ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 7, Issue 12, June 2018

Installation Strategy and Control System Design for Floating Bridges

Van Trong Nguyen, Young-Bok Kim and Sang-Won Ji
Department of Mechanical System Engineering, Pukyong National University, Korea
Korea Construction Equipment Technology Institute, Korea

***Abstract*—This paper presents a proposed strategy for floating bridge installation and its control system design. Floating bridges are well-known and practical alternative for water-crossing, especially in times of emergencies and conflicts thanks to their ability of heavy carrier. However, the installation process of the pontoon bridge is mainly carried out by human power that may lead to unexpected results usually happening in worst case as war time. With the above necessity, it is critical to develop the automated control system for handling installation and operation work. In this paper, the authors propose a new strategy to achieve the safe and fast process with regard to the hard conditions.**

***Index Terms*—bridge installation, floating bridge, pontoon bridge, water crossing.**

I. INTRODUCTION

Floating bridges contribute a strategic and important role for crossing water obstacles. The pontoon ribbon bridges, usually called foldable bridges, are employed to connect the gaps between shores. They are constructed by joining a series of floating units on water areas [1]. There are variety of factors that decide the successful of the installation process of the pontoon bridge in which speedy and safety play the most important. However, until now, both the installation and the linearity maintenance are done by human power along with support of erection boats that can raise the risk of operators, especially in case of combat situation. There is no doubt that it is hard to control the linearity of the long floating bridge under variety of external effects including moving loads, water currents, and wave attacks. Thus, in order to keep the installation and operation of the ribbon pontoon bridge faster and safer, it is critical to introduce a new strategy that applying automatic control technique.

To our knowledge, there has not many researches on the pontoon ribbon bridge. However, in recent years, a number of researchers pay more attention on that study. A study on dynamic analysis of the floating bridge has been proposed by Fu and Cui [2]. In term of image processing application on displacement measurement system for pontoon bridge, Hirono and co-authors have introduced an interesting study [3]. The most recent approach is presented by Nguyen et al [4] introducing the mathematical modeling and numerical study of the ribbon bridge model which allows new operation method to improve the performance of the pontoon floating bridges.

This study has assessed the applicable control method for maintaining the linearity among series of connected bays based on the observer-based controller. Consequently, the whole bridge system will be installed by yaw motion control by employing the integrated propulsion systems.

In order to verify the proposed strategy and the designed controller, a number of numerical simulations and experimental studies has been carried out. The simulation and experimental results show that our strategy and the controller based on state estimator have feasibility for the ribbon bridge installation and operation.

II. SYSTEM MODELING

In the numerical investigation, the floating units are described by the kinematic and kinetic model as the following [5]:

$$J\dot{\upsilon}+C_v\upsilon=\tau \,. \tag{1}$$

Where, $J\in R^{3X3}$ and C_v present the mass/inertia and the hydrodynamic damping matrix, respectively.
$\upsilon=[u,v,r]^T\in R^3$ describes the surge, sway, and yaw rate of the floating unit motion in body frame co-ordinate; τ is the control input forces and moments composed from the propulsion system. J and C_v are expressed as follows:

$$J=\begin{bmatrix} m-X_{\dot{u}} & 0 & 0 \\ 0 & m-Y_{\dot{v}} & -Y_r \\ 0 & -N_{\dot{v}} & I_z-N_{\dot{r}} \end{bmatrix}, \tag{2}$$

$$C_v=\begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & 0 \\ 0 & 0 & -N_r \end{bmatrix} \tag{3}$$

where m is the mass of a single bay; I_z is the inertial moment of the floating unit on z-axis. The expression of mathematical modelling of the multi-connected floating bridge shown in Fig. 1 is obtained by Nguyen et al [4].

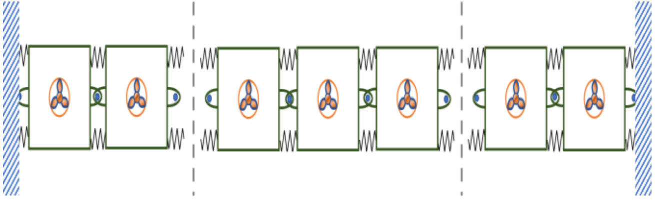


Fig. 1. General structure of multi-connected floating bridge system [4].

