May 17th, 2:50 PM

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7th International Symposium on Hydraulic Structures Aachen, Germany, 15-18 May 2018
ISBN: 978-0-692-13277-7 DOI: 10.15142/T34D2G

Description of Some Seal Vibration Problems at Hydraulic Gates on German Waterways

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Abstract: *Flow induced vibrations are a common phenomenon in hydraulic engineering. They affect the operation of gates and weirs and can lead to fatigue or damage of the construction. In this contribution, different types of vibration incidents on hydraulic gates are distinguished. By measuring the vibration frequency, it is possible to distinguish between the vibration of rubber profiles in the shape of a musical note (J-seals), vibrations involving the complete weir body and vibrations of spring supported seal systems. J-seals tend to vibrate in various arrangements. A laboratory study shows the vibration mode and evaluates a critical opening width of gates with a J-seal as bottom seal. For future work, numerical fluid-structure-interaction (FSI) solvers may be a tool to identify flow-induced-vibrations in the design process of hydraulic gates. First results of this method are shown.*

Keywords: *Flow-induced vibrations, hydraulic gates, seal-vibration, J-seals, on-site measuring, numerical simulation*

1. Introduction

During the last years an increasing number of vibration incidents on German waterways were reported to the BAW. Generally, it can be distinguished between vibrations of whole gates, such as bending of wide-span gates or rotary vibrations of radial gates around their trunnion points. Next to that, vibrations of gate parts could be detected, such as filling valves or sealing systems. There has been remarkable research on flow-induced vibrations (FIV) at hydraulic structures. Vibrations induced by flow-instabilities like vortex shedding or impinging shear layer were subject to a number of studies (Müller 1937, Petrikat 1955, Naudascher 1964). For underflow gates, some authors proposed a redesign of the bottom part of the gates in order to provide a stable flow separation or to eliminate regular vortices. Other authors proposed operational measurements and recommended the avoidance of critical opening widths, for example Pulina and Voigt (1994) for the weir Kachlet. Petrikat (1980) suggested to replace wooden beams by rubber seals, but he also mentioned that there is still the tendency for vibrations, especially for bulbous shapes like J-seals (see Figure 1). Kolkman (1976) described flow-rate fluctuation as a source for self-excited vibrations, which is also known as press-shut mechanism (Naudascher and Rockwell 1994, Ishii and Knisely 1992b). According to Naudascher and Rockwell (1994) this mechanism plays a significant role in the vibration-excitation of elastic rubber seals and spring supported seal systems at small gap widths. Excellent overviews on the topic of flow-induced vibrations on hydraulic gates are given by Naudascher and Rockwell (1994) and Kolkman and Jongeling (2007). One might think there is a solid knowledge base on excitation mechanisms and forms of flow-induced vibrations. Despite this, the number of new constructions with vibration issues increased. Additionally, there is a remarkable number of old constructions with vibration problems after repair. In general, a loss of know-how can be noticed. Hydraulic steel construction became a niche business and specialists are nearly off the market. With an upcoming need for renewal of many weirs and locks, there are strong efforts for standardization and automation on German waterways. But automation means also that there is no longer operational staff on site and it is difficult to detect and handle vibrations by using remote control properties. Against this background, this paper gives an overview of existing vibration problems at German waterways and shows how the causes were detected. Vibration types were classified (chapter 2) and on-site measurements of actual vibration incidents carried out. The measuring approach and data analysis are presented in chapter 3. In order to understand the mechanism of seal vibrations, experiments were conducted in the hydraulic laboratory. Through the use of a high-speed camera the vibration motion of a J-seal (musical note seal) was visualized (chapter 4). Numerical simulations are currently used to investigate flow-induced vibrations on hydraulic gates. A short summary is given in chapter 5 showing a glimpse of future possibilities.

