Modelling and Simulation of an Artificial Tide Generation System

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Abstract:
In this paper we consider a small-scale experimental apparatus that allows to reproduce and understand phenomena in large-scale typical lagoonal environments and to draw inferences about channel network ontogeny and evolution. In particular, the device reproducing the artificial tide is the core of the experimental apparatus and it is controlled in real-time to satisfactorily reproduce the natural phenomena. The experimental apparatus has an intrinsic complexity and it represents an example of a multi-domain physical system (electrical, mechanical, and hydraulic). In order to design and to assess suitable control strategies, we develop a Matlab-based simulation environment which is able to reproduce the behaviour of the artificial tide generation system. In particular, we use a hybrid modelling technique which integrates casual and acasual approaches. Finally, the dynamic model is calibrated and validated by using real experimental data. The developed model represents a good trade-off between accuracy and complexity and it is useful for control system development purposes.

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1. INTRODUCTION

Tidal systems are fragile and interesting environments based on a delicate balance between sediment transport and hydrodynamics. Understanding the main processes that underlie the formation and development of tidal networks is necessary to address issues of conservation of these habitats, exposed to the effects of climate changes and human interference. In a tidal system the primary external forcing is represented by the tide. The greatest difference between tidal networks and their fluvial counterpart is that they are forced by a bidirectional flux. Indeed, the velocity is direct towards the land during the flood and towards the sea during the ebb. Therefore a difference between the velocity experienced during the two phases of the tide has an important influence on the morphology of a tidal environment. This difference is referred as tidal asymmetry and can be described using the ratio \( p_s \) between the flood peak and the ebb peak of the cross-sectionally averaged velocity (Tambroni et al., 2017). Towards the goal of gaining further knowledge of some of the physical processes responsible for tidal network development under certain condition, in particular tidal asymmetries, we set up an experimental apparatus, schematizing a back-barrier lagoonal environment subject to tidal forcings (Stefanone et al., 2010).

It is worth highlighting that, the chance to conduct meaningful in-scale experiments relies significantly on the behaviour of the artificial tide, that has to exhibit predefined characteristics. To this aim, the height of the artificial water wave has to be controlled in real-time. Nowadays, it is a common practice in the design of advanced control systems, to make extensive use of Computer Aided Control Systems Design (CACSD) software tools (Chin, 2017; Beghi et al., 2017). These tools allow to simulate the relevant system dynamics, for a first assessment of the different control strategies. In order to setup a useful simulation-centric control system design project, there is a preliminary step to be taken into account, namely the derivation of a dynamic model (which translates certain interesting properties of the real system into mathematical equations) of the system to be controlled. In order to develop an effective model we need to knowledge the domain expert’s (i.e. the actual knowledge of the process and its properties) and the knowledge engineer’s (i.e. how the process functioning and its properties can be transferred into a useful model) (Ljung and Glad, 1994).

It is worth noticing that, the considered artificial tide generation apparatus is a non-trivial system from a modelling point of view. Basically, it includes a water pump and a vertical sharp-edge weir, which oscillates vertically thanks to a stepper motor. The artificial apparatus represents an example of a multi-domain physical systems (electrical, mechanical, and hydraulic). The system exhibits non-linear behaviours with fast dynamics (e.g. the electro-mechanical sub-system) and slow dynamics (the hydraulic sub-system), plus dead time (due to the water mass transport). On the other hand, new technologies provide new opportunities for modelling and simulation. In this paper, we exploit the...
potential offered by a hybrid approach that combine the traditional causal (i.e. block-oriented) modelling approach with the acausal (i.e. declarative) one (Kofranek et al., 2008). Beside this, these tools enable physical modelling of multi-domain physical systems. In particular, we develop a Matlab-based simulation environment for the artificial tide generation system by means of Simulink causal block diagram and Simscape acausal components (Dingyu Xue, 2013; Ramin S. Esfandiari, 2014). The model has been calibrated by using real data which have been gained from real experiments in the physical model. Several tests have been conducted on the experimental apparatus which show that the simulation tool is able to reproduce the relevant system dynamics.