Especially, three-bay connected floating bridge shown in Fig. 2 can be presented as:

DOI:10.17605/OSF.IO/AYHX7

$$
\begin{aligned}
&J_1\ddot{\theta}_1 + C_v\dot{\theta}_1 + C_0\dot{\theta}_1 + C_1\left(\dot{\theta}_1 - \dot{\theta}_2\right) = \\
&\qquad \left(F_0^{lu} + F_0^{ld} + F_1^{ru} + F_1^{rd}\right)h + \left(F_1^{p} - F_1^{w}\right)w_v \\
&J_2\ddot{\theta}_2 + C_v\dot{\theta}_2 + C_1\left(\dot{\theta}_2 - \dot{\theta}_1\right) + C_2\left(\dot{\theta}_2 - \dot{\theta}_3\right) = \\
&\qquad \left(F_2^{ru} + F_2^{rd} + F_1^{lu} + F_1^{ld}\right)h + \left(-F_{i-1}^{w}\right)w_v \\
&J_3\ddot{\theta}_3 + C_v\dot{\theta}_3 + C_2\left(\dot{\theta}_3 - \dot{\theta}_2\right) + C_3\dot{\theta}_3 = \\
&\qquad \left(F_2^{lu} + F_2^{ld}\right)h + \left(F_3^{p} - F_3^{w}\right)w_v
\end{aligned}
\tag{4}
$$

where $F_i^{lu}, F_i^{ld}, F_i^{ru}, F_i^{rd}$ are spring forces of upside and downside in left hand side and right hand side, h is the arm of spring forces, F_i^{p}, F_i^{w} are forces generated by actuators and the current flow force, and w_v is the arm of force generated by driving DC motor and current flow. More precise information about the 3bay system is illustrated in the reference [4].

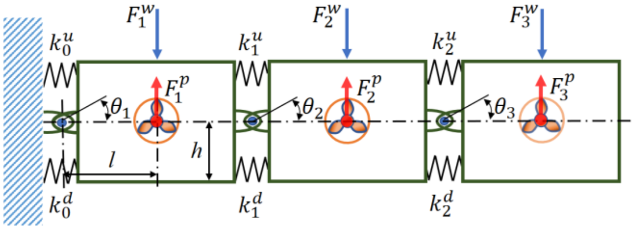


Fig. 2. The 3bay floating bridge system for experiment.

III. CONTROLLER DESIGN

As mentioned before, the objective of the control system design is automatically installation and position retain-ability by yaw motion control and keeping the multiple connected pontoon bridge system in the pre-defined desired position. As shown in Fig. 2, it is clearly seen that the under-actuated floating unit system is considered in our proposed control design. In other words, there are only two force generated propulsion system installed in the first and third floating unit of the bridge system and the second one are driven by the coupling forces produced by the connected springs.

For the class of multi-input multi-output system, the optimal control with the observer is well applicable. The conventional control structure with LQR controller and state estimator is illustrated in Fig. 3 to obtain the desired control performance.

By conducting multiple times of experiment, the parameters of mathematical modeling have been identified through numerical evaluation. Based on that, the controller gain $K(K_f, K_w)$ and the observer gain L should be calculated. Based on the system stability condition, if the gains $K(K_f, K_w)$ and L satisfy the conditions:

$$(A - BK(K_f,\, K_w)) < 0\,, \quad (A - LC) < 0 \tag{5}$$

holds, then the closed loop system shown in Fig. 3 is stable.

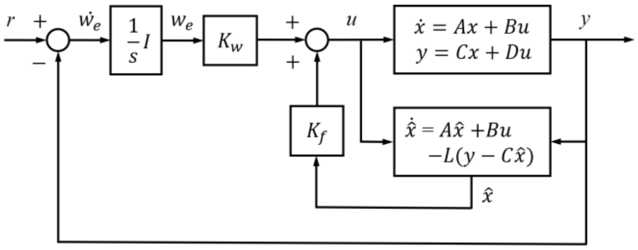


Fig. 3. A servosystem with observer for controlling floating bridge position.

