

A novel computer simulator for cable-towed submerged vehicles

ABSTRACT: This paper presents a fully non-linear, dynamic, six degrees of freedom computer simulator, 6DofTow, of the towed vehicle and its interaction with the ship, the outboard handling equipment, the towing cable, and the stern wake environment in ACSL. The simulator includes sub-modules of ship, vehicle, cable and outboard handling and control systems. The ship module reads in ship motion data obtained from sea trial or generated by a separated ship motion simulator. The vehicle module includes a set of differential equations which describes the motion of the submerged vehicle. The towing cable module is consisted of discrete damped spring elements with lumped masses at nodes. The outboard handling module describes the hydraulic handling equipment which launches, recovers the submerged vehicle and controls its depth and attitudes. The simulator has been developed for the purpose of aiding engineers, designers and operators in achieving improved directional stability, manoeuvrability, safety and control characteristics with cable-towed submerged vehicles. The simulated results demonstrate the elegance and robustness of the proposed simulator by comparing with the test results.

1 Introduction

Cable-towed submerged vehicles, in both shallow and deep water, have a wide range of applications in science, industry and defence. However, their technologies have not been fully accomplished due to the extreme complexity of the problem. For example, cable-towed vehicles in water experience loads generated by highly nonlinear hydrodynamic drag forces and cable towing forces. The cable forces depend on nonlinear hydrodynamics of cable, geometrically nonlinear and time dependent ship motion, and a variety of nonlinear outboard equipment. As a result, the stability, manoeuvrability, safety and control characteristics of a specific cable-towed submerged vehicle design usually were not evaluated until after it was constructed and actually in operation. Recently, rapid development of computer power makes the simulation of the highly nonlinear system of the cable-towed vehicles practically possible and economically affordable in the industry. The present work illustrates the properties of a simulation facility, 6DofTow, a fully nonlinear, dynamic, six degrees of freedom model of the towed vehicle and its interaction with the ship, the outboard handling equipment, the towing cable, and the stern wake environment. The simulator includes sub-modules of ship, vehicle, cable and outboard handling and control systems. The ship module reads in ship motion data obtained from sea trial or generated by a separated ship motion simulator. The towing cable model connects the ship and towed vehicle models and transfers ship motion to the towed vehicle. In the cable module, the towing cable is modeled with discrete cable elements. Each cable element is simplified as a damped spring with half mass lumped at each mode. A so-called force function method is adopted to calculate the hydrodynamic loading acting on the cable element. The vehicle module includes a set of hydrodynamic differential equations which describes the motion of the submerged vehicle. Due to the highly nonlinear nature, it is very hard to find the analytical solution of the hydrodynamic loading acting on the vehicle. As an alternative the hydrodynamic loading acting on the vehicle are calculated using hydrodynamic coefficients determined by water tank test. Finally, the outboard handling and control system, which is comprised of hydraulic subsystems, is presented in outboard module. Passive and active control systems, which involve advanced open and closed loop control technologies, are developed. The simulator has been developed for the purpose of aiding engineers, designers and operators from the standpoint of achieving improved directional stability, manoeuvrability, safety and control characteristics with cable-towed submerged vehicles.

2 Modelling

The 6DofTow is developed in modular construction. It includes the sub-modules of vehicle, towing cable, ship, stern wake, outboard handling equipment system, winch system, constant cable tension system, and some high level feedback controllers such as active ship motion compensation and variable depth control. Each sub-module is

represented by a set of time dependent, nonlinear differential equations. In order to allow for a high degree of modularity and flexibility, all the equations of sub-modules are established in their local coordinates.

2.1 Ship Motion Model

The ship motion model provides the position and velocity of the tow point which connects the towing cable model. The ship motion is assumed to be independent to the cable and submerged vehicle models because the ship mass is usually several orders larger than the total masses of cable and vehicle. As time progresses the mean ship frame is assumed to move in a horizontal plane relative to the earth frame.

The ship motion is composed of two parts: the motion relative to the mean ship frame and the motion of ship mean frame in the fixed earth frame. It is translated from the origin of the ship frame to the system tow point. The position of the tow point is described by specifying a position vector of that point relative to the origin of the ship frame. The relative ship motion to the mean ship frame is generated by using response amplitude operators (RAOs) of sea, or input directly from sea trial data or an independent ship motion simulator.

2.2 Towed Vehicle Model

The towed vehicle is represented as a rigid body moving in six degrees of freedom. Generally speaking, the accurate analytical expressions for the hydrodynamic force and moment are very hard to obtain. As an alternative, they are generally determined by water tank tests and defined in terms of the non-dimensional hydrodynamic coefficients of the vehicle.

2.3 Tow Cable Model

The tow cable is a flexible continuum subjected to concentrated and distributed loads, the later ones including hydrodynamics. Usually, it is simplified as a flexible string and only the axial stiffness is considered because of its extremely large ratio of length over cross section.

The cable is discretized into a series of elastic finite segments. Each segment has its own characteristics such as diameter, weight, length, stiffness, damping, bare, ribboned, faired, etc. The segment is further simplified as a mass-spring-damper element with the mass of the element lumped half at each of its nodes.

