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NUMERICAL SIMULATION OF FLOW-INDUCED VIBRATION ON GATES WITH UNDERFLOW

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ABSTRACT

Flow-induced vibrations are an important issue in the design and operation of weir gates. Various mechanisms of vibration excitation are known. For underflow weir gates, the so-called press-shut mechanism is known to be a possible source of excitation. Hereby, the movement of the gate affects the flow regime in a way that a force is produced that acts in the direction of the gates movement. This self-excited process can lead to severe gate vibrations. Due to the coupled nature of self-excitation, it is insufficient to compare the distinct flow-induced forces and the natural frequency of the gate in a static model. A coupled approach is required in which both the flow and the gate movement are represented in a fully transient manner.

Self-excited vibrations at hydraulic gates with underflow are often based on the coupling between vibration of the gate and the attributed flow-rate fluctuation. This phenomenon is referred as the press-shut mechanism. The investigation of self-excited vibrations requires the use of coupled models that reflect the transient flow-regime and the motion of the body. A practical approach is developed which employs coupled numerical simulation to model the interaction between the vibrating gate and surrounding flow field. The energy that is transferred from the flow to the vibration is estimated as a value for vibration tendency. The method is applied to two practical examples of gates with underflow and verified with field measurements.

Keywords: Flow-induced Vibrations, self-excitation, Press-shut, numerical simulation, OpenFOAM

1 INTRODUCTION

In hydraulic engineering, vibration problems are prevalent and manifold. Despite the intensive research on the topic (see e.g. Naudascher and Rockwell 1994), problems with vibrations are still present and it seems that the number of incidents even increases (Göbel et al. 2018). Besides vibrations on small parts of weir or lock gates like seals or filling valves, large scale vibrations of full weir gates with modern box girder constructions are reported. These gate vibrations have frequencies in the range of 1 to 5 Hz and amplitudes of about one centimeter. For examination, different methods are available: analytical models like the stability criterion (Kolkman 1976) that was successfully applied on different kinds of gates. The method demands a deep insight on the mechanical properties of the gate and the exciting mechanism. Moreover, it still contains simplifications that can affect the result. Laboratory investigation involves scaling of the hydraulic and mechanical properties. This makes it complicated and expensive and the result can be vague. In this paper, a method is presented that employs computational fluid dynamics (CFD) to model the gate vibration and considers the energy transfer from the flow to the vibration during one vibration period as a quantification of the proneness to vibration. The method is applied on two different gates with underflow and verified by prototype measurement.

2 REVIEW OF THE PRESS-SHUT MECHANISM

Gates and seal arrangements are often designed in a way that the closing process creates additional forces in the direction of closure. This is frequently called a press-shut configuration.

Figure 1 shows different gates, valves and seals that are constructed in a press-shut manner. The inclined weir plate (a), the radial gate with an eccentric trunnion point (b) and the J-seal (e) are illustrative examples. When they are closed, an upstream surge develops due to the reduced discharge beneath the gate. The resulting pressure increase tends to push the gate in a further shut position. Ishii and Knisely (1992) call those constructions “geometric press-shut” devices. Furthermore, gates with a square bottom (c) or protruding gate lips (d) can also be excited to vibration by the “hydrodynamic press-shut” effect (Ishii and Knisely 1992).

Kolkman (1976) explains that this is due to the fluctuating gap width and the inertia of the flow. When the gate is moving downwards, the cross section becomes smaller and the flow rate decreases. Since the flow adjacent to the gate is inert, the flow beneath the gate decelerates and the pressure drops. This means that downwards movement of the gate induces a downwards directed force on the gate. If the gate is moving upwards the flow rate increases, the flow has to accelerate and the pressure rises.