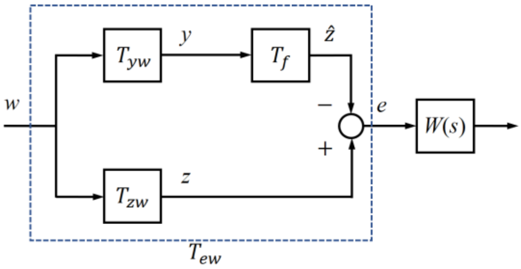


Fig. 4. The 3bay floating bridge system for experiment.

Therefore, at first, we calculate the observer gain L using H_∞ control theory. A basic concept of robust estimator design problem is illustrated in Fig. 4 [6]. Where,

$$T_f(s) = \left[\begin{array}{cc} A - LC & L \\ E & 0 \end{array}\right], \tag{6}$$

$$T_{ew}(s) = \left[\begin{array}{cc} A - LC & B - LD \\ E & 0 \end{array}\right] \tag{7}$$

and $W(s)$ is a weighting function for designing an observer. It can be defined as a candidate:

$$W(s) = \left[\begin{array}{cc} A_w & B_w \\ C_w & D_w \end{array}\right]. \tag{8}$$

The specification of an observer design is defined by

$$\left\| W(s)T_{ew}(s) \right\|_\infty < \gamma \ (> 0) \tag{9}$$

which is the H_∞ error bounded robust estimator design method.

Then, the observer gain L satisfies condition (9) if and only if there exist

$$
\begin{aligned}
P = P^T &= \begin{bmatrix} P_1 & P_2 \\ P_2^T & P_3 \end{bmatrix} > 0, \\
\Pi = \Pi^T &= \begin{bmatrix} \Pi_1 & \Pi_2 \\ \Pi_2^T & \Pi_3 \end{bmatrix} > 0
\end{aligned}
\tag{10}
$$

satisfying

$$\bar{A}P + P\bar{A}^T + P\left(\gamma^{-2}\bar{E}^T\bar{E} - \bar{C}^T\bar{C}\right)P + \bar{B}\bar{B}^T + \Pi = 0\,. \tag{11}$$

In the result, the observer gain is obtained as follows:

$$L = P_1C^T - \Pi_2\Pi_3^{-1}P_2^TC^T\,. \tag{12}$$

Based on this fact, an observer gain (12) can be calculated and a candidate is presented as following.

$$L = \begin{bmatrix} 50.38 & 2.16 & -0.86 \\ 714.14 & 106.31 & -34.27 \\ 120.54 & 51.23 & -18.87 \\ -1024.6 & 104.89 & 30.87 \\ 1.88 & 32.86 & 1.73 \\ 85.95 & 190.17 & 94.05 \\ 0.26 & -5.65 & 57.07 \\ 10.66 & -170.74 & 992.56 \\ 1.02 & -41.7 & 194.21 \\ -16.88 & 562.7 & -1455.2 \end{bmatrix}. \qquad (13)$$

Also, the state feedback gain $K(K_f, K_w)$ is obtained based on optimal control theory and given as follows:

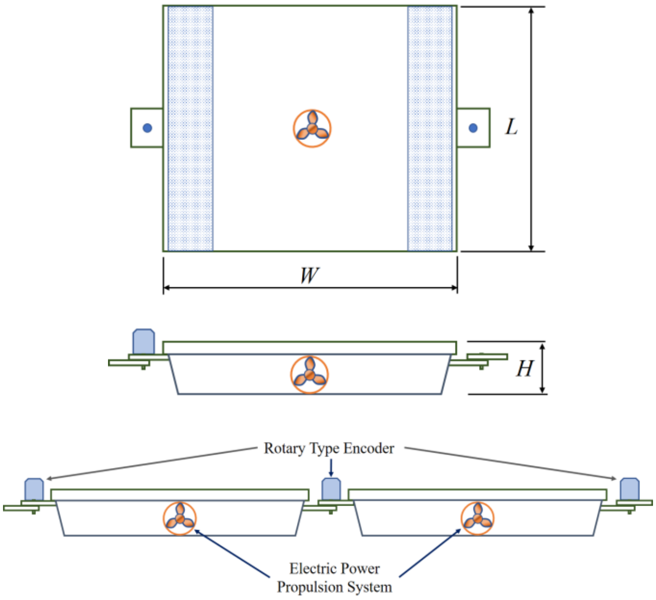
$$K_f = \begin{bmatrix} 0.0318 & 0.0127 & 0.0432 & 0.0061 & 0.0191 & 0.0135 & 0.0033 & 0.0102 & 0.0349 & 0.0049 \\ 0.0054 & 0.0101 & 0.0345 & 0.0048 & 0.0257 & 0.0223 & 0.0433 & 0.0311 & 0.1063 & 0.0150 \end{bmatrix}, \qquad (14)$$