2. Classification of Vibration Incidents

FIV is a well-known phenomenon in hydraulic engineering. There are many reported cases with FIV on hydraulic structures like the damage of the power unit housing of a roller gate near Stuttgart due to vortex induced vibration on a roller gate (Maschinenfabrik Augsburg-Nürnberg A.-G. 1912) or the complete distortion of a radial gate on Folsom Dam in the United States (Ishii et al. 2014). Naudascher and Rockwell (1980) collected and discussed a number of case studies of flow-induced vibrations on hydraulic structures. Those examples and results from measurements (further described in chapter 3) are analyzed to find indicators to identify the excitation mechanism on hydraulic structures without extensive on-site measurement or modal analysis. Indicators may be vibration frequency, amplitude or wave pattern in the headwater. In the following, the indicators of three different vibration types are described. This includes two types of seal vibration and vibration of the full gate to point out the main differences between seal and gate vibration. While the expert engineer in this field may understand the mechanism and source of vibration based on his experience, some may need these indicators to identify the source of vibration and decide further approach to the problem.

2.1. J-seal Vibration

Elastic rubber seals in the shape of a musical note are also called J-seals (Figure 1). J-seals have multiple advantages, if they are installed properly. The flexibility of the soft bulbous shapes makes the seal adaptive on varying sealing surfaces. Contrary to wooden beams, the surface has not to be shaped perfectly for sufficient tightness, because the seal can deform and compensate unevenness. On miter gates, which can deform or deflect in horizontal direction with varying water head, a soft seal keeps tight without bringing additional tension to the structure that was not considered in the design. If they are applied in a way that the upstream water head is pressing the seal in a tight position (Figure 7 right), tightness can even be improved. But, as already explained by Naudascher and Rockwell (1994), this configuration can also be a source of flow-induced vibrations during small openings or leakage.

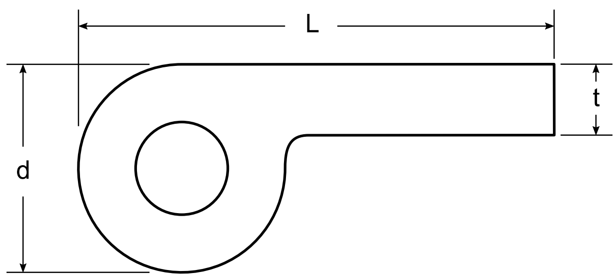

Figure 1: Sketch of a J-seal.

Krummet (1965) reported on the vibration susceptibility of J-seals. Petrikat (1980) continued the research on this topic (see also chapter 4). Today it is known, that J-seals of typical sizes tend to vibrate in a frequency between 35 and 50 Hz (Naudascher and Rockwell 1994). Countermeasures and precautions for this type of vibration can be found for instance in Krummet (1965).

2.2. Vibration of Spring Supported Seal Systems

Underflow gates often have spring supported sealing systems, in particular if the sealing acts against the water pressure. In general, these systems tend to vibrate in closed or slightly opened position because they are elastically mounted. The construction is very diverse (Figure 2) and the resonance frequency may vary between the different systems. Experience shows that there is a relatively large frequency range between 15 and 40 Hz. During vibration, the upstream water surface tends to show small standing waves with wavelengths in the cm range (Figure 3 left).