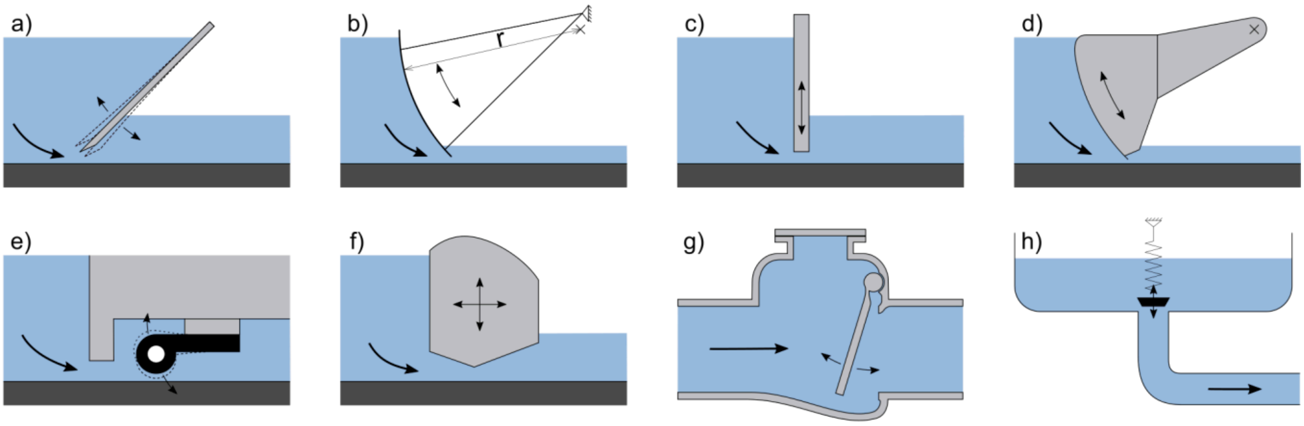

Figure 1 Different Types of gates, valves and seals that are prone to the press-shut effect. Examples reproduced from Ishii and Knisely (1992) (a, b, c, f), Petrikat (1980) (e), Weaver et al. (1978) (g) and Kolkman (1976) (h).

Figure 2 b) shows qualitatively the vibration of a gate and the force from pressure fluctuations beneath the gate. During upwards movement the pressure rises and during downwards movement the pressure drops. These pressure fluctuations originate from the vibration of the gate. On the other hand the pressure change is also the driving force of the vibration. This coupled process is called self-excitation (Kolkman and Jongeling 2007) or movement-induced excitation (Naudascher and Rockwell 1994) and leads to severe vibrations. Turbulence buffeting or vortex excitation are not contributing to the vibration, however the fluctuation in the discharge may produce regular shed vortices.

Intensive research on this topic has been done by Weaver et al. (1978, 1980) who describes the problem for check valves (Figure 1 g) and other kinds of hydraulic structures, including gates and seals. Kolkman (1976) developed a stability indicator to check vibration tendencies for a bath-plug type valve (Figure 1 h) and transferred the results to different kinds of gates. While Thang and Naudascher (1986) proposed that galloping is the main reason for self-excitation on gates with underflow, Kanne et al. (1991) showed that both effects can play a significant role in the self-excitation process. Ishii and Knisely (1992), Ishii et al. (1994) and Ishii et al. (2014) developed additional models for press-shut mechanisms involving the coupling of multiple degrees of freedom (Figure 1 f), calling it the “coupled mode press-shut” effect. An extensive summary of research, construction recommendations and applicable solutions can be found in Naudascher and Rockwell (1994), Kolkman and Jongeling (2007) and Ishii et al. (2018). Most of this research has been carried out on scale models to verify analytical models and gain general knowledge about the behavior of flow-induced vibrations.

The practical application of the mentioned research presumes a profound knowledge and understanding of vibration excitation mechanisms; this knowledge is not wide spread and obviously decreasing (Göbel et al. 2018). In addition, the use of laboratory models for preliminary investigations is hindered by the combination of hydraulic and dynamic scale effects.

Erdbrink et al. (2014) used computational fluid dynamics (CFD) to evaluate the positive effect of a new gate lip design on cross-flow vibration. This approach involved a transient flow-simulation coupled with solid body motion. The benefit of numerical simulation as opposed to a laboratory investigation is the lack of model scaling and the continuous presence of pressure and velocity data.

3 ENERGY IN VIBRATIONS

In a free, undamped mechanical vibration, energy is constantly exchanged between the potential energy of the loaded spring and the kinetic energy of the moving mass-body. When the spring is fully loaded, all energy is stored as potential energy and at the zero crossing all energy is converted to kinetic energy. If the vibration is damped, there is an energy loss and the amplitude decays over time. On the other hand, if the vibration is excited, energy is added so that the amplitude increases over time. In flow-induced vibrations, this energy is transferred from the flow to the motion of the mass-body in form of a hydraulic force F_H (Figure 2). In the case of self-excited vibrations, this hydraulic force is coupled to the vibration which can be described by Eq. [1][a].

