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A Comparison Study of Underwater and Land Flexible Manipulators

Abstract*-New results for experimental comparison of flexible underwater and land manipulator have studied in this research. A new experimental rig and test basin have designed to present the manipulators behavior. Several electronic devices used to capture the data that relates with land and underwater manipulators. Experimental parts have consisted on studying of hub-angle and vibration of end-point as in-line forces affection under static and moving waters conditions as a distributed flow speeds. The experimental outcomes appeared that the in-line forces influence on land manipulator case is more than the underwater manipulator. The outcomes revealed that angular displacement influence and vibration at the end-point of the land manipulator is unlike with underwater manipulator at disturbance cases about 80% and 59% for the first amplitude respectively while, very few vibration has been recorded for underwater manipulator behavior at static and moved waters after first amplitude compared with land manipulator.*

Keywords*- Flexible Land Manipulator, Underwater Manipulator, In-Line force, Vibration, Hub-Angle, Vortex.*

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1. Introduction

Robot manipulator are designed to help the human increase the productivity as well as avoiding unwanted problems relate environment beside another problems [1]. The manipulators are utilized in the industrial processes for instance grinding, sensors, material handling systems, drilling, painting, instrumentation, coating and vehicle systems [2-3]. On the other hand, many other applications concerned by underwater manipulators such as underwater welding, underwater pipeline examination and installation, finding out the coral reef, and employing to set the valves in a nuclear power plants [4-5]. Nowadays, many other applications concerned by robot manipulator for example in surgery and space applications. Robot manipulators are divided depending on the link material type which are; rigid in additional to flexible and hybrid systems [6]. Rigid manipulators are concerned with heavy materials in order to obtain a stable action leads to control the manipulator vibration. But, the heavy weight, installing and maintenance costs, in additional to slow tracking, low performance and other reasons considered not preferred in spite of its still using in many applications. Therefore, the attempts are still interesting by researchers to use the flexible materials [7-8]. Nowadays, the industrial applications trend to shad of the bodies' weight in many applications for instance aircraft and medical applications. In addition, decreasing the cost is considering one of the important matters by using light materials [8-9]. With a view to enhance the performance of rigid robot manipulator, the focusing on lightweight and flexible manipulators have increased in recent years [10]. The advantages of flexible manipulator are pushed the researchers to prefer the flexible on rigid manipulators because of high performance, lightweight, quick response, longer access, low cost as well as safer and easy to transport it in spite of the lightweight leads to serious vibration problems when subjected to disturbance forces [11]. Several researches have studied the land manipulator that related with the manipulators modelling in additional to control it [11-12]. However, no researches concerned with studying of flexible underwater manipulator (FUM) system. Because of the flow leads to complicated forces, is important to define how many forces face the FUM in this research. Before presenting the forces, it should be known that the manipulator movement is coming from the torque that provided from the motor [13]. However, several forces have been observed by previous researches effect on FUM, which are; lift, drag, buoyancy and gravity forces [13-14]. It can be divided the hydrodynamic forces that effect on submerged pipe or cylinder underwater

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into two forces, which are; in-line and transverse forces. Transverse forces are forces that lead the body to move in the perpendicular direction of water flow, which called also, lift forces. While, In-line forces are forces that lead the body to move in the parallel direction of water flow, which called also drag forces as shown in Figure 1 [15].

