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Modelling flow-induced vibrations of gates in hydraulic structures

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1 Introduction

1.1 Motivation

Flood defence systems are of paramount importance for the safety of vulnerable low-lying areas. In coastal and riverine regions civil engineering structures are built to control the water levels and to protect the hinterland. The river delta of The Netherlands is an example of a densely populated and economically significant area where many hydraulic structures were constructed for this purpose.

Gates are movable elements of barriers and form essential parts of flood defence systems, because they regulate the discharge between bodies of water. Management of inland water levels is unthinkable without gated weirs in rivers and channels. Coastal sluice structures use gates to provide outflow to the sea and protection from high sea levels at the same time. In busy navigation channels large floating sector gates are standby to be closed during storm surge events. These structures are for instance found near Rotterdam and in Saint Petersburg, Russia, where a large dam with multiple gate sections protects the city from floods. Smaller gates are found in pipes and in culverts of navigation locks. Reliable operation of gates of civil engineering structures and prevention of gate failure are crucial for the reliability and safety of flood defences.

Hydraulic engineering is the branch of civil engineering that is concerned with the design of structures related to the flow and transportation of fluids: hydraulic structures. This field combines structural engineering with hydrodynamics. The gates of hydraulic structures are called hydraulic (structure) gates. The adjective 'hydraulic' in this context can always be traced back to the hydraulic engineering discipline and should not be confused with hydraulic devices used to operate all sorts of mechanical appliances, such as –indeed– gates.

Hydraulic structure gates are found in many shapes and sizes as part of various types of structures. Their primary function is in all cases the regulation of flow discharge, water pressure or water levels. Depending on the application, gates in hydraulic structures may be completely opened, closed, or partly opened for long periods of time. This defines the challenge of design and operation: they need to have the strength to endure extreme forces, and they must be opened or closed at exactly the right moment.

The fact that hydraulic gates are in direct contact with powerful flows makes the judgement and quantification of forces on the gates demanding. The interaction of hydraulic gates with passing currents can lead to *flow-induced vibrations* (FIV). Under certain circumstances these vibrations can grow in size and attain the form of regular oscillations with considerable amplitudes. Such manifestation of FIV poses a threat to hydraulic gate operation. The associated exposure to impermissible dynamic forces can lead to unexpected downtime, untimely maintenance, and even failure during emergency situations. In extreme cases, the stability of the structure as a whole is threatened.

The design of gates of hydraulic structures elementarily follows the same approach as other structural elements. There is a compromise between several criteria dictated by the gate's chief function. In a proper design procedure, static and dynamic loading cases are identified and assessed. For static design forces, analytical approaches provide reasonable estimates; rules of thumb based on extreme static loading situations (e.g. maximum head difference) facilitate engineering decisions. For dynamic loading this form of quantification is usually not an option. The reason why FIV of gates defer a straightforward analytical approach is that the combination of structural details and flow conditions leads to complex interplays, the details of which are decisive for the initiation and growth of vibrations and related dynamic forces.

Every study in hydraulic engineering –for academic and consultancy purposes alike– starts with a choice between physical modelling, numerical modelling and a desk study based on literature and expert knowledge. Physical modelling can be a laboratory study of a scaled-down version of a (part of a) structure or field measurements of the actual structure, called prototype or in situ measurements. The most prominent and traditional way of investigating gate vibrations, as reflected in publication numbers, is through physical scale model experiments in the laboratory supplemented with analytical studies for achieving physical interpretations of the measurement data (e.g. Kolkman, 1984; Thang and Naudascher, 1986; Jongeling, 1988). The bulk of experimental research was done in the period 1965-1995, with only a small number of studies at later dates (e.g. Billeter and Staubli, 2000). Experimental studies performed in The Netherlands were partly motivated by the construction of hydraulic structures for the Deltaworks project, which ended in 1997 with the construction of the Maeslant barrier, see Figure 1.1. The Dutch laboratory research on gate vibrations was done at the research institute Deltares (formerly WL|Delft Hydraulics). Knowledge on the dynamic behaviour of hydraulic gates gained by physical scale model studies and field tests is collected in Kolkman and Jongeling (1996).