The paper is organized as follows. In Section 2, the experimental apparatus is depicted. Section 3 is devoted to the system modelling, and to the model calibration and validation. Examples of simulation are shown in Section 4. Some conclusions and remarks are drawn in Section 5.

2. EXPERIMENTAL APPARATUS

To reproduce a typical lagoonal environment we have used a large indoor apparatus, that is schematically depicted in Fig. 2. The system includes two adjoining basins representing the sea and a back-barrier lagoon (the plant view Fig. 2a). A section of the apparatus is shown in Fig. 2b, while Fig. 2c depicts the lagoon basin and the pantograph. The ultrasonic probe and the recirculating tank are shown in Fig. 2d. The lagoon basin is 5.3 m long and 4.0 m wide, while the much deeper adjacent sea basin is 1.6 m long and 4.0 m wide. The sea is separated from the lagoon by a barrier of wooden panels, which can be moved to create inlet with different shape and position and a shelf enable us to represent the gentle slope of the sea bed in front of the lagoon. During the experiments, the lagoon is covered with a layer of sediments made of cohesionless plastic grains. The tide is generated at the sea by the combined action of a pump and a vertical sharp-edge weir, which is moved by a stepper motor and oscillates vertically. The water continuously flowing over the weir is collected in a separate tank, where the pump recirculates the flow. The apparatus is equipped with two ultrasonic probes that provide a measurement of the water level in the sea, a potentiometer to measure the position of the weir and a computer driven pantograph to survey the bed elevation within the lagoon. It is worth highlighting that, the wave generated at the weir does not maintain its form during the propagation to the lagoonal inlet, because of inertia. This is the reason why the tidal wave cannot be imposed in the section of the
while the much deeper adjacent sea basin is 1

To reproduce a typical lagoonal environment we have used

by a stepper motor and oscillates vertically. The water

of a pump and a vertical sharp-edge weir, which is moved

lagoon. During the experiments, the lagoon is covered with

a barrier of wooden panels, which can be moved to create

in Fig. 2d. The lagoon basin is 5

representing the sea and a back-barrier lagoon (the plant

in Fig. 2. The system includes two adjoining basins

a large indoor apparatus, that is schematically depicted

Some conclusions and remarks are drawn in Section 5.

calibrated by using real data which have been gained from

diagram and Simscape acausal components (Dingyu Xue,

multi-domain physical systems. In particular, we develop

Fig. 1. Example of tidal meanders in the Venice Lagoon

which are shifted seaward with respect to the apex

why the tidal wave cannot be imposed in the section of the

weir does not maintain its form during the propagation to

modifies because of inertia (i.e. it reduces the amplitude and

experiences a time delay). Therefore, the signal imposed at

the weir, does not overlap the signal in front of the lagoon.

A block diagram of the system is depicted in Fig. 3. In

broad terms, the system can be outlined as two sub-systems

that interact with each other in a structured manner:

- the electro-mechanical sub-system, which includes: the
  driver, the stepper motor, the worm gear, the lead-
  screw, and the sharp-edge weir;
- the hydraulic side sub-system, which includes: the
  water, the sea, the shelf, the lagoon, and the water
  pump.

In order to conduct meaningful in-scale experiments, which

relies significantly on the characteristics of tide, the water

level at the sea is controlled by manipulating the stepper

motor position, which in turn, determines the sharp-edge

weir height position, while the water pump is set to a fixed

flow rate.