2. Manipulator Model

Modelling of flexible manipulator has been represented previously using finite element (FEA) as well as Lagrangian methods as shown in Figure 2 [8-9]. Modelling steps are consisting of three stages. The first stage is analyzing the system using FEA then, method of steady space (SSM) using to represent the system and finally estimate the outcomes [8]. The beam specification is l represents the length and I represents the inertia while, q represents the torque that leads to make the motor rotate for hub, m is represents the mass, E refers to Young Modulus and ρ refers to the mass density [9]. The beam rotates between moving and stationary coordinates x, y and $\bar{x}, \bar{y}$ respectively, with small angle θ as an angular displacement and lead to deflect the beam by u. The total displacement refers as Z where,

$$Z(x,t) = x\,\theta(t) + u(x,t) \tag{1}$$

Using FEA, the equation above become:

$$u_n(x,t) = S_n(x)\, r_n(t) \tag{2}$$

S_n and R_n are represent function shape and displacement. After using i as constant number which equal to 1, 2, 3,….N, the kinetic energy (K.E) become:

$$K.E_i = \frac{1}{2}[r_n]_i^q\, [m_n]_i\, [r_n]_i \tag{3}$$

Final representation of K.E is:

$$K.E = q + \sum_i^N q_i + q_P = \frac{1}{2} r_n^q\, \dot{m}_n\, \dot{r}_n \tag{4}$$

The potential energy (P.E) introduced by FEA and be represented by:

$$K.P_i = \frac{1}{2}[r]_i^q\, [k_n]_i\, [r_n]_i \tag{5}$$

Final representation of P.E is:

$$K.P = \sum_i^N K.P_i = \frac{1}{2}\dot{r}_n^q\, \dot{k}_n\, \dot{r}_n \tag{6}$$

Using the Lagrangian approach, derivation of equation of the system become:

$$K.E - P.E = \frac{1}{2}\dot{r}_n^q\, \dot{m}_n\, \dot{r}_n - \frac{1}{2}\dot{r}_n^q\, \dot{k}_n\, \dot{r}_n \tag{7}$$

All derivation of the system modelling was be found in [6]. The Final equation that represent the system after using SSM become:

$$A = \begin{bmatrix} B_{n_1} & \vdots & I_{n_1} \\ \cdots & \cdots & \cdots \\ -m^{-1}k & \vdots & -m^{-1}D \end{bmatrix},\ B = \begin{bmatrix} B_{n_1} \\ \cdots \\ m^{-1}c \end{bmatrix},$$

$$C = [B_{n_1} \;\vdots\; I_{n_1}] \text{ and } F = [0_{2n_{1*1}}] \tag{8}$$

$B_{m_1}$is zero matrix, I_{n_1} is identity matrix, $B_{2n_{1*1}}$ is an n_{1*1} zero vector, and c is a vector inside the first identity matrix column.

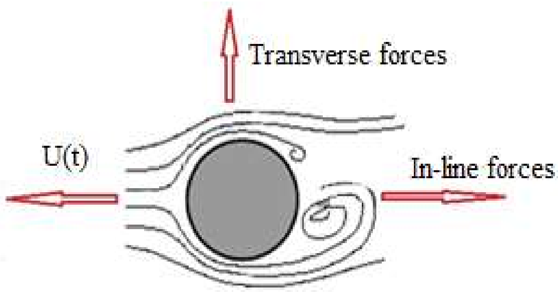


Figure 1: Hydrodynamic forces Schematic [13]

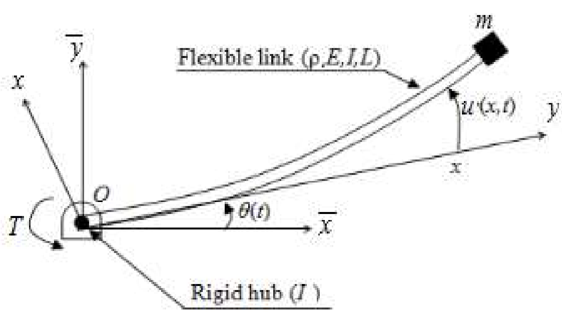


Figure 2: FUM schematic [9]

3. System Hardware

The system presented in this paper as a mechatronic system that consists of electric component, mechanical parts and computer control integrations. Firstly, the mechanical parts have designed. Then, the electrical components were selected based on the environmental properties of the underwater system.