$$K_w = \begin{bmatrix} 0.0136 & 0.0058 & -0.0020 \\ -0.0007 & 0.0063 & 0.0134 \end{bmatrix}.$$

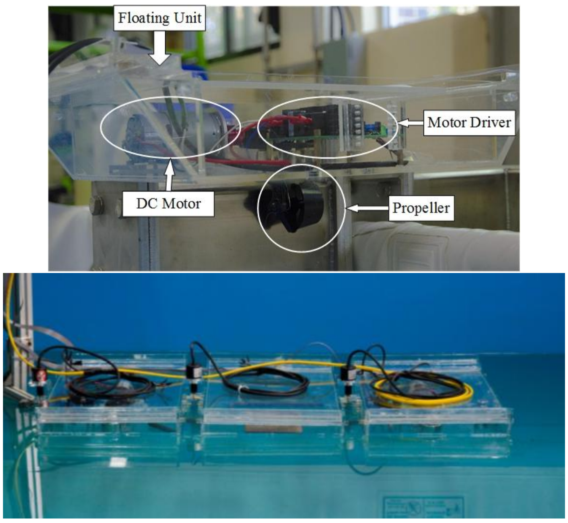
The designed controller and state estimator are verified by several simulations. Consequently, the obtained results are applied to a real experiment system and the experimental results will be discussed in the next section.

IV. EXPERIMENTAL RESULTS

In this section, the authors present and discuss the experimental results obtained by applying the previous mentioned controller and observer design when the controlled system is exposed to wave disturbance. To do this task, the experimental apparatus is set up as shown in Fig. 5 where L=250[mm], W=440[mm], H=80[mm], and weight of vessel unit is 3.79[kg].



(a) System configuration and specification of floating bridge unit.



(b) Experiment apparatus made by 3 floating units

Fig. 5. The floating bridge system for experiment.

As can be seen from above figures, there are two active bays (first and third floating unit) in which the electric power propulsion systems are installed, and the second one is the passive bay without the power propulsion system. Each active bay is equipped with a DC motor, motor driver and a propeller that can be generated controllable force to move the bay forwardly and backwardly. In addition, the yaw angle alteration of all three bay are measured by three incremental encoders. Besides, to illustrate the actual operation of the bridge system, a continuous wave attack is considered in this study.

Assuming that the target is to keep the bridge system at the desired position, for instance, the crossing line of the river. It is required to maintain the bridge position and the linearity along the multiple connected floating unit under the wave attacks as the external disturbances as can be seen in Fig. 6.