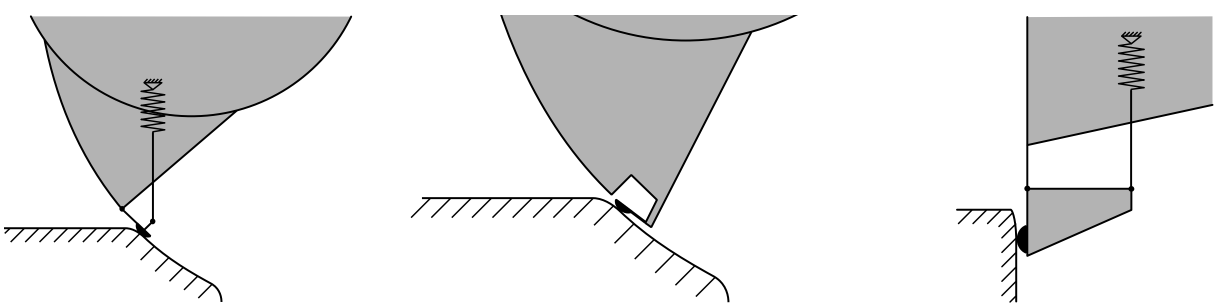

Figure 2: Sketches of different spring supported seal systems.

2.3. Bending and Rotating Vibration

Long span gates, such as roller gates or lifting gates, have in common that they are driven on one side or both sides by chains or hydraulic cylinders. The end points of the gates are mounted in the niches of the weir pillar by means of fixed bearing. Due to the relatively high elasticity of the gates, bending vibration might occur, if the gate is excited to vibrate by under- or overflow (Ishii and Knisely 1992a). Göbel (2017) describes a 42 m wide lifting gate that vibrates with 1.5 Hz in a bending motion. For comparison, a 30 m wide roller gate was vibrating with 9 Hz. Radial gates with shorter span width would vibrate in a rotary movement around the trunnion point. Reports (Ishii et al. 2014) and own experiences show, that the frequency of this vibration would not exceed 10 Hz. Thus, it can be concluded that vibrations of a whole gate will take on a single-digit frequency. However, size and shape of the construction can differ massively from one to another; the more or less small range of resonance frequencies is not surprising at all. Mass distribution and mass-to-stiffness ratio may be similar in all those constructions. If the amplitude is noteworthy, they are accompanied by large standing waves (Figure 3 right). Even if those constructions have sealing systems, which are susceptible for flow-induced vibrations, the occurrence of the described indicators show, that the sealing system is not the actual source of vibration.

Figure 3: Left: standing waves in the headwater of a lifting gate with underflow. The waves are caused by the vibration of the spring-supported seal system. The vibration frequency is between 15 and 20 Hz. Right: standing waves in the headwater of a 42 m wide vibrating lifting gate during underflow. The bending amplitude at the midpoint of the gate is 1.6 cm and the frequency is 1.5 Hz. In Both pictures the flow direction is marked with an arrow.

3. Measuring Data

With on-site vibration measuring, critical operation conditions can be identified. This includes combinations of opening width, flow rate and tailwater level at which flow-induced vibrations can be expected.

To measure the vibration signal, acceleration sensors with different sensitivity are required. In our tests, magnets were used to fix the sensors on the construction. For underwater application, the sensors were packed in a waterproof can. Analog signals are converted to digital signals and captured on laptop. To convert the signal from time domain to frequency domain, Fast Fourier Transformation was used. A sketch of the setup is shown in Figure 4.

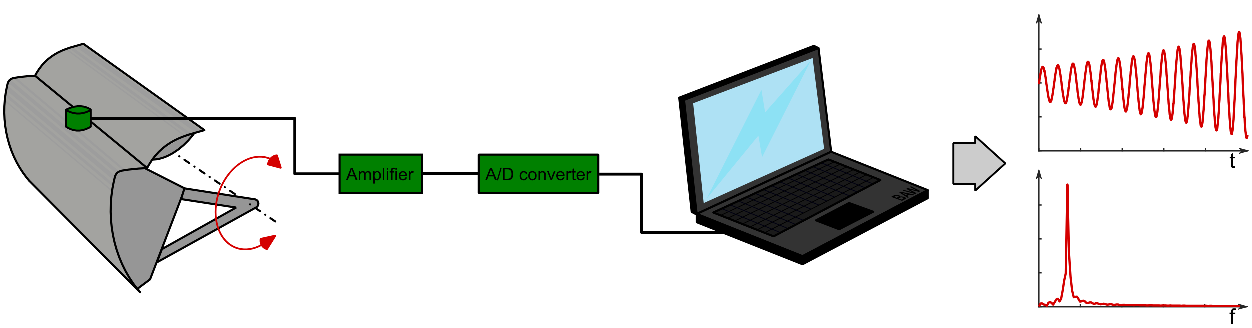

Figure 4: Measurement setup. Acceleration sensors are fixed on the gate with magnets. Depending on the type of sensor, there is need for a measurement amplifier. Analog signals are converted to be processed digital.