I. Mechanical System

The diagram shown in Figure 3, states the mechanical component of rod, frame, motor case and manipulator model of the system. On the other hand, the real tank of testing including the mechanical parts is depicted in Figure 4. The emulation for underwater environment is included for the manipulator system. To handle the devices and components of the mechanical parts, rigid frame of aluminum is made with a rectangular shape. The function of motor case is to hold the encoder and motor that made from aluminum plate with thickness dimension of 0.3 mm. The properties of the hollow pipe were 85 cm as length with 1.8 cm as inner diameter and outer was 2 cm with 1.225 g/cm3 material density and 17.41 MPa as a yield strength. Importantly, the presented system follows the works in previous literature [16-17] with 85 cm as a length in order to study the flexible model advantages to access the far positions. It is important to remark that the flexibility of the manipulator is coming from the end-point vibration test experimentally and not from the diameter and thickness ratio. According to the environment conditions of underwater system model, the basin is constructed in rectangular shape with of 8 m, 1 m and 0.7 m for length, wide and height respectively, that made from aluminum sheet and covered by glass with thickness of 12 mm as shown Figure 4. An aluminum profiles with different dimensions are used to frame the glass tank's outer structure. In order to make the water circulation, the tank has divided into two parts in additional to submersible pump has been used. In order to generate different velocities of current flow through submersible pump, a controller is equipped with the pump to tackle this process. Inverted electrical box is used to control the flow velocity and deeper information of such test can be explored in [18].

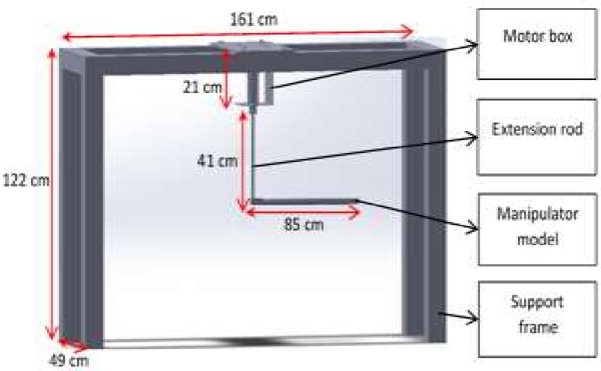


Figure 3: Mechanical components for FUM model

Figure 4: Actual test basin

II. Electrical Components

In addition to the mechanical components employed in this paper, many electrical and electronic parts are used for instance accelerometer, DC motor to rotate the manipulator rig, driver, data acquisition device (DAQ) and encoder. Maxon type DC motor with 40 mm shaft diameter (Ø) and 150 Watt is used in the design. Many properties are taken in consideration to choice the motor driver. ESCON 50/5 servo controller by Maxon is selected due to its small size, lightweight and the powerful performance to control the motor. This controller provides three characteristic modes namely current, open and closed loop controls. The software package of ESCON Studio is used to change the operating mode and controller configuration. The motor's angular position measured using HEDL-5540 encoder with closed-loop control ability. A submersible accelerometer model 3217A by Dytran Company is used to obtain the vibration of end-point from the link with lightweight of 5 g. This device can be used underwater with water pressure of 1.206 MPa and 100 mV/g sensitivity with measuring range of 50 g. BNC connector module SCB-68 of DAQ is used to ease the connection of the accelerometer.

DAQ model PCI-6259 from National Instruments (NI) is used to handle the input and output data through SCC-68 connector model with MATLAB Program interfacing. The pin out configuration includes 16 input analog channels and 2 output ports. The input and output of digital data are represented by 24 channels. The sampling rate of the system is 1.25 MSamples/s for voltage range of input equal to ± 10 V.