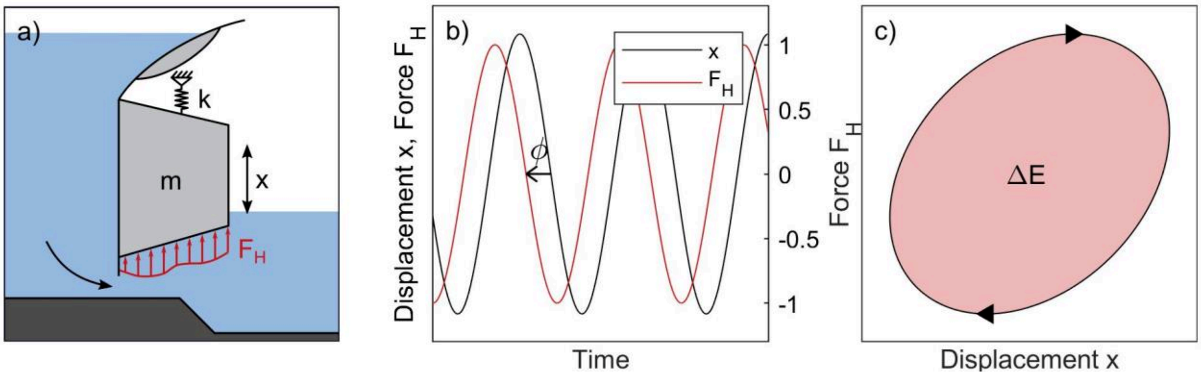

Figure 2 a) Systematic sketch of a vertically vibrating gate with underflow. b) Displacement x and hydraulic force F_H as a function of time. Φ displays the phase shift between displacement and force. c) Parametric representation of the vibratory displacement x and the hydraulic force F_H. The enclosed area of the parametric representation is the net energy ΔE transferred during one vibration period T from the flow to the vibration.

$$\underbrace{m \cdot \ddot{x}(t) + d \cdot \dot{x}(t) + k \cdot x(t)}_{\substack{mechanical \\ vibration}} = \underbrace{F_H(x, \dot{x}, \ddot{x}, t)}_{\substack{external \\ hydraulic\ force}} \qquad [1]$$

Note that Eq. [1] represents a transversal vibration with one degree of freedom where x is the displacement of the rigid body. m symbols the mass of the body, k the stiffness of the spring and d the damping factor of the vibration. Similar formulations can be found for rotational vibrations or systems with multiple degrees of freedom. For some self-excited processes, mathematical methods exist to describe the coupling (Naudascher and Rockwell 1994). These models often assume either linearity or are based on potential theory, or even both, which makes them valid only for special cases, such as vibrations with small amplitudes. For the press-shut mechanism, there is no mathematical model to date. Additionally, self-excited vibrations are often accompanied by flow-instabilities and turbulent effects which make the mathematical description even more difficult.

The net energy ΔE that is transferred from the flow to spring-mass-vibration is calculated with Eq. [2]. If this value is positive, the vibration is excited, if its negative, the vibration is damped.

$$\Delta E = \int_0^T F_H(t) \cdot \dot{x}(t)\, dt \qquad [2]$$

A useful tool for energy considerations in vibrations is the parametric representation as shown in Figure 2 c), where force is displayed as a function of displacement. The enclosed area equals the work done in one vibration period. Note that with clockwise rotation, the work is positive, and counterclockwise, it's negative. This corresponds to a positive or negative phase shift Φ between the displacement and the force signal in Figure 2 b).

4 DESCRIPTION OF THE NUMERICAL MODEL

OpenFOAM is an open-source CFD software package which is widely used for the simulation of fluid dynamic problems near hydraulic structures (Thorenz and Strybny 2012). For the simulation of gate vibrations, the interDyMFoam solver of the version 2.3.1 is used which combines the simulation of free surface flows with solid body motion. The governing equations of the flow are solved with a finite volume method (FVM), while a

[a] This formulation foregoes the use of added terms like added mass, added stiffness and added damping for the sake of a strict division between mechanical vibration and hydro dynamics. Hence, the left hand side assembles the mechanical vibration, while the right hand side symbolizes the external hydraulic force. The strict division between mechanical vibration and external force implicates, that the common 'negative damping' is not used in this formulation.

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volume-of-fluid (VOF) method is employed to handle the free surface between the two faces air and water. The solid body motion is coupled to the flow regime with a two way coupling; pressure forces on the body's surface are taken into account for the solid body motion, while the displacement of the solid body is used to deform the fluid boundaries. A dynamic mesh algorithm is used to deform the mesh, which means that the mesh is deformed in every calculation time step. (OpenFOAM Foundation 2019)

The application of fluid-structure-interaction models which include the deformation of the solid body by the means of a finite-element solver is preferable because deformation modes are represented more accurately. However, for practical purpose this method is still not suitable. The mass of the water that surrounds the vibrating gate is high, compared to the gate mass. This makes the interaction between structural solver and fluid solver prone to instability and extensively time consuming (Förster et al. 2006).