2.4 Stern Wake Model

Past experience has shown that the wake left behind a ship can have a significant influence on the success of launch/recovery operations of the towed vehicle. The stern wake model provides such an environment to simulate the hydrodynamic interaction between the ship and the towed vehicle in the period just prior to capture. Since the stern wake is random and very complicated in nature, there is no accurate analytical method available to describe the stern wake. As an alternative, an experimental approach based on spectral correlation is developed to simulate the wake behind a ship.

The experimental data, such as mean, standard deviation and spectrum of the fluid velocity behind the ship are collected at a number of sampling points in a spatial grid, which is assumed to be fixed to the stern. The values of mean and standard deviation of fluid turbulence velocity at each nodes of the grid are linearly interpolated to obtain their spatial distribution.

2.5 Outboard Equipment Model

The outboard equipment model represents the dynamics of outboard handling equipment as they influence the attitude of the towed vehicle and the cable tension significantly. The outboard equipment consist of passive compensating spring damper device termed constant tension stabilizer (CTS), winch drum/hydraulic driven system, active ship motion compensation and variable depth control sub-models. The towing cable is connected to the winch drum through CTS. The CTS can be switched on and off by adjusting the pre-charge pressure. It is usually turned on as an energy absorber to reduce the peak tension in cable due to ship motion in the normal tow operation. The winch drum receives and pays out cable. It is powered by a servo driven closed loop hydraulic drive system through a suitable gearbox to launch, recovery and actively control the towed vehicle. Compressibility, leakage, viscosity of fluid and mass inertia terms are modelled for completeness.

2.5.1 CTS Model

The CTS is basically a damped spring element consisted of sheaves and a pneumatic/hydraulic cylinder. The cylinder is usually pre-extended. When a cable tension exceeds a preset value due to the ship motion, the cylinder is compressed and extra cable is paid out to release the cable tension. After the peak, the cylinder is extended automatically by compressed gas inside it and keep the cable stretched to maintain the cable tension constant.

2.5.2 Winch Model

The winch model describes the dynamics of the winch drum.

3 Validation

Validating model of this type of system is a hard and chronic process. First, the model is validated with other models, which are well validated, for steady state. Then, validation sea trials were conducted using full size submerged vehicle. The computer model is checked and validated against the sea trial data in both steady and dynamic states.

3.1 Steady State Validation

Steady state variables such as vehicle's depth, cable tension and trail as functions of scope and speed were first compared with program TOW, v2.5, a well validated steady state code.

The agreement is generally very good between the predictions of 6DofTow and TOW. Some modelling differences between the two codes can explain the deviation. The most significant difference is the hydrodynamic representation of the towed vehicle. The towed vehicle is modelled as a 6-DOF rigid body in 6DofTow and simplified as a sphere in TOW. This results in an overestimation in drag force of the towed vehicle for TOW, causing a more shallow depth and higher tension prediction.

The next model is checked against sea trial data with the cable tension at tow point versus towing speed. The trial was conducted in a very calm sea at different towing speed. The simulation agrees with the trial very well.

3.2 Dynamic Validation

Dynamic validation checks were run against sea trial data. No ship motion compensation devices (active and passive) were installed. To run the simulation, real ship motions measured from sea trial such as position, orientation and speed are input to the ship motion module. The responding motions of towed vehicle are recorded and compared with vehicle's sea trial data. In order to improve the accuracy of simulation, the hydrodynamic coefficients of the real vehicle should be calibrated with sea trial data.

3.3 Stern Wake Model Validation

The stern wake model was calibrated and checked against water tank test data in a statistic meaning due to its random nature. The 6DofTow is run with the vehicle being towed in the real and generated stern wake, respectively.

4 Applications

After the credibility of 6DofTow is verified. It is applied in design of a variable depth towed vehicle system. One of the important issue in the design is the ship motion compensation. The goal of motion compensation systems are generally twofold: to improve the towed vehicle stability; and to reduce the mechanical stress on the outboard equipment. In both cases, a properly designed motion compensation system can effectively extend the operational envelope of the towed vehicle system.

A second application in which 6DofTow has been employed concerns the recovery of the towed vehicle when the surface tow ship is subjected to rough sea. The application requires no ship motion compensation, since the towed vehicle should pass the stern wake as quickly as possible in order to reduce the effect of the stern wake to minimum. The vehicle follows the ship motion firstly when it is at recovery position. When recovery starts, it is towed towards surface quickly and stably until it enters into the effective region of the stern wake and its motion becomes volatile. Since the stern wake is random, this kind of simulation must be performed repeatedly with Monte Carlo process to determine the arriving profile of the vehicle.

5 Summary and Conclusion

The 6DofTow computer simulator provides a cost effective approach for the simulation of a wide range of applications of submerged cable-towed systems. The use of a sophisticated simulation language makes the module structure of the simulator easier to include subsystems with the cable and towed vehicles. A linear finite element formulation for a cable segment contributes to model efficiency and flexibility for different type of cable. The credibility of the simulator is verified by sea trials and other well established model. The 6DofTow the design and analysis of marine submerged cable-towed vehicle systems can be performed time-efficiently and cost-effectively with higher confidence in the directional stability, manoeuvrability, safety and control characteristics of the delivered systems.

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