Modelling flow-induced vibrations of gates in hydraulic structures

Erdbrink, C.D.

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10 Conclusions and perspectives

10.1 Collected conclusions

Two lines of thought have been pursued throughout the thesis: contributing to solutions to the hydraulic engineering problem of flow-induced gate vibrations and putting new computational tools to the test. In doing so, the work has explored four different approaches: physical experimentation, physics-based numerical modelling, data-driven modelling for control and data-driven system identification.

A survey of past research showed that a damped mass-spring oscillator partly submerged in a flowing fluid provides a useful analogy, but also that the excitation mechanisms can be complex and the added hydrodynamic coefficients are not readily quantified. It has been made clear that numerical modelling from fundamental equations alone cannot fully predict the fluid-solid behaviour of real-life gates. Modelling techniques coupled to measured gate responses introduced in this study are a step forward.

Parameterized modelling of the flow around the structure with a fixed gate was coupled to a CFD simulation model for resolving the free surface. A benign application of discharge modelling is achieving gate opening scenarios with smoother discharges guided by PID-controlled operation. This gave the insight that including near-field flow modelling in structure operation will enable more sophisticated water reservoir management with respect to issues such as salt water intrusion and fish migration. The model results can also help to avert unsafe gate use in extreme events and prevent instability of bed protection.

Analysis of data from a physical scale model experiment showed how gate vibrations vary over a range of conditions signified by the gate opening and the reduced flow velocity parameter V_r. For a rectangular-bottom vertical-lift gate with submerged underflow, significant cross-flow vibrations were observed in two distinct V_r regions at gate openings between half and full gate thickness. Most significantly, tests of an adapted gate profile with added ventilation slots indicated reduced dynamic response forces compared to the standard profile.

With the framework of application-centred modelling in mind, a finite element model was set up to simulate turbulent gate flow and the vertically moving gate. The arbitrary Lagrangian-Eulerian method was used to create a moving mesh following the gate motion, but it could not be applied to simultaneously compute the free surface disruptions. The simulations successfully captured the response of both gate types at $Vr \approx 10$. A motion-induced excitation was observed for the standard rectangular profile powered by wake entrainment. The leakage flow through the ventilated slot greatly attenuated this mechanism for the new gate type – causing a positively damped response instead. The experiment and the simulations combined give confidence in the intended working of the novel ventilated gate design. Further studies should determine how the design of the ventilation slots can be adjusted for optimal effect and if the attenuation also works for in-flow vibrations and other gate types. It is also concluded that at present this type of fluid-structure interaction simulations is too costly to cover a wide enough range of conditions necessary for a complete view on the gate response.

In an effort to outline a feasible data-driven system for controlling gate dynamics based on sensor data, it was found that a machine learning approach can be applied to classify future states and hence avoid critical flow-induced vibrations. Actual implementation of a smart monitoring system for gate dynamics will depend more on recognition of its usefulness by flood defence authorities than on technical hurdles.

A new computational method applied to system identification of dynamical systems, evolutionary computing has proven its value for inferring motion equations from time series. Several tests on synthetic displacement data indicated that this method is suitable for recognising self-excited vibrations, including non-linear terms. The differential evolution algorithm is a robust way to derive the ODE's coefficients with a limited number of strategy parameters. The computation time of this method is relatively long, but its flexibility provides unique possibilities for analysing the vibration system and testing theoretical conjectures. It has been shown that by including a minimum of system knowledge, it is possible to derive physical coefficients of the motion equation from the measured support force signal.

Finally, it has been shown how the same evolutionary computing method can solve a special reverse initial value problem, in which the ODE and the time series are given and a suitable solver algorithm is derived. The relative ease and accuracy of the performed numerical experiments suggest a wider applicability. This raises fundamental questions about the development and use of numerical algorithms and the customisation of computational methods.

All research aims listed in Section 1.3 have been achieved. The next section proceeds with a reflection on the accomplished work and Section 10.3 ends with recommendations for future research.

10.2 Reflection

An evaluation of the results and the effort that was done to arrive at those results leads to a few remarks.

In the physical experiment, the choice of only measuring the response forces had an effect on all later investigations. The use of pressure sensors in the gate profile would have added to an even greater complexity of the experimental set-up, but would have enabled direct excitation analysis, additional validation of the simulation model and input-output system identification. Of course, these pressures are not easily monitored in prototype structures either, so computations should not be designed to rely on its availability.

