-the-art Rankine Panel Method SWAN which has been widely used and validated for the treatment of steady and unsteady ship flows as described in [2].

2 Ship Steering Next to a Wall

The optimal ship maneuvering problem considers a ship advancing parallel to a vertical wall at a prescribed separation distance. The hydrodynamic suction force and yaw moment that would cause the vessel to crash into the wall in the absence of rudder and speed control, are modelled by SWAN using potential flow theory and assuming a double-body flow free surface condition. The vessel small amplitude sway-yaw equations of motion around their zero mean values are also modelled by SWAN and cast in state-space form. Viscous effects are modelled by an equivalent linear model for small sway and yaw displacements. Control inputs are the rudder angle and vessel speed variation. A Linear Quadratic Integral Feedback control algorithm has been developed and shown to be able to set in real time the rudder angle, its rate of change and the ship speed for the vessel to maintain its initial mean distance from the wall.

The LQ-IF regulator introduces a restoring mechanism shown to act as an effective spring bringing the ship back to its intended trajectory via the closed-loop settings of the controls - the rudder angle and ship speed. The closed-loop controller also introduces an effective sway-yaw damping mechanism which is far more significant than the physical damping mechanism caused by flow separation effects. It is concluded that for this ship maneuvering problem an effective control mechanism mitigates the need to develop accurate physical models of flow separation and ship maneuvering coefficients. The detailed development of the method is presented in [3].

3 Motion Control of Catamaran Vessel

The motion control problem of a catamaran vessel was treated next. This involves the minimization of the vessel heave and pitch motions via the active control of bow and stern hydrofoils in head random waves. The linear time-domain equations of motion are modelled by SWAN and are cast in state-space form for use in the development of an LQ regulator. A complexity present in the seakeeping problem is the presence of strong wave memory effects which are absent in the maneuvering problem. Their modelling has been undertaken in two stages. For hydrofoil vessels with small waterplane area the leading contribution to the memory effects in the radiation problem is contained in the impulsive component of the free surface flow subject to the pressure relief condition of a vanishing velocity potential on the free surface. Using this approximation, an LQ regulator was developed in regular and random waves and was shown in [4] to stabilize and reduce significantly the heave and pitch motions of a high-speed hydrofoil vessel.

When wave memory effects are important, their account into the state-space model underlying the LQ regulator is nontrivial. Their modelling has been carried out by truncating the semi-infinite time-convolution integral which accounts for memory effects in the radiation problem followed by the evaluation of the resulting finite-time integral by quadrature. This leads to a discrete vector auto-regressive state-space formulation of the vessel equations of motion. In the seakeeping problem, the state vector includes not just the time-local values of the ship displacements and velocities but also their time-lagged values arising from the evaluation of the truncated convolution integral. The ensuing development of the LQ regulator leads to the derivation of a closed-loop feedback law which determines the optimal real time values of the controls, namely the bow and stern hydrofoil angles of attack, in terms of the known history of the heave and pitch displacements and velocities of the vessel. No stabilization via an integral feedback mechanism is necessary in this seakeeping problem since ample hydrostatic stability is supplied by the vessel waterplane area. The details of this development are presented in [5].

4 Adaptive and Feedforward Control

It follows from these studies that efforts towards the development of increasingly accurate flow and vessel response models may not be always necessary when effective control devices and methods are available. This is evident from the significance of the feedback gains in the closed-loop ship maneuvering equation, where parameters of the open-loop equations of motion may not be known with high accuracy. The performance of these controllers can only be expected to improve when measurements are also available of the vessel response history and of the ambient seastate in the vicinity of the vessel. This extension of the present algorithms entails the use of the Kalman filter with Gaussian errors for the online estimation of uncertain model parameters and system states. These real-time estimates may then be used as input to the LQ regulator as dictated by the *certainty equivalence principle*. This and other techniques of adaptive and feedforward control theory are described in [6] and [7] for linear systems and in [8] for nonlinear systems. The availability of these powerful control methods underscores the significance of striking a balance between the accuracy of the physical model and the design of robust controllers.

The application of methods of linear and nonlinear optimal control theory to the seakeeping of vessels is not as widespread as is the case for ship autopilots and vessel dynamic positioning where PID controllers are common. The present abstract highlights how the LQ methodology may be applied to the motion reduction of a catamaran vessel equipped with actively controlled foils in a manner that can be readily implemented in practice. The use of linear theory is not limiting since the reduction of the vessel motions by the controller enhances its validity.

5 Nonlinear Ship Seakeeping

Nonlinear extensions of the present LQ and LQG regulator framework are discussed in [1] for the low-frequency ship maneuvering and vessel dynamic positioning problems. Extensions are also possible for the nonlinear ship seakeeping problem. Large amplitude motions in roll, pitch and other modes of motion may arise in steep waves, in quartering seas and for vessels with significant positive or negative flare. Realistic, but not necessarily too complex, models of such nonlinear seakeeping problems are needed in steep ambient waves. The stabilization and control of such large amplitude motions may be achieved via the use of anti-rolling fins, rudder control and the selection of the variation of the vessel speed and heading relative to the ambient waves. The formulation and treatment of such challenging vessel motion stabilization and control methods may be carried out by using the Lyapunov based nonlinear adaptive control methods developed in [8] and [9].

6 Motion Control of Offshore Structures

The elements of the LQ regulator developed for the motion control of the catamaran vessel may be extended to the development of analogous LQ regulators for the reduction of the responses of other floating structures at zero speed. Unlike the ship maneuvering and dynamic positioning problems, memory effects are significant over time scales comparable to ambient wave periods and may be accounted for in the development of the controller along the lines of [5]. The nature of control devices appropriate for the motion control of floating structures at zero or low speeds varies. They include active lifting appendages and anti-rolling gyroscopes for the roll motion control of yachts, internal water tanks with active or passive controls for the reduction of the roll motion of ships and other floating structures, and internal passive or actively tuned mass-dampers which have found widespread use for the mitigation of the vibration of tall buildings.

7 Ship Routing

Finally, the use of marine hydrodynamic models for the vessel resistance, propulsion and seakeeping coupled with control theory underlie the development of ship routing algorithms aiming to minimize route specific cost functions, e.g. time to destination or ship fuel consumption, in calm water or in uncertain weather conditions. Ship routing problems can in principle be cast as stochastic dynamic programming problems which are very hard to solve in their generality. The development of robust solutions for specific ship routing problems using the methods discussed above is possible yet it remains a challenging undertaking.

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