4. Water Flow System Description

Water's circulation conception is used to generate many water flow disturbances by a submersible pump model L-63 with horizontal orientation to face the system of the manipulator. However, generating different water flow speed by the pump was challenging issue. For this reason, inverter model ABB–ACS550–01–012A–4 is employed as depicted in Figure 5. This inverter can control the frequency of pump manually with range of frequency of 0-50 Hz. For measuring the speed of water inside the basin, a Vernier Sensor DAQ from NI has employed. The other information of Vernier sensor and DAQ system have clarified in [18]. In order to measure the flow rate, a propeller has been employed and working on sending the signal to the PC through the Vernier data acquisition system and LABVIEW program (Sensor DAQ module) as shown in Figure 6.

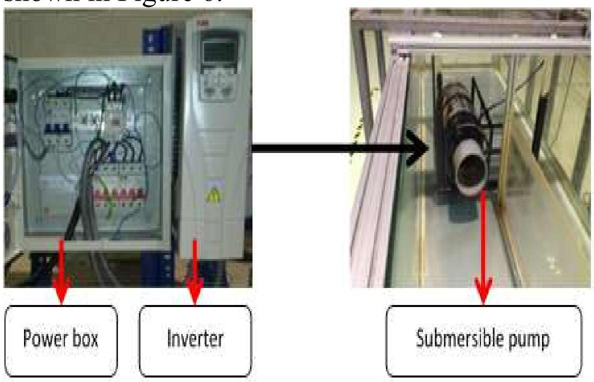


Figure 5: pump speed control schematic

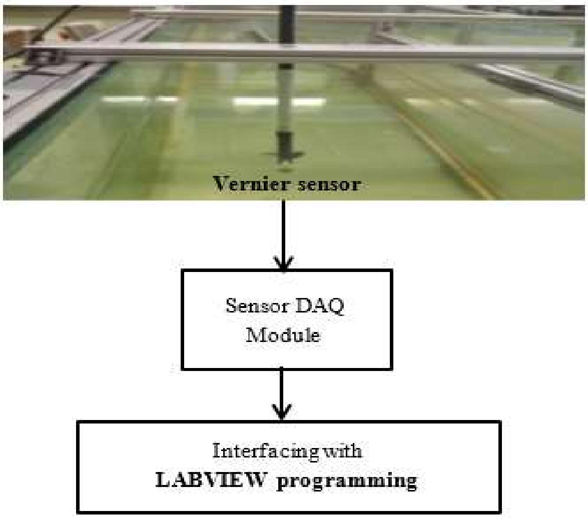


Figure 6: schematic of flow data collecting

5. Experimental Setup

As shown in Figures 7 and 8. FUM consists of a single-link with DC motor through an extension rod in order to put it inside the basin. After applying the torque signal, DC motor receives the signal by motor driver that leads to move the manipulator as angular displacement. Then, the encoder senses these displacements and record it by MATLAB Program. On the other hand, the torque as input signal working on vibrating the link with additional sudden change such as water currents and be measured by submersible accelerometer that placed at the end-point of the link. Figure 9 presents the manipulator model position inside the test area of the basin. Submersible pump is selected in order to study the effect of the water currents on manipulator system.

