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DYNAMIC POSITIONING CONFERENCE
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New Applications

Dynamic Positioning for Heavy Lift Applications

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ABSTRACT

A dynamic positioning (DP) control system has been successfully commissioned for a heavy lift barge supporting the construction of a road bridge. Each bridge segment, with a mass in excess of 500 tonnes, is held in position in DP. A crane, located 75 m above, is connected. Gradually, the crane applies tension, and the segment is lifted from the barge.

DP control systems react in a particular way to position and velocity errors. This response is tuned to provide optimal vessel control. Heavy lift applications naturally impart large forces on a vessel. These forces, unknown to the DP controller, cause position control instability when coupled with the normal DP controller response. To maintain position and stability, the DP controller has been tailored to provide a special response during heavy lifting operations.

The system has been further enhanced with the provision of optional manual control of individual axes. If an axis is in manual control and the bridge segment position is oscillatory, the dynamic positioning operator's (DPO's) natural reactions are likely to apply thrust inappropriately, causing larger oscillations.

This paper explores the problems associated with heavy lifts. It details how the controller was modified for automatic position keeping and the training provided to the DPO for manual positioning

INTRODUCTION

Stonecutters Bridge will be a high level, dual 3-lane, road bridge. It will straddle the Rambler Channel at the entrance to the busy Kwai Chung container port in Hong Kong, see Figure 1. With a main span of 1018 m, Stonecutters Bridge will be one of the longest span cable-stayed bridges in the world.

The main span will be supported from towers located on land either side of the Rambler Channel. The partially constructed bridge's deck is about 75 m above water level. The span will comprise 65 segments, each with a mass in excess of 500 tonnes. Construction of the span is achieved by connecting these segments, one at a time, to the existing span. Construction occurs at both ends and will meet in the middle.

Figure 1 – Stonecutters Bridge under construction

The barge supporting the construction of this bridge is known as Chang Sheng 302. It is fitted with a Converteam A-series duplex dynamic positioning (DP) system.

Each segment to be connected is placed on the barge. Using DP, the segment is positioned vertically below its final position in the span. A crane, located on the bridge deck level at the end of the existing span, lowers hoist cables which are attached to the segment, see Figure 2. Tension is gradually applied and the segment is lifted from the barge.

HEAVY LIFT FORCES

This section explores the problems associated with heavy lifting when one or more of the barge axes is being controlled manually by the DPO or when the vessel position and heading is being controlled automatically by the DP system. In both manual and automatic control, there is a problem with position control stability. The problem is exacerbated by the size of the barge. The distance between the segment when placed on the barge and the wheelhouse is only about 4 m. There is a significant risk of a collision if the vessel surges forwards as the segment is lifted.

Figure 2 – bridge segment on barge

For manual and automatic control, the problems unique to this application are attributable to the unknown external force being applied by the crane. If the segment is not exactly vertically below the crane, applying tension will impart a horizontal force on the vessel. Figure 3 illustrates the magnitude of the forces involved. For a bridge segment of 500 t, the tension in the cables totals approximately 5000 kN. For a 1 m deviation from the vertical position, this tension resolves into a horizontal force of about 67 kN on the vessel. The system therefore behaves as a spring with effective stiffness 67 kN/m. This compares to a nominal stiffness of the DP system of about 7 kN/m (depending on the operator settings). The unknown external force from the crane is up to 10 times the thruster force normally requested by the DP controller.

The stiffness due to the crane cables is not constant, however. The stiffness in the horizontal plane increases as tension is applied by the crane, until the segment just lifts off the barge when the stiffness seen by the vessel rapidly decreases to zero.