Figure 1.1. The Maeslant barrier in The Netherlands, a storm surge barrier with two floating gates (picture from <https://beeldbank.rws.nl>, Rijkswaterstaat).

Past physical model research has produced a reasonably good understanding of the physical working of gate vibrations (see Section 2.3). Design manuals nowadays contain short overviews with beneficial gate geometries and warn for undesired construction details (e.g. Novak et al., 2007). In spite of this, problems still arise in practice with unpredictable frequency. This is attributed to one, or a combination of, the following causes:

- The gate design contains suboptimal characteristics with respect to FIV because the problem was underestimated or overlooked completely.
- Physical model tests were done to check and improve dynamic response properties of the gate section, but unfavourable conditions nevertheless led to vibrations (e.g. Thang, 1990). Despite awareness in the design stage, there is still a risk of unknown or unanticipated failure modes occurring in real life.
- Negligence or ignorance leading to improper operational decisions.
- A change of hydraulic conditions during the lifetime of the structure such that design conditions are exceeded.
- New operating procedures are introduced, for example in connection with updated environmental requirements.
- Gradual deterioration of the structure or substandard maintenance can contribute to a different dynamic response.

This list reflects the fact that gate vibrations constitute a non-standard point of attention within design and operation of hydraulic structures. Preventive measures are as a rule relatively easy to implement when the issue is recognised at an early stage (i.e. well before finalising the design), but consequences can become far-reaching later on.

The tremendous increase in available computing power in the last three decades has promoted the usage of computational fluid dynamics (CFD) in environmental engineering projects (Bates et al., 2005). CFD models have become household tools for solving problems in hydrology (Solomatine and Ostfeld, 2008), coastal management (Roelvink et al., 2009) and river morphology (Van Rijn 1987, Mosselman and Sloff, 2008). Moreover, they are being used in operational systems in those areas. Very few examples of model applications exist in which vibrations of barrier gates are simulated, however. Numerical research on FIV and fluid-structure interaction (FSI) has focused on more prominent fields of application, such as aerospace engineering or nuclear power engineering, and fundamental activities, such as benchmarking of computational models. As a result, there are no off-the-shelf computational models today that are capable of simulating hydraulic gate dynamics to an extent that enables practical usage.

Investigations into the reduction of gate vibrations for the large Saint Petersburg barrier (Figure 1.8) involved both physical and numerical modelling, see Klimovich et al. (2006) and Lupuleac et al. (2008). This resulted in an adjusted design of the bottom part of the main sector gates. Construction of this barrier finished in 2010. For the large barriers in The Netherlands, no CFD analyses were performed to simulate and assess the FIV loads. For the Maeslant barrier hydraulic design conditions were determined and physical scale model tests of the structure design were done specifically for checking FIV properties; design improvements were made accordingly.

The motivation for this thesis first of all originates from first-hand experience in projects at Deltares in the period 2009-2011 involving real-life structures, among which the Haringvliet discharge sluices (Figure 1.2). Prior to engaging in the PhD, physical model measurements were done in the laboratory of Deltares, reported in Erdbrink (2012). An underlying motivation is also to raise the level of knowledge on hydraulic gates and generally on the dynamics of hydraulic structures –knowing that this remains a salient topic in design and maintenance of large structures worldwide– and to improve judgement of vibration risks.



Figure 1.2. Discharge through a gate of the Haringvliet barrier, The Netherlands (picture by Deltares).

1.2 Terminology of computational modelling

Because computational models are employed in a variety of ways in this thesis, it is important to make clear from the start how they are built and used. Terminology can be quite different across research fields and therefore a zoomed-out view is needed. Strangely, the distinction between model building and model usage is not always recognised. This omission is a sign that a proper view on the relation between problem description and model employment could be lacking, notwithstanding the fact that sometimes for a computer scientist making a model is the ultimate goal – and, sometimes, for an engineer applying a model is the only thing that matters.