If there is an obvious single resonator system, such as bending or rotary vibrations (see 2.3), it is easy to find the right location for sensors in order to record the required magnitudes (see Göbel 2017). On complicated systems with multiple oscillators or degrees of freedom, it can be difficult to find the primary excitation source. A typical example is a miter gate (see 3.1), which can vibrate in various bending modes or around hinge points. Additionally, parts of the structure, for instance filling valves or sealing systems, might vibrate solely and other parts act as resonators.

If extensive measurements are not possible, the sound track of video signals can be used in order to determine the vibration characteristics. However, the scope of application is limited. Sensors are connected directly to the construction. In contrast, sound signals will be emitted also from other vibrating parts of the construction. Some frequencies will be amplified acoustically, because they involve a strong acoustic resonator (e.g. box girders) and thus, dominate the acoustic signal. Ambient noise may overlay the signal. Finally, the microphone itself can induce measuring errors as well. Overall, good experiences were made with this method. Three examples of measured seal vibrations are described in the following.

3.1. Filling Valve of a Lock Gate

Figure 5 shows the filling valve in the bottom part of a miter gate. The valves are radial gates with J-seals at the top. During commissioning, heavy vibrations occurred when the filling valve was opened a few centimeters. The vibration was loud and clearly to feel even on top of the gate. To identify the source of vibration, sensors were applied on different positions of the gate. They all showed a matching dominant frequency of 40 Hz. By comparing the signals, it could be identified that vibration was induced at the skin plate above the top seal (see the red arrow in Figure 5). It was not possible to modify the top seal arrangement in order to avoid fluctuations in the gap. Therefore, the construction was stiffened by welding vertical beams onto the skin plate (Figure 5). Figure 6 shows the acceleration signal of the skin plate before and after stiffening. It can be seen, that the acceleration amplitude decreased to a hundredth.

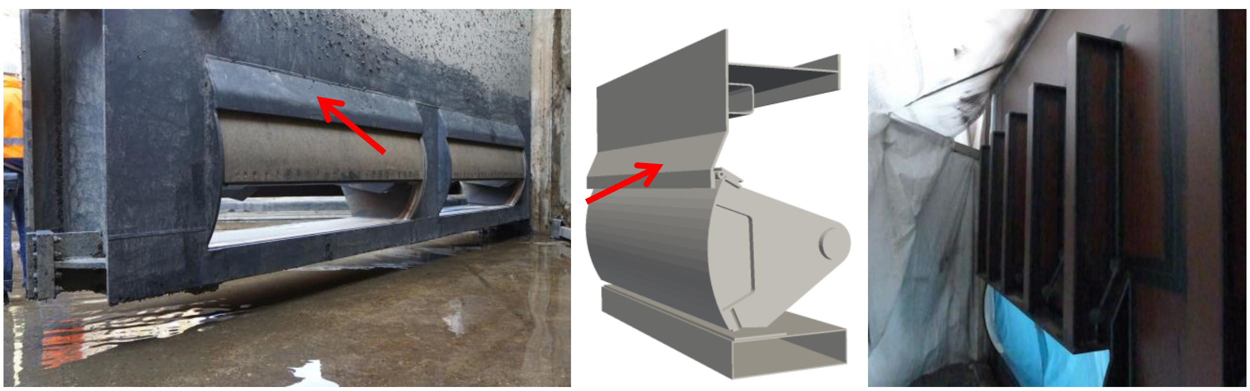

Figure 5: Miter gate of the lock Neckargmünd: Filling valves (left); 3D sketch of the radial gate and top seal arrangement (center); welded beams on the skin plate (right). Note the buckled skin plate is marked with an arrow.