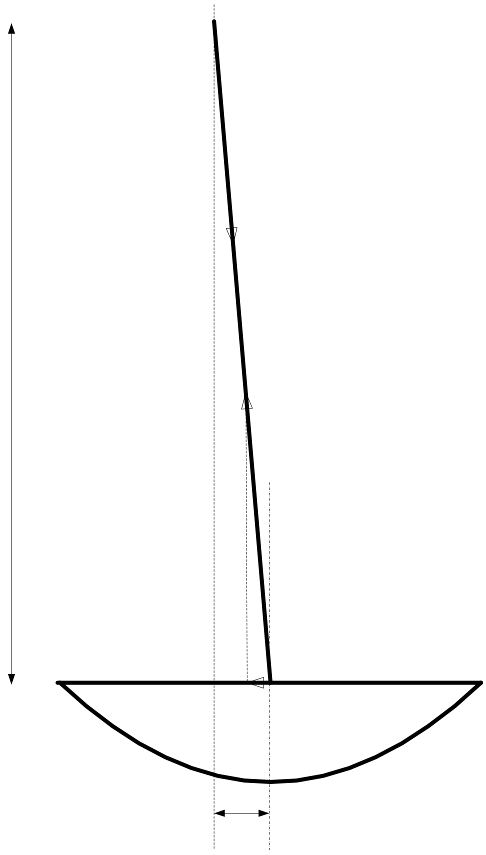

Figure 3 – Horizontal force due to cable tension

If there is a position error, i.e. a segment is not at its natural central position when tension is applied, the horizontal force will cause the barge to accelerate towards the natural centre. The accelerating force reduces to zero when the barge is at the natural centre position. The vessel continues moving and the force changes direction. Now the barge decelerates, and reaches zero velocity at a position error roughly equal and oppositie to the original position error. This process now repeats in the opposite direction, i.e. the forces from the crane tension cause the barge position to oscillate. Hydrodynamic drag will gradually attenuate the oscillations.

A simplified transfer function of the motion of one axis of the barge whilst connected to the crane is:

$$G_{ship}(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2 + ds + K} \tag{1}$$

where $X(s)$ is the Laplace transform of the position, $x(t)$, $F(s)$ is the Laplace transform of the forces acting on the ship (excluding the crane force), $f(t)$, m is the mass of the vessel (including added mass) in that axis, K is the equivalent stiffness of the crane and d is the vessel drag in the relevant axis. The form of equation (1) is indicative of an oscillatory system with natural frequency given by $\omega_n = \sqrt{K/m}$ and natural damping factor of $\zeta_n = d/2\sqrt{Km}$ (D'Azzo and Houpis, 1968). Since d for a ship is generally small, particularly in the surge axis, the natural damping is low, giving a damping factor, ζ, perhaps less than 0.01. In order to damp oscillations it is necessary to apply thruster force in anti-phase (i.e. in direct opposition to) the velocity, not the position.

Manual control problem

For most vessel applications, the normal reaction of a DPO is to apply thrust in the direction to reduce any position error, back off the thrust, and apply a decelerating thrust as the vessel approaches the target position. This procedure is unsuitable during heavy lift operations. For example, at the peak of an oscillation, the operator will be tempted to apply thrust towards the natural centre. Applying thrust in this manner causes a vessel to accelerate more quickly towards the natural centre. The vessel overshoots further and the amplitude of the oscillations increases. A DPO untrained in heavy lift applications is therefore likely to exacerbate the problem by his actions. One important task for the Stonecutters Bridge was to train the DPOs in the correct control of the vessel.

Automatic control problem

There is no measurement of the horizontal forces from the cables, no measurement of the cable tensions and no way to include a model of the system into the DP system controller. The forces due to the cables are therefore completely unknown to the DP system.

At the heart of the DP system controller is a mathematical model of the vessel and a Kalman filter (KF). Given noisy position measurement equipment (PME) measurements, other sensor information, and the thrust being applied by the thrusters, the purpose of the KF is to provide best estimates of the vessel's position, velocity, and the steady state environmental force. Given these estimates the DP controller calculates thrust references to maintain position. The large external force from the crane degrades the position and velocity estimates provided by the KF. At the same time, the DP system is attempting to correct for position errors by applying thrust towards the aim position, this action adds to the already large cable forces. These two factors lead to poor damping of the oscillations, or even instability.

Simulation of the Chang Sheng 302 under the conditions of Figure 3 have been performed to illustrate and investigate the problem. Figure 4 shows a typical simulation run for the surge axis. The vessel was initially distrubed from its equilibrium position by applying a step in the environmental force. The DP system then attempted to return the vessel to its original position. The figure shows that the vessel became unstable with increasing oscillations. Clearly this is unacceptable and a way of stabilizing the system was required.