3. MODELLING

In this paper, we design a model-based simulation environ-

ment for the artificial tide generation system to preliminary

asses different control algorithms. To this aim, it is a

common practice to build a mathematical model of a

complex system like the considered experimental apparatus

by aggregating sub-models of its constituent parts, i.e.

by using a modular modelling approach. From this point

of view, two options are generally available: causal (or

procedural) approach and acausal (or declarative) one. It is

worth highlighting that, the causality can explain the evolu-

tion which was in the past declared as the evolution from

block oriented tools into object oriented tools. In the first

approach, one assumes that a system can be decomposed

into block diagram structures with causal interactions, the

model is described in a form which is close to the numerical

solution algorithm and the interaction between the models

is formalized in terms of input and output variables. In this

way, it is rather straightforward to simulate elementary and

aggregate models. On the other hand, often a significant

effort in terms of analysis and analytical transformations is

needed to obtain a problem in this form (e.g. the equations

would be converted to ordinary differential equations,

ODEs, form manually). Furthermore, the causal model

exhibits low re-usability and the corresponding code may

be difficult to read or modified a posteriori. Conversely, in

the acausal approach, the model is described by equations

in a context-independent form, without caring about the

actual solution algorithm (equations are represented as

acausal implicit differential algebraic equations, DAEs).

It is worth noticing that, in nature real systems are

acausal. Furthermore, the interaction between the models

is formalized in terms of connection equations without any

specification on causality. The acausal approach exhibits

both high re-usability and high readability of the basic

models. On the other hand, it is more difficult to go from the

mathematical model to the numerical simulation algorithm.

It is worth highlighting that, each of the aforementioned

approaches has its intrinsic advantages and disadvantages.

In this paper, we want to exploit the advantages provided

by both approaches and so a mix of causal and acausal

models are used. In particular, we develop a Matlab-based

simulation environment for the artificial tide generation

system by means of Simulink and Simscape components.

In traditional Simulink block-oriented tools (causal), the

signals are transmitted through links between individual

blocks and they serve to transfer values of individual

variables from the output of one block to the inputs of

other blocks. Input information is processed in the blocks

to output information and the interconnection of blocks

reflects both the structure of the modelled real system and

the calculation procedure (Perelmuter, 2017). Conversely,

Simscape lets use and define components as textual files,

complete with parametrization, physical connections, using

DAEs.

In the following, the main physical components of the

systems, such as the electro-mechanical sub-system and

the hydraulic one are modelled by means of Simscape

blocks, while the control systems are modelled by means

of traditional Simulink causal blocks.

3.1 Electro-mechanical sub-system

The experimental apparatus is composed by the following

main electro-mechanical components: a driver, a stepper

motor, a worm gear coupled with a lead-screw, and a sharp

edge-weir.

Fig. 3. The electro-mechanical sub-system main components are: the driver and the stepper motor, the worm gear with

the lead-screw, and the sharp-edge weir. The hydraulic sub-system includes mainly: the sea, the lagoon, the water,

and the water pump. The water level in the sea $y$ is controlled by manipulating the stepper motor position $u$. The

stepper controller (highlighted by the red coloured dashed-line) is modelled by means the causal approach while

the electro-mechanical and hydraulic sub-systems (highlighted by the blue coloured dashed-line) are modelled by

using the acausal approach.
By way of an example, we show the dynamic equations model (1) that reproduce the behaviour of the electric motor, where $e_A$ and $e_B$ are the back emfs induced in the A and B phase windings, respectively, $i_A$ and $i_B$ are the A and B phase winding currents, $v_A$ and $v_B$ are the A and B phase winding voltages, $K_m$ is the motor torque constant, $N_r$ is the number of teeth on each of the two rotor poles. $R$ is the winding resistance, $L$ is the winding inductance, $B$ is the rotational damping, $J$ is the inertia, $\omega$ is the rotor speed, $\theta$ is the rotor angle and $T_d$ is the detent torque amplitude. The nominal values of the main parameters of the stepper motor are shown in Table 1.