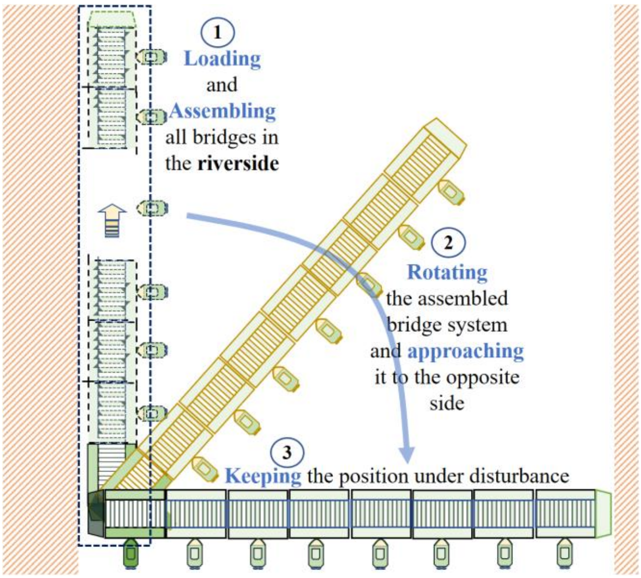
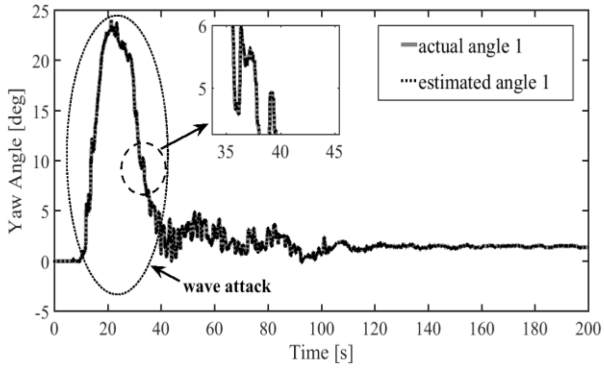
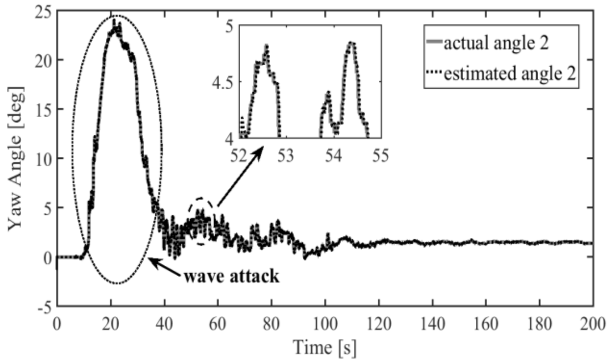


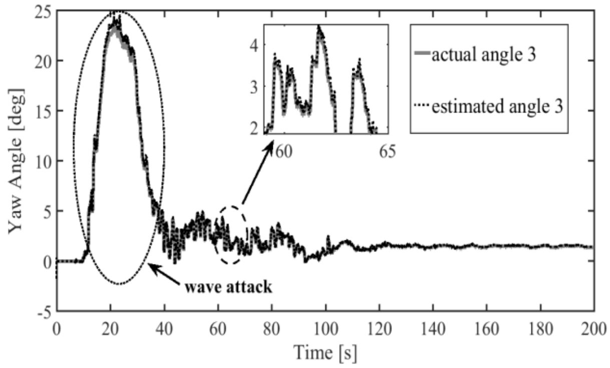
Fig. 6. The strategy of ribbon bridge installation.



(a) Controlled output (yaw angle of #1 unit)



(b) controlled output (yaw angle of #2 unit)



(c) controlled output (yaw angle of #3 unit)

Fig. 7. Controlled yaw angles under continuous wave disturbance.

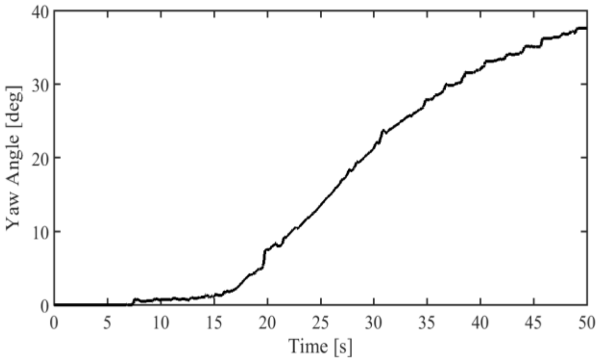


Fig. 8. Yaw motion under continuous wave disturbance without control action.

