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Propulsion and Thrusters

Cross Forces

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Cross Forces

The Problem

Thrusters and main screws for use in dynamic positioning are normally expected to produce thrust in the direction and magnitude commanded by the control system. This expectation is usually based on the assumption that the water drawn through the thruster was still or not moving before being sucked in by the propeller. This expected or primary thruster force is generated by the change in momentum of accelerating the still water up to the velocity of the water through the thruster.

When operating in the presence of a current from any direction there is another force generated by the thruster in the direction of the current flow. This added force is caused by the change in momentum of all of the water going through the thruster resulting from reducing the velocity of the current to zero to satisfy the still water assumption. These forces have been called cross forces although they also occur with currents coaxial with the thruster.

Dynamically positioned vessels, particularly those using fixed axis thrusters and main screws, are subject to position control upsets caused by these cross forces when operating in the presence of a current, if they are not compensated by feed forward control. As an example, if the ship is pointed into a three knot current and a sudden wind is taken on the beam, the lateral thrusters will immediately respond with a force to oppose the wind. Because of wind feed forward control the ship will not lose position by being blown down wind. But all of the lateral thrusters are now suddenly generating cross forces which move the ship aft, with the current, until the position movement is sensed and main screw thrust increased to restore position. Such position upsets are unwelcome at any time but especially at the onset of a squall. Variations of wind force cause variations of cross force. When sensed only by the slower response to position offset, the result is poor position control. Under different combinations of wind and current the main screws cause lateral components of cross force which reflect in degraded heading control.

Cross Forces Are Significant

At full thrust and in a three knot current, the cross forces amount to 20 to 30 percent of that full thrust. When multiplied by the number of thrusters, this presents a very sizeable extra burden for the main screws in the above example. If the capacity to accommodate this extra load has not been provided, it can result in main screw saturation and loss of position, not just sloppy control. In many cases these extra forces have not been included in the design loads, nor have they been included in the calculation of holding capability against the environment.

Cross forces are directly proportional to current, but they are proportional to the square root of the primary thrust. As a result they become an even greater percent of primary thrust at reduced thrust levels and therefore a greater upsetting influence to control performance. At half thrust, the cross forces become 28 to 42 percent of primary thrust compared with the above 20 to 30 percent when at full thrust.

These forces are not as easy to analyze when the vessel is in the process of turning in the presence of a current, but they have been shown in simulations to cause considerable upsets in position keeping while turning. This is verified in full scale drillship operation where turns have been limited to only a few degrees at a time with low turn rates of 4 to 6 degrees per minute and then with long pauses for the ship to recover position. With sudden squall winds on the beam, such slow turns are frustrating and dangerous.

Given the significance of these cross forces, it is important that they be included in the design calculations of thrust and power required and in the holding capability that results. It is also important to find a way to provide feed forward compensation to reduce their upsetting influence in DP control.

As large as these forces are in the presence of strong currents, they appear not to be widely known or understood. The first measurement of these forces of which we are aware was taken by NSMB in model tests of the thrusters for the Sedco 445 in 1970. These tests were done under the direction of Dietmar Deter. Since then at my suggestion they were confirmed in thruster model tests done by Mitsubishi Heavy Industries in the late eighties. Until the mid eighties and the upgrade of the Discoverer Seven Seas, no explanation or analytic derivation of these forces or effort to compensate for them is known

Calculating the Forces

The primary force produced by a thruster, based on the change in momentum from still water, is approximately

$$F_T = \rho A(V_T)^2 \qquad \text{Equ 1}$$

where ρ is the mass density of water in lb. sec^2 /ft^4, A is the area of the cross section of water through the thruster in ft^2 and V_T is the velocity of the water through the thruster in ft/sec. See Ref 1. In this equation, AV_T is the volume of water going through the thruster in ft^3/sec and its mass is ρAV_T. Multiplying this mass by the velocity to which it was accelerated by the propeller gives the force required to do it, or the primary thrust. Instead, multiplying that same mass quantity by the velocity of the current V_C gives the force required to drop that quantity of water to zero momentum at the thruster inlet. This is the cross force

$$F_{CF} = \rho AV_TV_C \qquad \text{Equ 2}$$

This has assumed that all of the momentum of the current flow was stopped or that all of the water was changed in direction from that of the current to that of the axis of the thruster. For a ducted propeller this is essentially true. For an open propeller this may be only about 40 percent true.