1.2.1 Model building

The traditional approach to setting up a numerical model (the adjectives numerical and computational are used interchangeably) is from a mathematical model, which is a description of the physical process in formulae. This mathematical model is a result of the evaluation of measured data of the physical process by an expert. See Figure 1.3. Often the evaluation that is used to define the mathematical model is not explicitly based on new

measurements, or is skipped altogether, when the mathematical equations are adopted from previous studies.

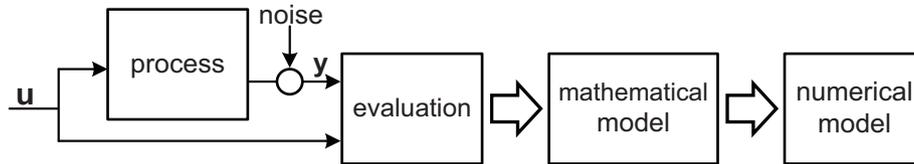


Figure 1.3. Building a numerical model from a mathematical model.

In this approach the model structure consists of mathematical expressions that are derived from an analytical endeavour to capture the physical process. The magic of the mathematical model here is that it acts as a bridge: it provides the numerical relations necessary for computation *and* it contains compact physical descriptions that are meaningful outside of the numerical realm. See Stelling and Booij (1999) for a guideline how this approach is used in hydraulic engineering to establish a connection between numerical models and reality.

A second, different approach is called system identification (SI), defined in Figure 1.4. A measured time signal \mathbf{u} acts simultaneously as input for the process (or system) being studied and as input for the numerical model. The difference of the outputs \mathbf{y} and $\hat{\mathbf{y}}$, the error signal, is subsequently used to adapt the numerical model; this improves its performance. In most real-life situations the measured process output is influenced by noise.

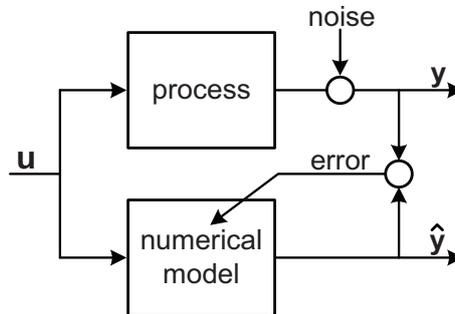


Figure 1.4. Setting up a numerical model by system identification. After Nelles (2001).

The act of repeatedly applying the error signal for improvement of the model (i.e. of reducing $|y - \hat{y}|$) is called training. In machine learning, originally a branch of artificial intelligence but today arguably too extensive a topic itself to be considered a single research field, this type of training is called supervised learning. This means that both input and output signals are available for gradually improving the model. Note that these ‘signals’ can have all imaginable shapes: they can contain a physical quantity varying in time, for example pressure $p(t)$, but they can also be a discrete variable x that indicates inclusion or exclusion of an object in a set, for example $x \in \{blue, red\}$. The model resulting from the training basically gives well-tweaked rules for a mapping from input to output. The described

approach makes intensive use of the (measured) data and is therefore termed empirical or data-driven modelling.

The first described approach (Figure 1.3) based on a mathematical model that describes the fundamental principles is referred to as physics-based modelling and provides maximum insights in the process. It is a form of white-box modelling. The second approach (Figure 1.4) is an example of black box modelling. This second approach requires a minimum of domain expertise and can give apt numerical representations of complicated systems that are badly understood. On the downside, its accuracy depends on the (quality of) the available data and extrapolation to ranges outside of training conditions is precarious. Needless to say, many hybrid forms were developed that are sometimes called grey models.

1.2.2 Model use

Depending on the problem type that is to be solved, there are various ways to use the numerical model. Figures 5 to 7 schematically show how computational models can be used (after Nelles, 2001). In the figures, $u(t)$ is an input value at time t and $y(t)$ and $\hat{y}(t)$ are output values from the process and the model, respectively. Predictive models use past input and output signals from a monitored process to compute a prediction for one or more steps into the future. In the left scheme of Figure 1.5, a one-step ahead prediction is shown.