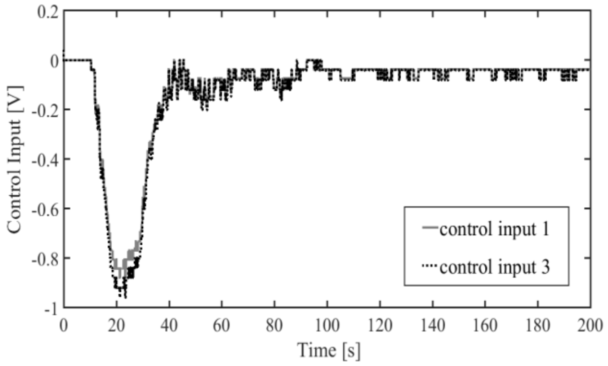


Fig. 9. The control input voltages to the propulsion systems (#1 and #3 floating units).

It can be seen from Fig. 7 that the yaw angle of each floating unit is affected by the strong wave attack and the controller can quickly cope with the disturbance to drive the bridge back to the initial and desired position. Fig. 8 indicates that without controller, under the similar wave attack, the bridge is kept moving away from its initial position. Besides, Fig. 7 also shows the relatively good accuracy of our designed state estimator. The control inputs provided to the propulsion systems is shown in Fig. 9.

The above results confirm that our control strategy based on the observer for bridge installation and position keeping has significant feasibility for the system of multi-connected pontoon floating bridge.

V. CONCLUSION

In this study, the authors present a control strategy that can be applicable for installing the pontoon floating bridge constructed by a number of floating units.

The controller is designed based on observer to estimate the unmeasurable states in order to keep the linearity of the whole system and desired position whether the continuous disturbance appears or not.

The given results from numerical investigation and experimental study confirm that the abovementioned control strategy is applicable for position displacement control and installation of floating bridge system automatically for high speed and especially safety purposes.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (Ministry of Education) (No. NRF-2015R1D1A 1A09056885).

Also, this work was supported by the Innopolis Foundation of Korea (Busan Innopolis) grant funded by the Korea Government (Ministry of Science and ICT) (Title: Development of Movable Fender Practical Technology, No.17BSI1008).

REFERENCES

[1] Improved Ribbon Bridge, General Dynamics, 2012.

[2] S. Fu and W. Cui, "Dynamic response of a ribbon floating bridge under moving loads," Marine Structure, vol.11, pp. 29-46, 1998.

[3] Y. Hirono, Y. Mizuchi, Y. B. Kim and Y. W. Choi, "Positional displacement measurement of floating units based on aerial images for pontoon bridges," Lecture Notes on Electrical Engineering, Springer, vol. 415, pp. 309-318, 2016.

[4] V. T. Nguyen, M. S. Choi and Y. B. Kim, "A study on automated ribbon bridge installation strategy," Journal of Institute of Control, Robotics and Systems, vol. 23, no. 8, pp. 661-666, 2017.

[5] T. I. Fossen, Marine Control System, Trondheim, Norway, 2002.

[6] Y. B. Kim, H. H. Jeong and J. H. Yang, "Tracking control system design for the transfer crane: design of full-order observer with weighted H_∞ error bound," Journal of the Korean Society for Power System Engineering, vol. 12, no. 6, pp. 42-49, 2008.

AUTHOR BIOGRAPHY

Van Trong Nguyen received the B.S degree at Thai Nguyen University of Technology, Viet Nam in 2012 and M.S in Mechanical System Engineering at Pukyong National University, Korea in 2016 where he is now pursuing Ph.D degree. His research interests include marine system control and applications.

Young-Bok Kim received the B.S. and M.S. degrees in maritime engineering from National Fisheries University of ㅠusan, Busan, Korea, in 1989 and 1991, respectively, and the Ph.D. degree from Kobe University, Kobe, Japan, in 1996. He is currently a Professor with the Department of Mechanical System Engineering, Pukyong National University, Busan, Korea. He is member of ICROS, ASME, KSME and senior member of IEEE. His research interests include control theory and application with dynamic ship motion control and crane control system design, etc.

Sang-Won Ji received the B.S. degree in mechanical system engineering from Pukyong National University, Busan, Korea, in 2004, and the M.S. and Ph.D. degrees in Control & Mechanical Engineering from Pukyong National University, Busan, Korea, in 2006 and 2009, respectively. He is working for Korea Construction Equipment Technology Institute as a senior researcher. His research interests include fluid power system design and control.