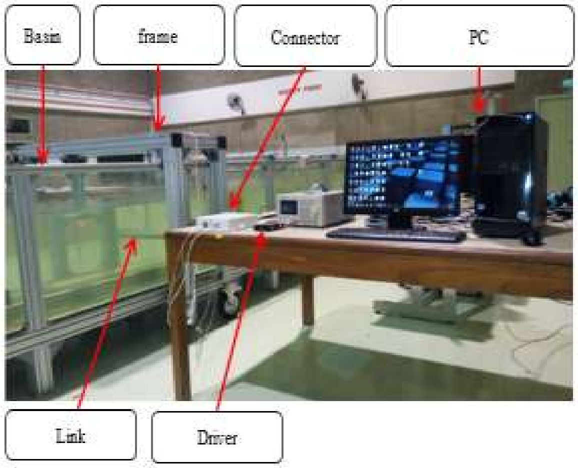


Figure 7: Experimental setup

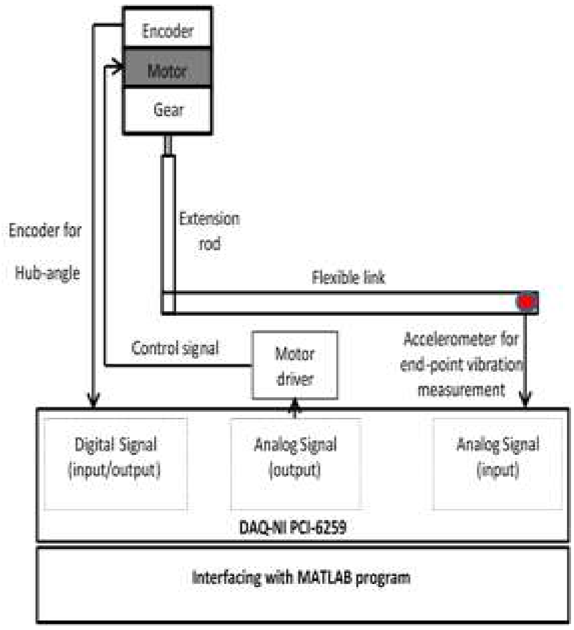
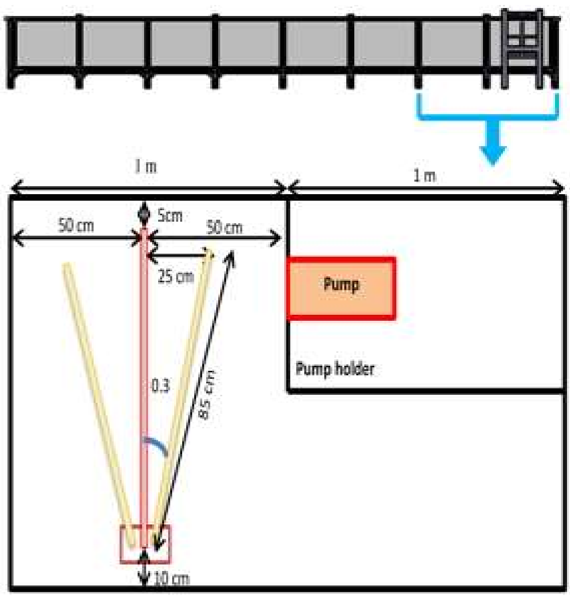
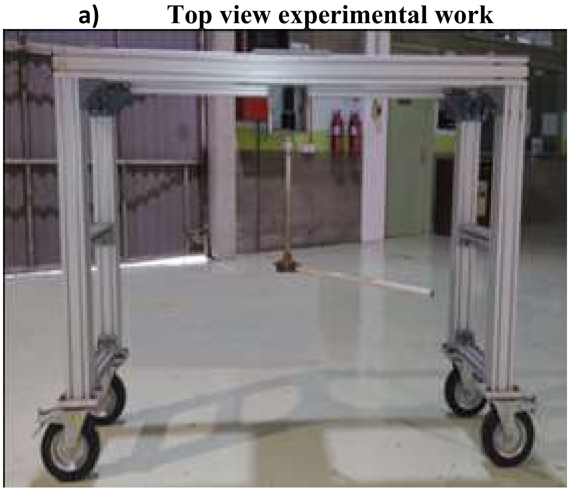