5 INVESTIGATION PROCEDURE

One method for the investigation of self-excited vibrations is enabling free vibratory movement of the gate in the flow (Göbel et al. 2016). This method is complex and difficult to set up with repeatable accuracy for different operation conditions. As an alternative, Kobus (1984) proposed to prescribe the vibration $x(t)$ of the gate with an external drive and to measure the force $F_H(t)$ acting on the gate. The pressure field in the flow is still coupled to the vibration of the gate and creates the same pressure fluctuation as in a full coupling. But, the vibration is controllable and repeatable. To draw conclusions on the nature of the vibration, the force signal $F_H(t)$ has to be evaluated with respect to the external driven vibration $x(t)$. Therefore, the described procedure considers the energy transfer from the flow to the vibration.

The first step is to determine the governing vibration mode and frequency. This is done by prototype measurement. In this investigation, deforming modes are be simplified to a one- or two-dimensional rigid body motion. For vibration investigations in design phase, the governing vibration mode and frequency have to be evaluated by the means of a modal analysis. Care has to be on the fact that natural frequencies can differ considerably between dry and submerged conditions due to the added mass of the surrounding water.

The solid body motion can then be implemented into a numerical model. Based on the measuring data, the gates movement is prescribed with frequency and amplitude. Upstream and downstream water levels are fixed by pressure boundary conditions to preserve the water head across the gate (Thorenz and Strybny 2012). Since the solid body motion is one- or two-dimensional and the predominant flow structures are also two-dimensional, the model can be reduced to a two-dimensional vertical plane of one meter thickness. The two-dimensional approach prohibits the use of eddy resolving models and a k-ω-model is used for turbulence modelling.

Opening width and tailwater level influence the vibration behavior of a gate during operation. To evaluate the gates vibration tendency, these two factors have to be varied within a reasonable range. 'm' different openings and 'n' tailwater levels result in $m \cdot n$ simulation runs. Every single simulation run is evaluated by means of the transferred energy as described in chapter 3. This results in an overview of vibration tendency over a range of operation conditions.

The accuracy of the results can be affected by numerous factors at different stages of the process. The results of prototype measuring can be imprecisely or incomplete. The reduction of the vibration to one degree of freedom can neglect possible mode-coupling effects. The numerical model may not represent all flow structures that are involved in the vibration process. This may be due to the mesh size, the considered turbulence model or due to the two-dimensional approach. Depending on the model geometry, the tailwater can be influenced by an unstable hydraulic jump that causes additional fluctuation forces on the gate. These fluctuations can be filtered off by a bandpass filter. This filtered signal is used to calculate the transferred energy and this filtering can have an effect on the result.

The energy of the vibration can be dissipated by mechanical damping due to friction at the side sealings or due to material damping. It has to be noted, that the prescribed motion approach used here neglects the mechanical damping and therefore overestimates the vibration tendency.

6 CASE STUDIES

6.1 Vibration tendency of a radial gate with underflow

6.1.1 Description of the gate

A recently commissioned radial gate showed heavy vibrations during underflow with small openings. The gate is part of a barrage with three 35 m-wide spans. The bottom part of the gate consists of a short protruding skin plate and a low box girder. Under normal conditions, the gate is only lifted during flood events, while the flap gates on top are used for the water level regulation up to a discharge which corresponds approximately to a tailwater level of 2.35 m. The concession water level is 4.45 m above the weir sill.

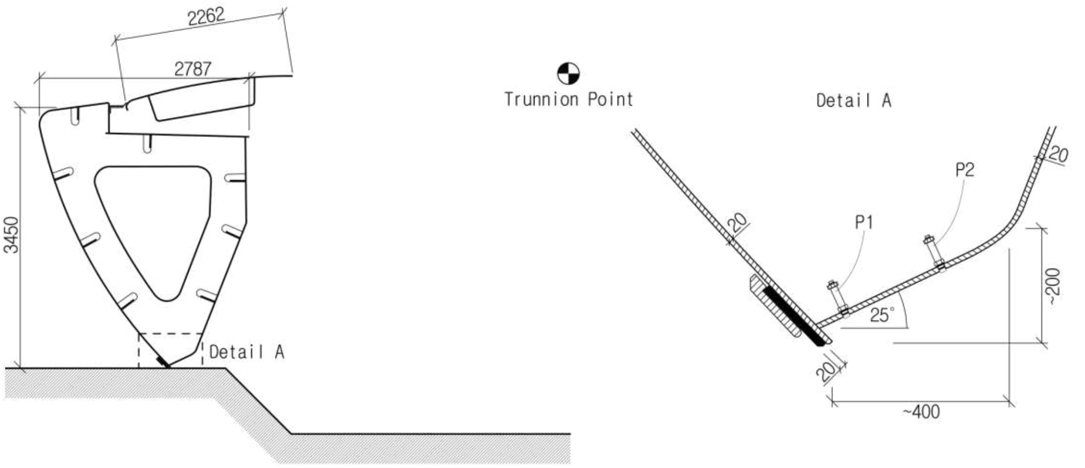

Figure 3 Cross-section of a radial gate with flap gate on top and the bottom part of the gate with the seal configuration on the upstream side of the skin plate. The two pressure transducers P1 and P2 are placed at the midpoint of the gate span.