$$e_A = -K_m\omega \sin(N_r \theta),$$
$$e_B = -K_m\omega \cos(N_r \theta),$$
$$\frac{di_A}{dt} = \frac{(v_A - Ri_A - e_A)}{L},$$
$$\frac{di_B}{dt} = \frac{(v_B - Ri_B - e_B)}{L},$$
$$T_e = J \frac{d\omega}{dt} + B\omega,$$
$$T_e = -K_m(i_A - \frac{e_A}{R_m})\sin(N_r \theta) + K_m(i_B - \frac{e_B}{R_m})\cos(N_r \theta) - T_d\sin(4N_r \theta),$$
$$\frac{d\theta}{dt} = \omega.$$

Fig. 4 shows different aspects in the electro-mechanical sub-system Simulink/Simscape modelling. Specifically, Fig. 4a depicts the topology and the typology of the hybrid model (causal and acausal). The diagram includes the causal position controller for the driver stepper motor and the acausal electro-mechanical sub-system, which comprises the stepper motor driver, the stepper motor, the worm gear, the leadscrew, the mass, electrical and mechanical references, and many sensor (e.g. load, position, velocity etc.). In particular, the position controller is developed by means of Simulink causal blocks, Fig. 4b, in which, the reference input defines the required motor angular position in terms of the number steps. The stepper controller provides the pulse direction and the pulse train at the input of the Stepper Motor Driver Simscape block. It is worth highlighting that, the Simulink-PS Converter cyan colored blocks convert the input Simulink signals into a physical signals and, in this way, we can build hybrid causal and acausal models. Moreover, by way of an example, Fig. 4c shows the Simscape source code of the ideal mechanical translational mass block. It has one mechanical translational conserving port and the block positive direction is from its port to the reference point. This means that the inertia force is positive if mass is accelerated in positive direction.

### 3.2 Hydraulic sub-system

The hydraulic components of the system can be described using the equation that govern the underlying physics. The experimental apparatus can be divided into two control volumes: $V_{c1}$, which represents the portion of the sea basin between the weir and the deflector panels, and $V_{c2}$, which includes the lagoon and the remaining portion of the sea basin. For each of these control volumes, we can write a...
Table 1. Main parameters of the stepper motor.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum supply voltage</td>
<td>230 V AC</td>
</tr>
<tr>
<td>Motor phase current</td>
<td>2 A rms</td>
</tr>
<tr>
<td>Nominal torque</td>
<td>4 N m</td>
</tr>
<tr>
<td>Rotor inertia</td>
<td>2.2 kg cm$^2$</td>
</tr>
<tr>
<td>Step per revolution</td>
<td>200 step</td>
</tr>
<tr>
<td>Winding resistance</td>
<td>5.8 Ω</td>
</tr>
<tr>
<td>Current time rise constant</td>
<td>9 m s</td>
</tr>
</tbody>
</table>

Fig. 5. Notation used for the hydraulic sub-system modelling.

continuity equation. For $V_{c1}$ it results as follows:

$$A_c \frac{dh_c}{dt} = Q_{in} - (Q_f + Q_{sf}),$$

where $h_c$ the water level, $A_c$ the area of the control volume, $Q_{in}$ is the pump flow rate, $Q_f$ is the flow rate exchanged with $V_{c2}$, and $Q_{sf}$ is the overflow rate from the weir; whereas, for the control volume $V_{c2}$, the continuity equation results as follows:

$$A_t \frac{dh_m}{dt} = Q_f,$$

where $A_t$ is the sum of the sea basin area and the lagoon basin area and $h_m$ is the water level in this control volume.

We add two equation on the discharge flow

$$Q_f = A_f \sqrt{2g(h_m - h_c)},$$

$$Q_{sf} = C_q B \sqrt{2g(h_c - h_p)^{3/2}},$$

where $C_q$ is the discharge coefficient, $B$ the width of the weir and $h_p$ the weir crest height.

Similarly to what has been done for the electro-mechanical sub-system, the hydraulic model has been implemented in the Matlab-based simulation environment by using Simulink/Simscape blocks.