Figure 8: FUM diagram with interfacing devices



a) Top view experimental work



b) Actual manipulator system

Figure 9: Top view and actual experimental work

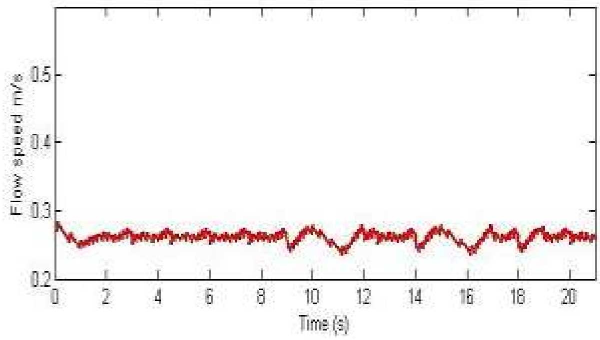
6. Experimental Setup Verification

Several researchers have studied the land manipulator as a flexible link material [10-13]. However, no experimental and simulation implementation have been recorded based on FUM system to study hub-angle and vibration effect of end-point under different water speed. Therefore, this research focusing on studying the influence of hydrodynamic forces on hub-angle as well as vibration of end-point whether for land or underwater conditions. Also, fix and disturbance waters have conducted for FUM system.

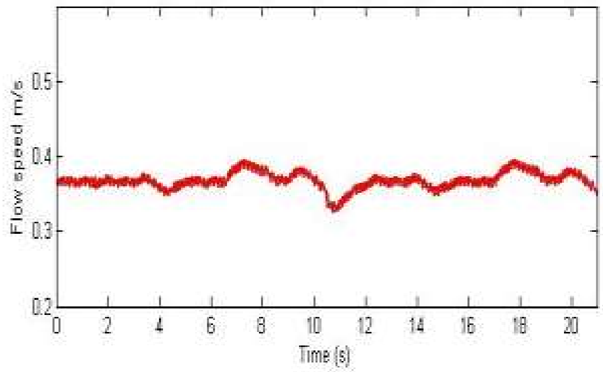
7. Results and Discussion

I. Flow results

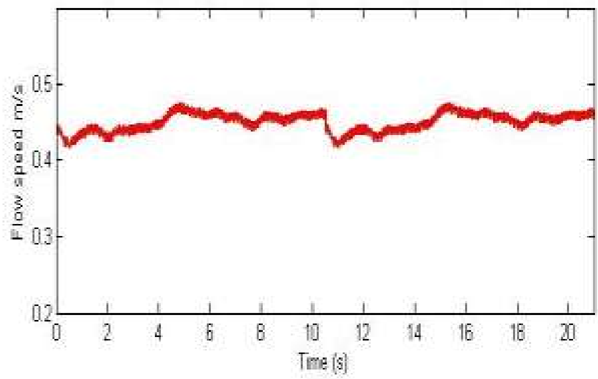
In the beginning, determination of water speed be important to specify the influence of water speed changing on FUM. Range of pump frequency are 0 to 50 Hz and controlled it by ABB inverter. No affection has been observed of angular displacement at disturbances speed below 11 Hz. In addition, water speed control is done through ABB inverter that convert the voltage to the pump from AC to DC then AC again. ABB inverter leads to control the pump power to get different power and different water speed as a result. However, at larger disturbances, the angular position was increases as the speed increasing. Therefore, three cases were presented in this work ranged between 12 to 14 Hz as pump frequency. The sampling rate was 100 data for 21 minutes.



a) Frequency at 12 Hz equal to flow speed range 0.23-0.28 m/s



b) Frequency at 13 Hz equal to flow speed range 0.32-0.39 m/s



c) Frequency at 14 Hz equal to flow speed range 0.41-0.47 m/s

Figure 10: Water flow speeds

II. Influence of In-Line Forces

Several works have accomplished to show the in-line forces influence for hub-angle and vibration of end-point whether land or FUM under static and moved water using MATLAB program as shown in Figure 11. The input signals was represented as a pulse signal equal to 1 V during 20 sec at 0.01 sec for sampling rate of hub-angle in addition to vibration of end-point.