Measurements showed that the vibration mode is a rotation of the gate body around the trunnion point. Bending was measured but the bending deformation at the midpoint of the gate was only around a tenth of the rotational displacement. The vibration mode therefore was assumed to be dominantly a solid body motion around the trunnion point. In reference to the bottom opening width, the maximum amplitude was around 6 mm and the frequency was 3.24 Hz. Pressure was measured by two piezo resistive transducers at the bottom of the gate at the midpoint of the gate (Figure 3). An example of a measuring result can be seen in Figure 4. There is a phase-shift between the vibration and the pressure fluctuation. Though the pressure signal is not purely sinusoidal, pressure and vibration are clearly coupled. Timewise, the pressure is first and the displacement of the gate follows with a lag of roughly a quarter of a period. This phase-shift $\phi \approx T / 4$ between displacement and pressure means that during upwards movement, pressure is higher and during downwards movement the pressure is lower than the mean value. This is a prerequisite for the press-shut mechanism. The high-frequency overlay is based on random turbulence and vortex shedding beneath the gate.

However seals are referred to as a potential source for vibration problems (Petrikat 1980, Krummet 1965, Naudascher and Rockwell 1994), the seal configuration at the gate is not causal for its vibration. This conclusion is based on the fact that frequencies of seal vibrations are significantly higher. Furthermore, identical vibrations was observed at the neighboring gate with an identical construction but different bottom sealing.

6.1.2 Verification of the numerical model

As described above, bending of the radial gate is negligible and radial motion around the trunnion point is dominant. The gate geometry is simplified by omitting the seal construction at the skin plate in order to minimize the meshing effort. The simulated region is 25 m long, 10 m high and 1 m wide. The hexahedral dominant mesh consists of 175 000 cells with edge sizes between 10 cm and 0.3 cm. For verification, a measurement result with an amplitude of 0.29 cm around a mean opening of 1.7 cm is chosen (Figure 4 a). Upstream and downstream levels are 4.45 m and 0.58 m above the weir sill respectively.

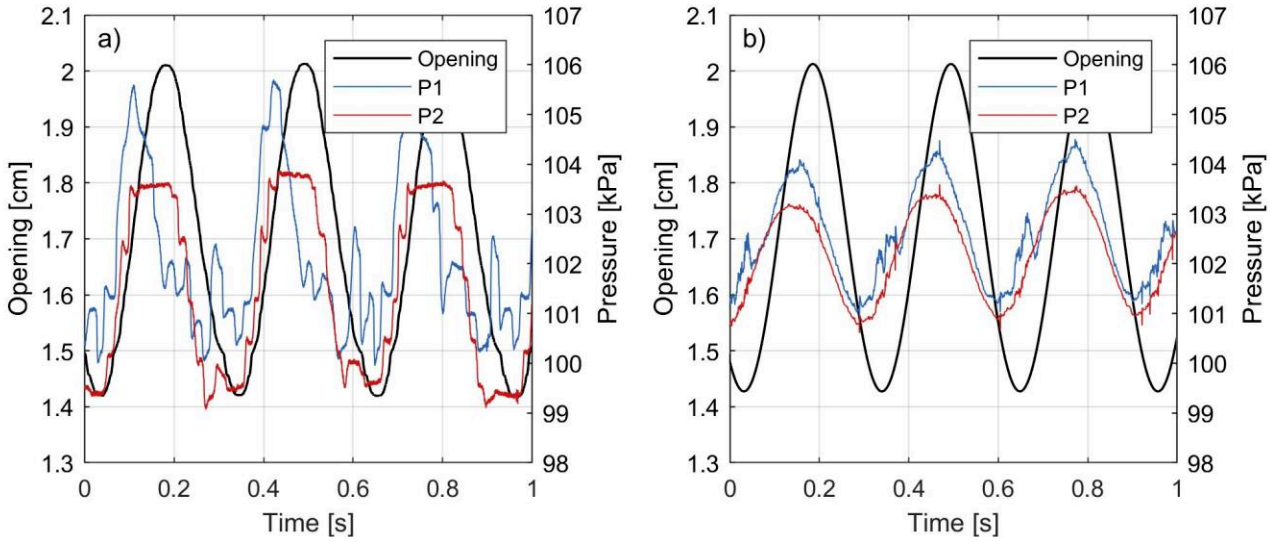

Figure 4 Vibration and pressure signal of an oscillating radial gate. a) shows the data from measurements and b) the data from the numerical simulation.