3.3 Models Calibration and validation

The aforementioned first-principle models include several parameters which can assume different values and so making the shape of the equations flexible while maintaining their structure. The nominal model parameters are provided from literature and technical data-sheet while others parameter values can be guessed by expert knowledge or can be estimated from real data. Anyway, in order to obtain a suitable representation of the processes of interest that satisfies pre-agreed criteria (e.g. goodness-of-fit or cost function), certain model parameters need to be adjusted around their nominal values. Here, the calibration procedure is carried out by comparing observed and simulated data. To this aim, an extensive experimental campaign has been carried out to obtain real data. In Fig. 6 an example of experimental test is shown: the considered input to the system is a triangular-wave reference signal to the driver while the considered output is the weir position. The data gained from the experimental tests have been split into a calibration dataset and a validation one. By exploiting the first dataset, we adjust the values of model parameters by solving offline an optimization problem that minimize the Root Mean Squared Error (RMSE) between the simulated output and the target one. Finally, the calibrated model is validated, i.e. it is tested to check its performances in the validation dataset. It is worth noticing that, validation is always appropriate, in view of the uncertainty affecting the models and for this reason it is appropriate to use different data for the calibration and validation steps. By way of an example, Fig. 7 shows the comparison between target and output data when the calibration of certain electro-mechanical parameters is
We consider here certain relevant simulations, the results of which are shown in Fig. 8. In particular, the wave height (blue line, Fig. 8a) presents a time delay and an amplitude reduction compared with the position of the sharp edge of the weir (red line), due to the propagation processes of the wave. The model output predictions restate that is necessary to generate the desired wave directly in front of the lagoon in order to be sure of the wave characteristics at the lagoon inlet. A comparison between the model output and the targets are sufficiently close each other, indeed the RMSE equals 0.56 mm.

Fig. 8. Results of the hydraulic sub-system modelling.

carried out. Specifically, Fig. 7a refers to the calibration step: certain electro-mechanical sub-system parameters (e.g. the worm gear friction loss coefficient) have been adjusted by using an heuristic technique (Genetic Algorithms, Beghi et al. (2011)) that minimize the RMSE. Beside this, Fig. 7b is related to the validation step and we can see that the outputs and the targets are sufficiently close each other, indeed the RMSE equals 0.56 mm.

4. SIMULATION RESULTS

We consider here certain relevant simulations, the results of which are shown in Fig. 8. In particular, the wave height (blue line, Fig. 8a) presents a time delay and an amplitude reduction compared with the position of the sharp edge of the weir (red line), due to the propagation processes of the wave. The model output predictions restate that is necessary to generate the desired wave directly in front of the lagoon in order to be sure of the wave characteristics at the lagoon inlet. A comparison between the model output predictions with the measurements of the ultrasonic probe, for the tide (blue markers), and of the potentiometer, for the weir position (red markers), assesses the capability of the model to correctly reproduce the real system. In addition to the wave height, the model can also predict the flow rate, hence the velocity values, as presented in Fig. 8b. When the flow rate $Q_f$ (blue line) exchanged between the two control volumes $V_{c1}$ and $V_{c2}$ is negative, the velocity is direct seaward and the sediments are eroded and transported from the lagoon to the sea basin.

5. CONCLUSIONS

CACSD software tools are very useful to simulate relevant system dynamics for a first assessment of the different control strategies. In this paper, we have developed and tested a Matlab-based simulation environment for the multi-domain artificial tidal wave generation system. In particular, we have used Simulink traditional block diagrams and Simscape components to integrate different causal and acausal sub-models in order to make them transparent to the users, to preserve their testability, and to gain the necessary user confidence. Constructing models for a slice of reality and studying their properties has proved to be very useful. A comparison between simulations and real experiments shows that the simulation tool is able to correctly reproduce the relevant system dynamics. Future developments will include the designing and testing of different control strategies, such as standard regulators and adaptive controllers.

REFERENCES