Figure 12 presents the response outcomes of hub-angle for land manipulator as well as FUM under static and moved water conditions. The first observation was the value of hub-angle for land case was 1.16 rad while, 0.23 rad has recorded for FUM under static water condition. Therefore, it is clear to say that the hub-angle of land manipulator is much greater than the FUM under static condition about 80 %. Another observation was the manipulator performance under moved water at disturbance flow 12 Hz. The results revealed that the angular displacement of the FUM was unsteady where; 0.15 rad was recorded for angular displacement at 1.68 sec and fixed until 8.45 sec. Then, these value was changed during 20 sec and amounted to 0.468 rad. The reason was the affection of moved water and in-line forces. In addition, no observation has been recorded for land manipulator behavior with small changing compared with FUM under static water. Where, at 2 sec until 20 sec the behavior of the FUM under static water was linear for hub-angle. The reason is due to the high damping for water that surrounding the manipulator while, the current speed working on changing this behavior in underwater disturbance case that lead to get more power to the motor to exceed the water resistance. Therefore, it is necessary to focus on hub-angle changing under moved water for FUM system and finding a proper controller to adjust this phenomenon.

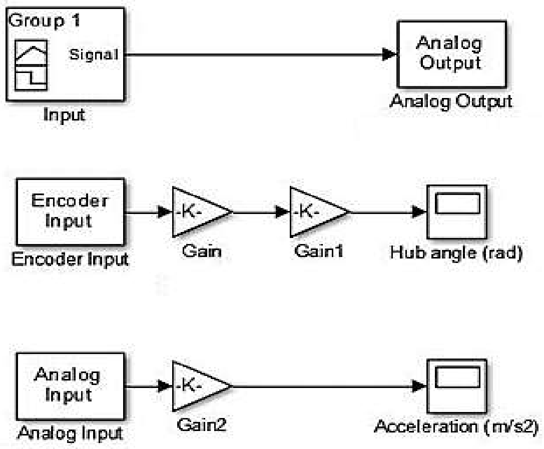


Figure 11: MATLAB block diagram

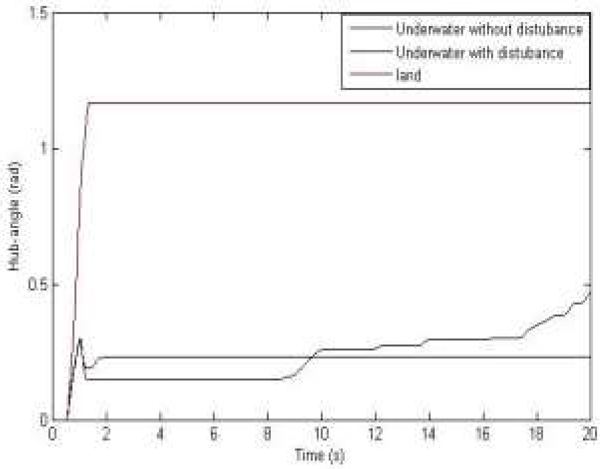


Figure 12: Hub-angle behavior for land and FUM model

The second important notice that relates with vibration phenomenon was the response of end-point for land and FUM for both static and moved waters as shown in Figure 13. For land manipulator, the max peak value of vibration has recorded 14.5 m/sec. As a result, a few vibration of FUM at static water case has noted especially after peak value of vibration. High damping for water was the reason behind these results. the vibration resulted about 6 m/sec2 (based on peak value) which equal to 59% compared with land manipulator with low attenuation after 2.1 sec cause by hub-angle position changing for moved water state. Thus, the vibration after 2.1 sec was near to be zero and no need to make a great effort compared with hub-angle problem. In order to study more cases, several disturbance flow were implemented to show FUM behavior for hub-angle. It was observed that no affection on hub-angle and vibration for FUM performance under disturbance frequency between 0-11 Hz. Thus, 12-15 Hz as disturbance frequency of water flow speeds were selected in this part as shown in Figure 14. For 20 secs, the hub-angle results have been recorded under different water speeds with 0.01 sec as a sampling rate. The values of hub-angle have started from 00 to -700 due to counter clockwise of manipulator rotation and varied based on disturbance flow. At disturbances flow 12 Hz, the results appeared that the manipulator motion be affected by the disturbance flow and this effect increases with the disturbance flow increasing. Also, the water resistance plays a big role on manipulator motion. Thus, the behavior of manipulator be fixed sometimes at 12 Hz and changed with flow increasing for other disturbance flow values. As a result, the hub-angle has changed by the in-line forces and the high disturbance works on to the higher movement for hub-angle.