6.1.3 Results of the verification

Figure 4 shows the vibration signal and the pressure signals P1 and P2 from the prototype measurement (a) and the numerical simulation (b). It can be seen that the global behavior of the pressure is similar. Pressure is leading with a phase shift of roughly $\phi = T / 4$ which implies that the pressure is the exciting force for the vibration. However, the detailed shape of the pressure signals is slightly different. The pressure from the prototype measurement is superimposed by higher frequency fluctuations while the pressure from the numerical simulation is nearly a pure sine wave only with small distortion during the low point of the vibration. The overlay in the measured pressure signal can be explained by turbulent effects beneath the gate. The numerical model however employs a k-ω-Turbulence model which has a strong smoothing effect on the turbulent flow. The large scale pressure fluctuation with 3.24 Hz is the dominant contributor of the vibration excitation. Regarding the phase shift and the amplitude, the representation in the numerical model shows a good agreement.

6.1.4 Investigation of the operation conditions

To evaluate the gates vibration behavior for different operational conditions, the opening and tailwater level was varied. The opening was varied between 2 cm and 20 cm in 7 steps. Tailwater level was varied between 0.95 m and 2.75 m in steps of 0.35 m. For every single data point the energy transfer was calculated.

Figure 5 a) shows the transferred energy per vibration period ΔE for the investigated range of operating conditions. It can be seen that there is an energy transfer for small openings. The energy transfer decreases with increasing opening and tailwater level and eventually becomes negative for sufficient high values.

6.1.5 Investigation of the gate bottom geometry

As a constructive countermeasure against vibration an elongation of the protruding skin plate is tested. The investigation procedure described in chapter 6.1.4 was repeated with a skin plate elongation of 30 cm. Figure 5 b) shows the resultant energy transfer. It can be seen that the energy transfer generally decreases by a magnitude compared to Figure 5 a) and becomes neutral or negative for all examined operation conditions. Interestingly, the negative value ΔE for higher tailwater levels and larger openings decreases for longer skin plates. This is due to the fact that while moving up and down, the gate constantly displaces water beneath the box girder and generates a current through the cross section between the box girder and the sill. This additional flow is called the plunger effect (Kolkman 1976). The generation of this flow dissipates the energy that is stored in the vibration and acts as damping. With a longer skin plate, the cross section between the box girder and the sill increases and the flow resistance decreases. The damping therefore decreases with a longer skin plate.

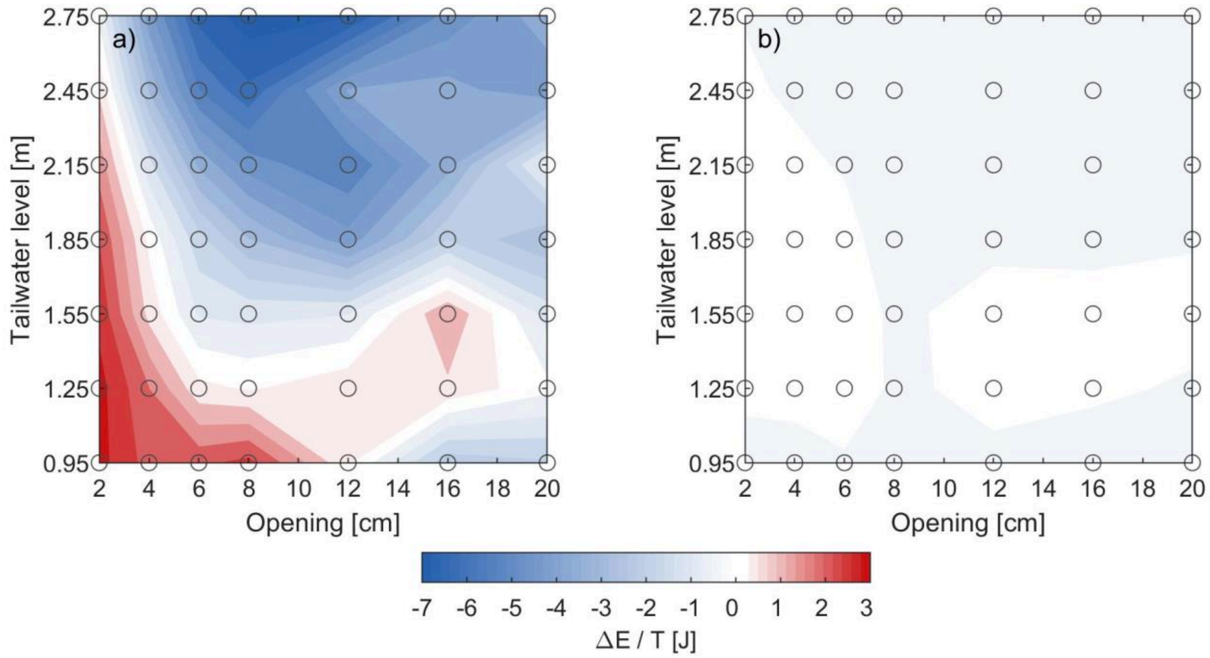

Figure 5 Energy input ΔE for different operation conditions of a radial gate with underflow for the standard configuration (a) and with skin plate elongation of 30 cm (b). Simulations were performed for all data points marked with a grey circle.