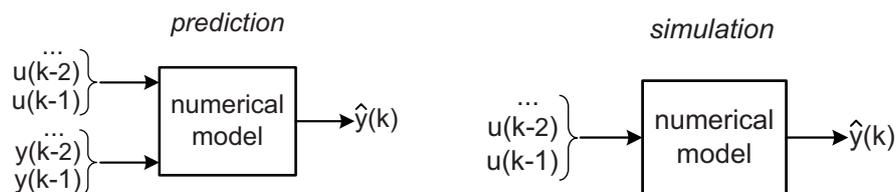


Figure 1.5. Use of numerical models. Left: prediction. Right: simulation.

Simulation is different. Here, the numerical model is used to mimic the process output using only preceding input data points. See Figure 1.5 (right). The number of time steps into the past $k-1, k-2, \dots$ is rather arbitrary for prediction and simulation. The number of future steps, however, has more profound consequences in terms of modelling requirements.

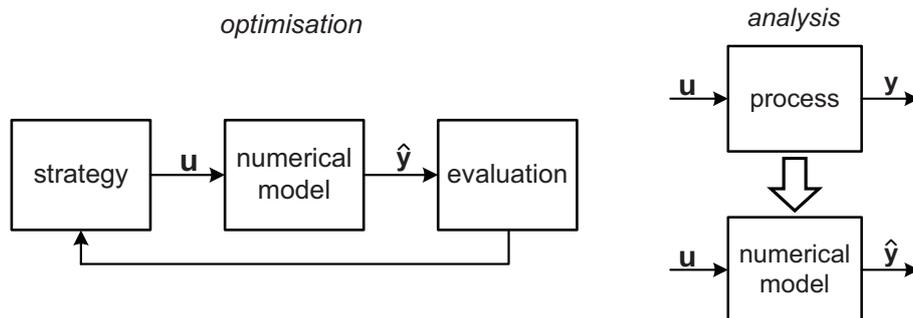


Figure 1.6. Use of numerical models. Left: optimisation. Right: analysis.

Very often, as is the case in the present study, a simulation model is used for optimisation or analysis. When a model is used in optimisation (Figure 1.6 on the left), the goal is to find a set of (strategy) parameters for which a certain desired system performance is reached (formulated as a minimisation or maximisation of a predefined objective function). This is done by evaluating the modelled output signal and looping the outcome back to adapt the strategy, until the desired performance is found. This is also called reverse modelling, because there is more information available about the desired model output than about the model parameters on the input side.

A rather subtle use of numerical models is analysis (Figure 1.6 on the right). Here, process and model coexist in parallel and the goal of running the model is to scrutinise the working of the process. What counts is uncovering details of the process, that are hard to measure directly, by looking at the results of the numerical model. This is usually more than just comparing outputs y and \hat{y} .

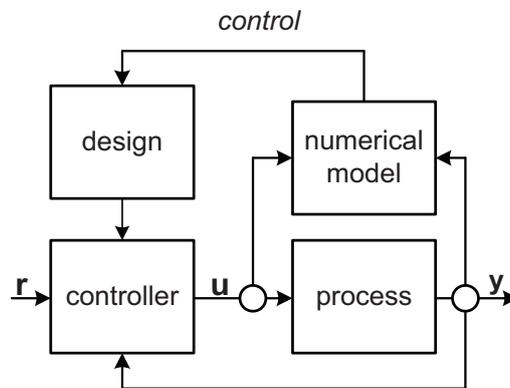


Figure 1.7. Use of numerical model in a control scheme.

A numerical model can be used inside a control loop to facilitate the design of a suitable control measure. Figure 1.7 shows an example lay-out of a controlled process. It is the performance of the controller that is the main concern, the extent to which the model replicates the process is of secondary importance. There exist different variants of the scheme in Figure 1.7. A last type of model use is fault detection (not shown in a figure), where several versions of the model run in parallel with the process in order to detect failure modes in a system.

It remains undiscussed so far which model usages benefit from which type of model construction. This all really depends on the problem type, the problem complexity, the specific questions that need to be answered, as well as the available data and the state of theoretical knowledge. The ways computational models can be used, as introduced in this section, is not synonymous with the *application* of a model. How we speak about applications again quite strongly depends on the focal length of the discipline. A computer scientist or applied mathematician may consider a moving mesh in CFD as an application of a certain algorithm, while an offshore engineer considers computations of a vibrating marine riser as an application of a CFD model containing a moving mesh. Section 3.1 digs deeper into application aspects of numerical modelling in hydraulic engineering.