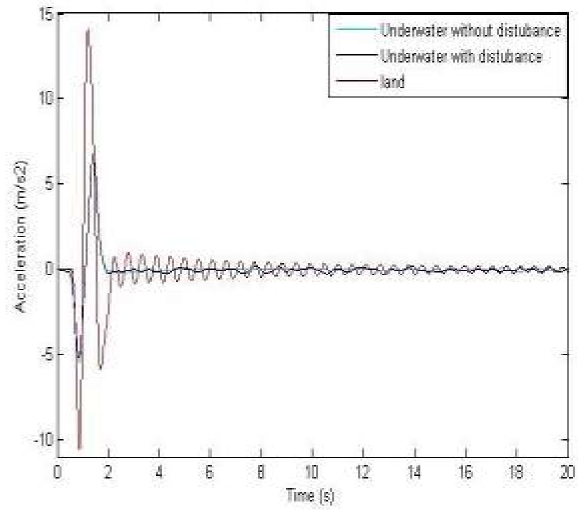


Figure 13: vibration behavior of land and FUM model

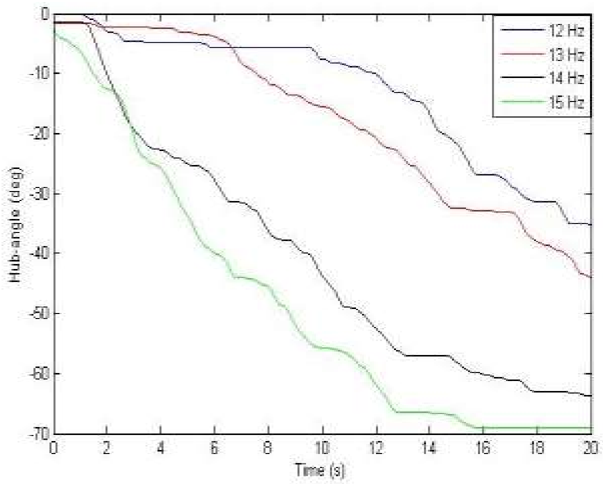


Figure 14: Behavior of Hub-angle under disturbance flow

8. Conclusions

New experimental outcomes have presented the comparison between the land and FUMs with considering of the hub-angle performance and vibration of end-point influences under several water flow speeds. After designing the tank, the influence of land and FUM depending on hub-angle and vibration of end-point have conducted. In addition, FUM with stationary water and FUM with moved water has considered. For same torque as input signal, the outcomes of hub-angle in case of land manipulator was bigger compared with FUM about 80% at disturbance flow 12 Hz. Also, the angular displacement of the FUM in moving water case was changed due to the in-line forces of disturbances. On the other hand, the vibration at end-point of FUM was near the zero value after first amplitude value it can say that a few vibration has be recorded due to the damping water effect while the difference between land and FUMs based on first amplitude recorded about 59%. Moreover, angular displacement of the FUM was different influence by the drag forces due to the vibrations of end-point at peak disturbance frequencies that leads to the bigger motion of hub-angle. A new donation in this work is to focus on land and FUMs differences. For land manipulator, not difficult to set the hub-angle by a traditional or intelligent controller while, the big challenge was the vibration. Otherwise, the big challenge faces the FUM is hub-angle control. However, the FUM behavior was reversed of land manipulator. The vibration of end-point for FUM is near to be zero after first amplitude.

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