6.2 Operation concept of a long-span lifting gate with underflow

6.2.1 Description of the gate

A vertical lifting gate showed bending vibrations in the vertical direction during underflow. The 45 m wide gate features a large box girder that supports the vertical skin plate and a flap gate on top (Figure 6). Typically the flap gate is used for the fine regulation of the upstream water level and underflow occurs during flood discharge. The lifting gate and the flap gate are operated with a common chain drive and the flap gate has to be raised completely before the lifting gate can be opened. Simultaneous over- and underflow is therefore not possible.

Measurements were carried out to capture the frequency and amplitude of the vibration as well as the critical opening. The vibration was measured with an accelerometer at the midpoint of the gate and the signal was integrated twice to obtain the displacement. The opening of the gate was measured with a position sensor at the endpoint of the gate. The tailwater level is dependent on the present discharge while the upstream water level is kept constant at 5.94 m. Measurements were carried out under two different conditions: At a tailwater level of 1.98 m, the gate vibrated in bending mode. The frequency was 1.5 Hz and the vertical amplitude at the midpoint of the gate was 1.6 cm. The vibration occurred at openings between 3 - 4 cm. The opening was measured at the end point of the gate. At a tailwater level of about 3.9 no vibrations occurred in the opening range.

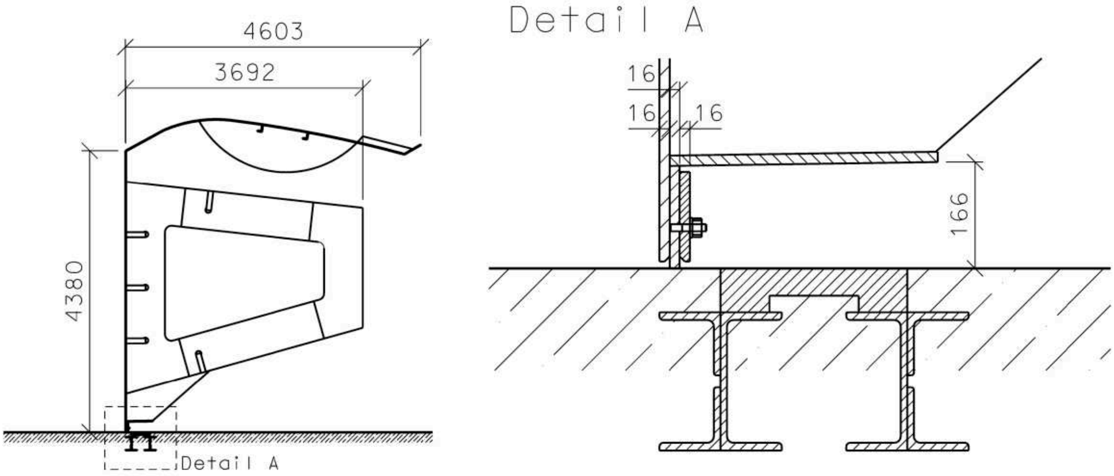

Figure 6 Cross-section of a lift gate with flap gate on top and the bottom detail. All measures are in mm.

6.2.2 Numerical investigation

The bending vibration problem is simplified by a vertical solid body motion. The numerical model therefore is a two-dimensional slice with a length of 25 m, a height of 12 m and a width of 1 m. The hexahedral dominant mesh consists of 175 000 cells with edge sizes between 10 cm and 0.3 cm. Different operation conditions are simulated with the same prescribed gate vibration with a frequency of 1.5 Hz and an amplitude of 1.6 cm. The tailwater opening is varied between 5 and 20 cm in steps of 2.5 cm and the tailwater level is varied from 0.5 to 5 m in steps of 0.5 m. In total, 70 simulations were performed, each one with a duration of 10 seconds. For every simulation, the transferred energy per vibration period ΔE was evaluated by calculating the enclosed area of the force-displacement diagram.

6.2.3 Results

Figure 7 shows the transferred energy for different openings and tailwater levels. It can be seen that positive energy transfer took place for small openings and tailwater levels between 1 and 4 m. For larger openings and higher tailwater levels, the energy transfer becomes negative. The largest amount of energy is transferred at a tailwater level around 2 m. Here, the bottom part of the box girder is completely submerged, which means the area affected by the pressure fluctuation is at its maximum (Figure 7 c). With further increasing tailwater level, two effects arise; firstly, a higher tailwater level leads to more surrounding water, which generally has a damping effect.

