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Reducing cross-flow vibrations of underflow gates: Experiments and numerical studies

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ABSTRACT

An experimental study is combined with numerical modelling to investigate new ways to reduce cross-flow vibrations of hydraulic gates with underflow. A rectangular gate section placed in a flume was given freedom to vibrate in the vertical direction. Horizontal slots in the gate bottom enabled leakage flow through the gate to enter the area directly under the gate which is known to play a key role in most excitation mechanisms.

For submerged discharge conditions with small gate openings the vertical dynamic support force was measured in the reduced velocity range $1.5 < V_r < 10.5$ for a gate with and without ventilation slots. The leakage flow significantly reduced vibrations. This attenuation was most profound in the high stiffness region at $2 < V_r < 3.5$.

Two-dimensional numerical simulations were performed with the Finite Element Method to assess local velocities and pressures for both gate types. A moving mesh covering both solid and fluid domain allowed free gate movement and two-way fluid–structure interactions. Modelling assumptions and observed numerical effects are discussed and quantified. The simulated added mass in still water is shown to be close to experimental values. The spring stiffness and mass factor were varied to achieve similar response frequencies at the same dry natural frequencies as in the experiment. Although it was not possible to reproduce the vibrations dominated by impinging leading edge vortices (ILEV) at relatively low V_r, the simulations at high V_r showed strong vibrations with movement-induced excitation (MIE). For the latter case, the simulated response reduction of the ventilated gate agrees with the experimental results. The numerical modelling results suggest that the leakage flow diminishes pressure fluctuations close to the trailing edge associated with entrainment from the wake into the recirculation zone directly under the gate that most likely cause the growing oscillations of the ordinary rectangular gate.

1. Introduction

This study presents a novel hydraulic gate design aimed at reducing vibrations induced by underflow. The dynamic response of a hydraulic gate due to its interaction with the flow strongly depends on details of the gate bottom geometry. Numerous

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experimental studies of flow-induced vibrations (FIV) of gates have previously looked into the characteristics of gate shapes (Hardwick, 1974; Vrijer, 1979; Kolkman, 1984). The gained insight in excitation mechanisms has resulted in widespread rules of thumb for unfavourable designs that should be avoided as well as favourable design features (e.g. Thang, 1990; Naudascher and Rockwell, 1994). However, fundamental knowledge and practical experience have not culminated in one ideal universal shape – partly because the surrounding structure is an important factor. Consequently, hydraulic engineers still stumble on the problem of gate vibrations when designing a new structure or when conditions of gate operation change over time.

Experimental and numerical models are incapable of capturing all degrees of freedom (d.o.f.) experienced by real-life gates (mass-vibration mode in cross-flow and in-flow direction, bending, torsion). Streamwise (horizontal) vibrations are usually studied separately (e.g. Jongeling, 1988) and sometimes in combination with the cross-flow mode (Billeter and Staubli, 2000). In this study we consider the most frequently investigated mode for a vertical-lift underflow gate: one d.o.f. in the cross-flow direction.

The discharge past a partly lifted gate is driven by a head difference, which causes a streamwise pressure gradient. At sufficiently high downstream water levels, the discharge is submerged and a quasi-stationary rotational cell with horizontal axis exists in the downstream region. The flow accelerates as it approaches the gate; the mean velocity reaches a maximum just past the gate in the point of maximal flow contraction called the vena contracta. Depending on the head difference, submergence and the gate's geometry and position, it experiences a steady positive or negative lift force (Naudascher, 1991). This quasi-steady description suffices as long as the gate does not oscillate.

The emergence and severity of flow-related dynamic forces on the gate are related to flow instabilities and body motion effects. To describe and explain relations between flow properties, forces and gate motion during oscillation, several excitation mechanisms were introduced. Periodic fluctuations of the separated flow's shear layer may cause an active response. For gates with a sharp upstream edge, this mechanism is called Impinging Leading Edge Vibrations (ILEV). If the gate bottom has an extending lip in streamwise direction, the shear layer separated from the upstream edge may reattach to the gate bottom in an unstable way, giving dynamic excitation. In a different mechanism, periodic forces are the result of initially small gate movements. This self-exciting process is called movement-induced excitation (MIE). The galloping phenomenon falls in this category.

Previous investigations have proved that most severe vibrations of underflow gates in submerged flow occur at small gate openings and are predominantly caused by ILEV and MIE mechanisms (Hardwick, 1974; Thang and Naudascher, 1986a, 1986b). The current study therefore focuses on small gate openings and does not look at the distinctly different mechanism of noise excitation. Other notable studies are Kapur and Reynolds (1967); Naudascher and Rockwell (1980); Thang (1990); Kanne et al. (1991); Ishii (1992) and Gomes et al. (2011). Overviews of flow-induced vibrations of gates are found in Kolkman (1976); Naudascher and Rockwell (1994) and Jongeling and Erdbrink (2009); Blevins (1990) treats FIV in a wider context. None of these authors considered holes in the gate as a means to weaken vibrations.

Assuming that adding structural damping or avoiding critical gate openings are unfeasible options, the shape of the gate bottom is the decisive factor determining the tendency to vibrate. If the flow passes the gate while remaining attached, or if there is a fixed separation point and a stable reattachment, or if the shear layer is kept away from the bottom in all circumstances, then the ILEV mechanism may be avoided. A thin, sharp-edged geometry with separation from the trailing edge is favourable, since potential shear layer instabilities occur downstream from the gate and a small bottom area inhibits the occurrence of large (suction) forces on the gate, thus minimising the risk of MIE vibrations. But such a design is often not practical or is influenced in an undesirable way by additional details such as flexible rubber seals. The investigation at hand takes the unfavourable thick flat-bottom rectangular gate as a reference gate and introduces a new design with leakage flow through openings in the bottom section as a potential way to improve its vibration properties, see Fig. 1.

Numerical simulations of gate vibrations based on elementary physics equations are inevitably complex and computationally involved. The computational Fluid–Structure Interaction (FSI) model needs to deal with very small displacements of varying

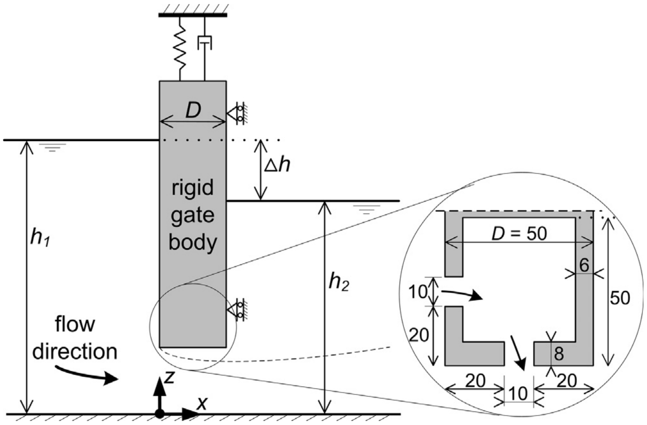

Fig. 1. Streamwise cross-section of gate configuration showing ventilated gate design (detail of bottom element on the right). Dimensions in millimetres, not drawn to scale. Details are given in Figs. 2–4.