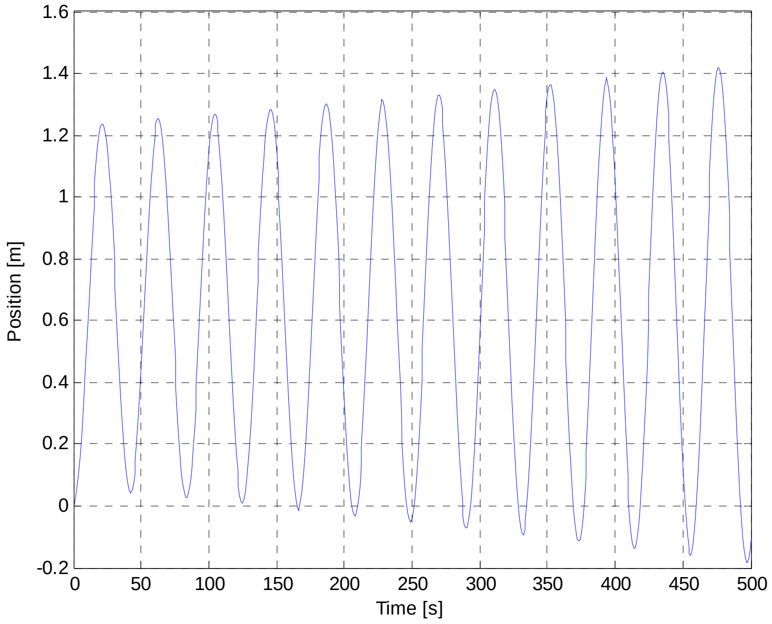

Figure 4 – Simulated position under normal DP control

SOLUTION

In order to overcome the problems highlighted above, and to ensure the safe operation of the vessel, a number of measures have been implemented. The operational procedures for conducting a heavy lift operation were reviewed and changes to the manual and automatic control modes have been implemented, as described below.

Manual control solution

The DP system has been upgraded to provide additional control modes, known as matrix modes. Matrix modes allow the operator to select which axes (surge, sway and/or yaw) are controlled automatically and which are controlled manually. It allows manual control of an axis without the operator being overwhelmed having to control all three axes. For example, an operator may prefer to perform a heavy lift operation with the surge axis being controlled manually, but sway and yaw axes being controlled by the DP control system.

Additional operator training has been instigated for manually controlled heavy lift operations. Once the operator understands the nature of the external forces the vessel position can be controlled effectively. The advice for operators inexperienced with heavy lift operations is:

- Do not attempt to dampen oscillations unless it is necessary to do so. Hydrodynamic drag forces will gradually reduce any oscillations.
- If it is necessary to change the mean position of the barge, adjust the joystick position to apply a different thrust and leave it constant.
- To damp out oscillations: at the peak of an oscillation, apply thrust *away from* the aim position. This ensures that the thrust is opposed to the vessel velocity by the time the thrust comes in to effect (taking thruster lag into account).

Automatic control solution

It is, of course, preferable to perform the operation in DP, so a stable and safe mode of operation was required. The DP system has been enhanced with the provision of new controller behaviour for use during heavy lift operations.

Since the stiffness of the crane is potentially much greater than that of the DP system itself, the aim of the controller for very high crane stiffnesses is merely to damp out oscillations. As mentioned above, to remove energy from the oscillations it is necessary to apply a force in anti-phase with the velocity. Therefore increasing the velocity gain and decreasing the proportional gain is beneficial. This contributes to damping and aids stability.

Since the stiffness of the crane system in the horizontal direction is variable, it is necessary to provide a means of introducing the changes to the controller gradually. A slider has been made available for the operator to choose a set of gains suitable for the lift operation. The instructions to the operator are to maintain the gains at ‘normal’ if possible and gradually introduce extra damping if oscillations start to become noticeable. This is reasonable since oscillations increase only slowly.