Secondly, the flow velocity is decreasing and with that also the resulting discharge when considering a constant opening. With lower discharges, the inertia effect is also decreasing which means that higher tailwater levels reduce the risk of vibrations. In contrast, up to tailwater levels of 1 m, the tailwater level is lower than the box girder and possible pressure fluctuation cannot act on the gate (Figure 7 c).

Enabling free vibratory motion of the gate and evaluating the resulting negative damping have led to the same results (Göbel et al. 2016).

It must be noted, that a comparison between the numerical results and the measurements on site is limited. But, the comparison between prototype measurement and numerical results shows, that vibrations occur in the range of positive energy transfer but not in the range of negative energy transfer.

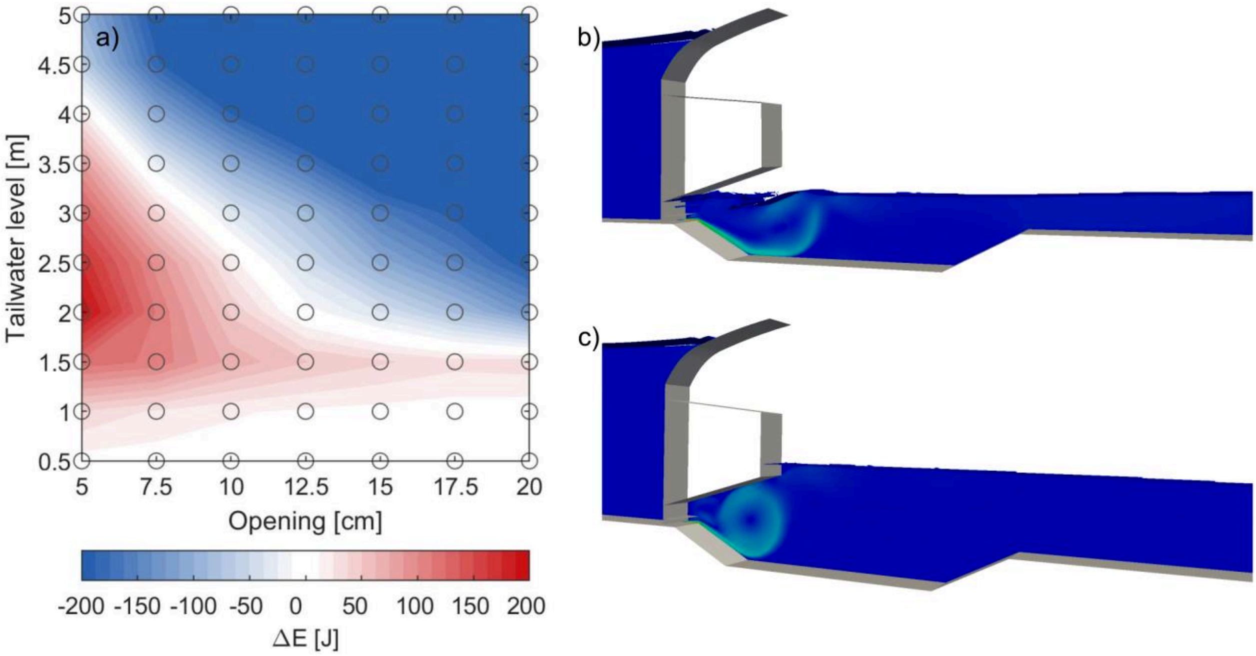

Figure 7 a) Energy transfer ΔE for different operating conditions of a long span lifting gate with underflow. b) Simulation result for a tailwater level of 1 m. The box girder is completely dry. c) Simulation result for a tailwater level of 2 m. The bottom part of the box girder is completely submerged.

7 CONCLUSION

Self-excited vibrations occur, if the motion of the solid body alters the surrounding flow field in a way, that hydraulic forces arise that work in the direction of movement. The press-shut mechanism is one of the coupling mechanisms that can cause self-excited vibrations and plays a significant role in hydraulic engineering. An approach is presented, that employs a coupled simulation of computational fluid dynamics and prescribed solid body dynamics. The energy that is transferred from the flow field to the solid body vibration is estimated and used as criteria for the gate's tendency to vibrate under different operational conditions. Two case studies are presented were this method was applied successfully. The comparison between numerical simulations and prototype measuring data showed that the predominant pressure fluctuations are reproduced sufficiently and the predicted vibration tendency shows good agreement with the prototype.

Besides the investigation of existing structures, this method can be used to assess gates in the design phase.

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