From equations 1 and 2 it is apparent that for ducted propellers the ratio of the cross force to the primary thrust is simply the ratio of their corresponding velocities.

$$F_{CF}/F_T = V_C/V_T \qquad \text{Equ 3}$$

When the current direction is into the thruster intake, the net or combined thrust, F, is found by scalar subtraction of the cross force from the primary thrust, $F_T - F_{CF}$, and the result is the familiar expression for the thruster force as degraded by current inflow.

$$F = F_T(1-V_C/V_T) \qquad \text{Equ 4}$$

Combining equations 1 and 3 allows derivation of an expression for cross force in terms of the variables current velocity with thruster force instead of water velocity through the thruster.

$$F_{CF} = V_C(F_T\rho A)^{0.5} \qquad \text{Equ 5}$$

For evaluation of these equations, the velocity of water through the thruster can be approximated by the expression

$$V_T = NEP/60 \qquad \text{Equ 6}$$

where N is the speed of the propeller in revolutions per minute, E is the volumetric efficiency of the propeller and P is the propeller pitch in feet. For ducted propellers at bollard pull a volumetric efficiency of 0.7 is about right. Since the full speed force of the thrusters will generally be known, that force can be used to determine a more accurate number for volumetric efficiency. The constant, ρ, is the weight of a cubic foot of sea water, about 64 lbs/ft^3, divided by the acceleration of gravity, 32.2 ft/sec^2, or about 2.

Since the cross forces are applied at the direction of the current, the primary thrust and the cross force must be added vectorially. The primary thrust is usually already built into any program to calculate holding capability or to drive the model in a DP control system. It is therefore necessary only to add the longitudinal X and lateral Y components of the cross force at each thruster or main screw location. If current direction toward the vessel is measured clockwise from the bow by angle, α, then for each thruster or main screw the lateral component of the cross force is

$$F_{CFY} = |F_{CF}|\sin\alpha \qquad \text{Equ 7}$$

and the longitudinal component of cross force is

$$F_{CFX} = |F_{CF}|\cos\alpha \qquad \text{Equ 8}$$

Note again that the direction of the cross force and its components are determined not by the direction of thrust of the propeller but instead by the direction of the current. That is why the absolute values of the cross forces are used. The sign of each of the X and Y components is determined by the sign of the sin and cos of the angle of current approach. Caution must be used to ensure that the sign conventions used in the application of these equations matches that used for the rest of the model.

Implementation of Cross Force Compensation

A good case can be made for the benefits of cross force compensation but not much experience is available to date. The only known implementation of cross force compensation was done aboard the Discoverer Seven Seas in the mid eighties. It appeared to be successful while it was operating but was ultimately abandoned for lack of reliable current sensors. See OTC Paper 4749, 1984.

To implement cross force compensation requires insertion of suitable algorithms, as outlined above and the input of current magnitude and direction measured on or near the ship. Due to the fact that current conditions tend to change very slowly, it may be most convenient to enter these values manually.

A second approach is to input current data automatically in real time from Doppler or other measurement devices on the ship. If this method is employed it will be important to program the control system to reject any rapid current changes to high values for as long as they endure. This data is sure to be false and is likely caused by the propwash of a supply boat or the DP propulsion itself.

Still a third alternative is to use the integral terms of the control system as a rough indication of the magnitude of current force and direction. This implies the assumption that essentially all of the integral term is caused by current force, and this assumption is subject to a number of potentially serious errors. In addition to the current force the integral terms also contain the residual from wind compensation errors, errors of calibration of the thruster command and feedback and wave drift forces. The back calculation for determining current would also be subject to errors in the drag coefficients for the vessel. While this approach might be suitable at times when currents are strong and wave drift forces negligible, the compensation could be worse than none at all at times when wave drift forces are high and current forces small.

Until experience can tell which of these approaches is most satisfactory it might be best to test all three.

Cross Force Damping

Although cross force as described here has been an upsetting influence in DP control, it has some very beneficial effects in stabilizing vessel motion against oscillatory forces as well. Significant reductions in heave amplitude had been seen in semisubmersibles when thrusters were turned on. A similar effect is seen in the stability of a speedboat underway compared with its motion at anchor in the presence of waves. This effect was modeled by Huse and Borrensen at Norwegian Hydrodynamic Laboratories and reported in their only recently noticed OTC paper, See OTC Paper 4605, 1983. They made an attempt to derive analytical equations, but propeller pitch and volumetric efficiency were not included, and the derivations were incomplete. For a ducted propeller their test data showed a maximum F_{CF} of 40 percent of F_T but at an unknown ratio of current to thruster velocity (perhaps about 40 %). Their open or unducted propeller test showed a cross force of about 39 percent of that of the ducted propeller. This indicates that the open propeller is less efficient at turning the entire current stream to the direction of the thruster axis. An appropriate reduction of the cross force for open propellers should probably be made for angles of current attack across the axis of the propeller. For main screws this reduction could be approximately proportional to the absolute value of the sin of the angle from the bow.

The explanation for this stabilizing or damping effect should be clear from the change of momentum forces derived above. That is that while a propeller is producing thrust in any direction, a cross force will be generated to resist motion of the propeller in any direction through the water. That force can act as a strong retarding or damping force against oscillations of the vessel. Since they are proportional to first power of velocity, cross forces are amenable to frequency domain analysis as opposed to velocity squared damping which generally requires more cumbersome time domain analysis.