Simulation results

Prior to implementing the heavy lift mode on the vessel itself, extensive simulations were carried out to validate the gains and assess the impact. The effect of the new heavy lift mode of operation is shown in Figure 5. This is a repeat of the scenario of Figure 4, the only difference being the selection of the heavy lift gains. The figure shows that the vessel position is no longer unstable and that the initial disturbance is quickly damped out.

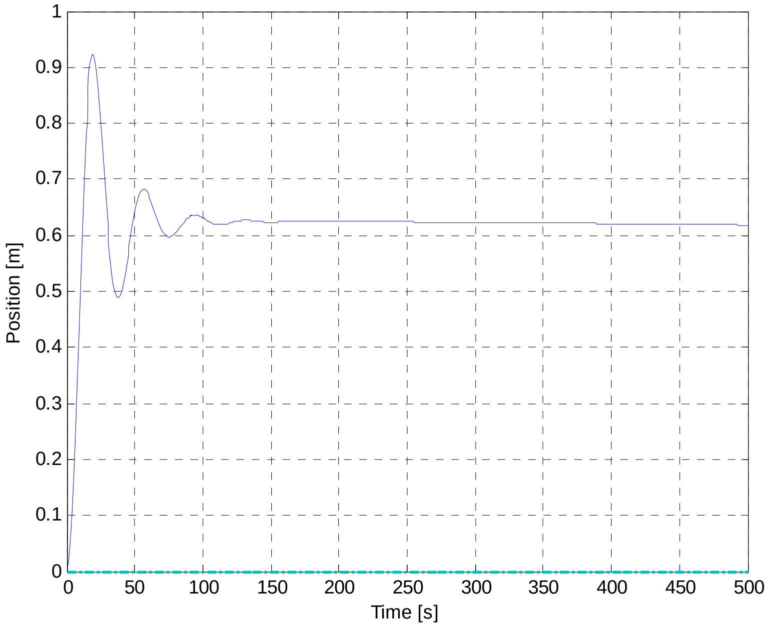

Figure 5 – Simulation position using DP 'heavy lift' mode

SEA-TRIALS

The new controller has been extensively tested in a lifting environment. During the trials various experiments were conducted to assess the controller's stability. Tensions equivalent to 10%, 25% and 50% of the segment weight were applied and held for long periods. To induce position errors, a tug was used to drive the barge off position. When the tug backed away, the barge position was observed, i.e. the effect of the dynamic positioning controller was observed. At all times the controller response was as expected and the barge was under control.

The barge was switched to manual control on the surge axis. The initial response of the operator was to make no interventions. The barge oscillated slighty in the surge axis, and a lift could have been safely conducted. However, after about 10 minutes, the operator intervened in an attempt to dampen the oscillations. At this stage, the operator had not received any training. Consequently, as expected, the interventions were inappropriate. The amplitude of the oscillations increased, and position control was rapidly lost.

APPLICATION TO OTHER HEAVY LIFTS

The problems associated with the Stonecutter Bridge operation are equally applicable to other heavy lift operations. For example, a crane barge lifting or lowering a large load onto a wharf, the seabed or a fixed structure will also experience the spring effect of the cable tension. Whilst the Stonecutter Bridge example is a severe case because the vessel is small in comparison to the load, the potential risks should not be ignored.

The heavy lift mode is now available for use on Converteam DP systems. The features include a slider for each axis (surge, sway and yaw) which can be used to introduce the gains changes as the loading increases.

CONCLUSIONS

Through a combination of analysis, simulation and full-scale trials, it has been shown that a DP vessel under-taking heavy lift operations can become unstable. This instability is due to the stiffness of the ship-crane system, the unknown forces acting on the vessel and the unavoidable lags associated with feedback control. This instability can occur under both manual and automatic control.

For manual control, extra operator training has been introduced, plus modes of operation to make the task easier.

For automatic control, the solution has been the introduction of Converteam's heavy lift mode of operation into the DP system. This mode enables the operator to inform the DP system that a heavy lift is in progress. The DP system in turn allows the natural spring of the crane system to maintain position, whilst providing additional damping to control oscillations. By observing that oscillation amplitudes increase slowly it has been possible to make it an operator-selectable feature. No additional sensors or other equipment has been necessary to achieve the aim of safe, reliable control.

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