Just as time consuming as physical modelling, CFD simulations are indispensible for FIV research – as physics-based modelling generally will be for the whole of engineering and science (NSF, 2006). Persisting points of attention, though, are pinpointing the modelling requirements and validation. It was not producing a response signal, but reproducing the exact conditions (water levels, discharge, natural gate frequency) that was the biggest challenge of the finite element modelling in this study. Had there not been experimental validation data available, then the simulations would have taken a fraction of the time and still would have produced colourful plots – the main caveat of CFD.

A tempting idea is to apply machine learning to train a black-box meta-model that mimics the outcome of the slow and complex CFD model. This would then directly give the gate response from a set of water levels. However, the meaningful subset of simulation results covered a quite limited range of input conditions – there is simply not enough training data. Incidentally, making extrapolations and even interpolations from these FSI simulations is not recommended. The data-driven model proposed in Chapter 7 is more suited to this, but the caution with this model is that its main goal is to assist in gate operation, i.e. to optimise control, and not to analyse the process.

Computations based on analytical formulae for estimating isolated quantities such as hydraulic stiffness (see Section 2.4 and Chapters 5 and 6), that describe specific *parts* of the fluid-solid system, have not become obsolete. These can now serve as initial estimates or optimisation constraints for new system identification methods which seek to derive a description of the *entire* system.

10.3 Perspectives and recommendations

This thesis can be seen as an attempt to pivot solution strategies for vibration issues of hydraulic structures: continuous monitoring in combination with data-driven modelling yields valuable information on safety and provides better operational control. As already remarked by Kolkman and Jongeling (1996), hydraulic structures are increasingly being operated remotely. If the reduced human observations of the structure's behaviour that is a result of this, is not compensated by automated observation techniques, then this could lead to higher risks of gate vibrations. Investments of permanent sensor installations on civil engineering structures most probably outweigh current approaches of last-minute laboratory testing and occasional field measurements. Moreover, this idea fits in a wider trend of smart monitoring of civil engineering structures (Owen et al., 2001; Magelhães et al., 2008; Pyayt et al., 2014).

This new perspective could contribute to a more comprehensive problem solving strategy (in line with Section 2.5) in the following way. For an existing structure, the idea is to first gather data from sensors and thus derive the dominant eigenmodes. Then, this information can be used within an automated operational system for avoidance of critical conditions by means of machine learning. The same data could also be used to establish links between the gate response and hypothesized excitation mechanisms (in the form of ODEs) with evolutionary computing, so that the causes of the vibrations can be uncovered and perhaps be understood better. It is good to mention that none of the approaches pretends to be able to predict whether significant vibrations will indeed occur in a newly built structure or new gate design. But the development of new methods is thought to result in a higher state of preparedness for the possibility of unanticipated vibrations and a more effective prevention of critical situations. All this does not imply, by the way, that solid knowledge of the physical phenomena is not necessary for studying FIV and for solving FIV problems in practice.

Physical experiments of hydraulic gates in the laboratory have not lost their value – on the contrary, this remains an indispensable way of performing physical analysis of new gate types and testing real-life designs. Additionally, it fulfils a renewed role in the development of data-driven tools. The main challenges in this field are continuity in expertise and long-term reservation of research budget.

In simulation from fundamental principles (CFD), turbulence remains a huge challenge in the foreseeable future. In the specific context of gate vibrations, turbulent flow has to be combined with resolution of the free surface and a moving object. Main concerns are validation (with a focus on damping) and expanding the range of physical conditions that the numerical model can handle. Progress will only be possible when the application and domain knowledge have prominent places next to the development of computational techniques. The framework of Section 2.3 serves as a guide in this.

The data analysis revolution in automated scientific knowledge discovery ignited by evolutionary computing deservedly achieves ample attention. It is expected that more application-oriented software tools will emerge as the universal success of genetic programming is translated to specific engineering disciplines. The full potential for non-linear system identification will be reached when evolutionary algorithms are combined more closely with existing signal processing and data regularization techniques. The viability of automated derivation of solver algorithms is uncertain; the next step is to apply the presented method to other algorithm design problems.