1.3 Thesis aims

Studies into FIV of gates up to now can be categorised in four groups:

- Physical scale modelling of gate sections complemented by analytical study with the goal of gaining fundamental knowledge on excitation mechanisms and optimal gate shapes.
- Elastically-scaled physical scale modelling for checking and improving the design of actual structures.
- Field measurements on prototype structures: monitoring of gate behaviour for a certain time period after an incident has happened or when there is uncertainty about gate operation protocols.
- CFD simulations as a purely academic study or complementary to physical modelling.

All four types have proven their value, but are time-consuming. Given the ongoing developments in computational methods and the variety of uses of numerical models, an exciting idea is to examine new ways to study gate vibrations. This leads to three research aims for this thesis:

Aim 1

This study sets out to critically evaluate previous research work in the field of gate vibrations, examine new design improvements and measures for prevention and attenuation.

Aim 2

The second aim is to contribute to the development, testing and application of novel computational techniques with the purpose of providing the engineer with new tools for addressing gate vibration issues in design, operation and maintenance. By explicitly discussing and interpreting model building and usage, this thesis aims to strengthen the bridge between numerical modelling and problem solving.

Aim 3

The topic is a blend of research areas; the multidisciplinary nature comes on the one hand from the combination of hydrodynamics (the flow), structural mechanics and mechanical vibrations (the structure), on the other hand it comes from the numerous sub-branches of computational science and the large number of available techniques. The question rises how to deal with model choice and use at the intersection of disciplines.

The third aim, related to the second, is therefore to explore computational ways to tackle multi-disciplinary problems that are unsolvable by available conventional means from the disciplines separately. Looking at it from a reverse angle, the question becomes how to increase the relevance and find 'killer applications' for emerging computational techniques.

Before commencing two remarks are in order.

- It is not an aim of this thesis to assemble and incorporate all previous work and provide an anthology of the topic, since this has been done already to satisfaction in textbooks. A substantial amount of accumulated knowledge is found in Kolkman (1976). The same author contributed to other, updated overviews, of which Kolkman and Jongeling (1996) is the most complete. The two books by Naudascher (1991) and Naudascher and

Rockwell (1994) together contain a wealth of analyses, usable guidelines and references to further studies.

- The work done for and presented in this thesis is not related to any specific barrier in real life.



Figure 1.8. One of the two large sector gates of the Saint Petersburg dam.

1.4 Thesis set-up

The chapters are organised according to different uses of models. The focus frequently shifts between hydraulic engineering and applied computer science. A run-through of the chapters. Chapter 2 introduces the necessary physics background. This makes the computational challenge more clear. As such it serves as a foundation for the approaches and choices made in subsequent chapters. Chapter 3 goes into numerical models based on physics equations. In Chapter 4, a cascade of physics-based models is presented for computing the impact of flow through hydraulic gates. Then Chapter 5 discusses a physical laboratory experiment of two types of underflow gates. Chapter 6 proceeds with fundamental numerical modelling of the same two gates in a finite element model. After this, Chapter 7 introduces a data-driven system for barrier operation that avoids gate vibrations. Chapters 8 and 9 explore recent computational techniques in the field of evolutionary computing and make an attempt to apply these to the vibration problem. The final chapter states the conclusions of the thesis.

Table 1.1 classifies each chapter for the reader's convenience. Short intermediate evaluations are added where applicable, to keep an eye on how the research fits into the bigger picture.

Table 1.1. Overview of chapters.

	chapters					
thesis backbone	1					10
framework / methodology / discussion	2	3			8	9
results from numerical experiments			4	6	7	8
results from physical experiments			5			

The introduced notions regarding model type (numerical or physical), building of numerical models (data-driven or fundamental) and model use enable another classification, as shown in Table 1.2.

Table 1.2. Chapters according to model building and use.

model type	model building ↓	model use →	analysis	optimisation	control
numerical model	data-driven		9	8, 9	7
	fundamental		3, 4, 6		4
physical model			5		