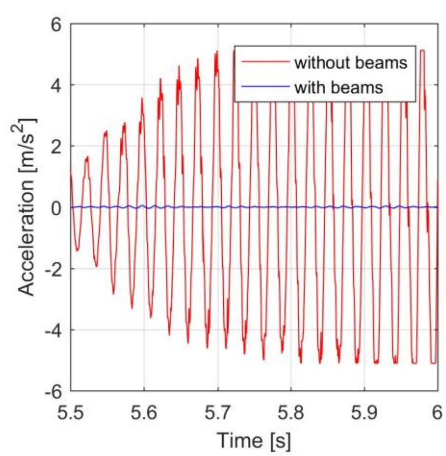

Figure 6: Acceleration amplitude of the skin plate vibration before (red) and after (blue) stiffening the plate.

3.2. Bottom seal of a Radial Gate

Recently, a double lift gate was replaced by a radial gate with a flap gate on top. The average water head is 3.75 m. The skin plate is in the shape of a segment of a circle. The midpoint of this circle is located higher than the trunnion points of the gate. Hence, the water head creates an additional opening torque on the gate. Figure 7 shows a sketch of the gate and the seal construction. It can be seen that the box girder is placed with a small vertical offset to the edge of the skin plate. During commissioning, loud humming vibrations were noticed at small opening widths. The J-seal is placed in a way, that the upstream water head increases tightness in closed position. However, Naudascher and Rockwell (1994) have already noted that this kind of construction can be susceptible to flow-induced vibration (see also chapter 2.1).

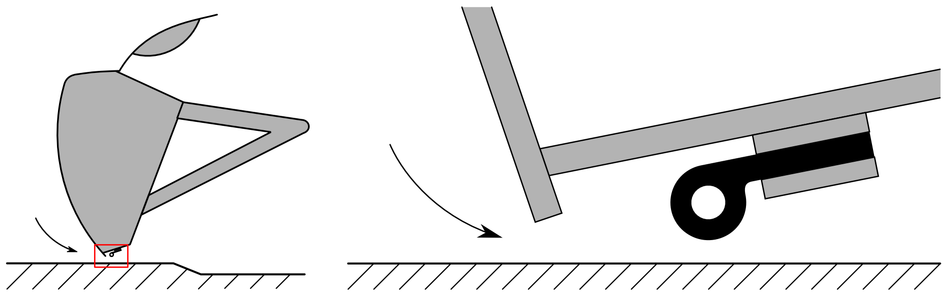

Figure 7: Radial gate with flap gate on top: sketch of the full gate (left) and seal construction on the bottom side of the gate (right)

In order to determine the resonance frequency of the vibrations, the sound track of a video was analyzed. The dominant frequency was 37 Hz, which fits quite well in the known frequency range of 35 to 50 Hz for vibrating J-seals. After removal of the J-seal, the buzzing vibration was gone. Unfortunately, the gate showed additional rotary vibrations at small openings. Those vibrations are still present after removal of the seal and will be investigated in future research.

3.3. Spring Supported Seal Construction of a Roller Gate

The spring supported seal construction was renewed at a submersible roller gate. The system is sketched in Figure 2 left. In the original configuration a spring like it is shown in Figure 8 was used. After replacing by coil springs heavy vibrations occurred. Measurements were carried out and several acceleration sensors were applied: one on the pole of a spring (Figure 8, center) and one at the roller itself (Figure 8, right) near its midpoint.

Figure 8: Submersible roller gate: replaced spring (left); renewed spring supply with applied acceleration sensors (center); acceleration sensor near the midpoint of the gate (right).

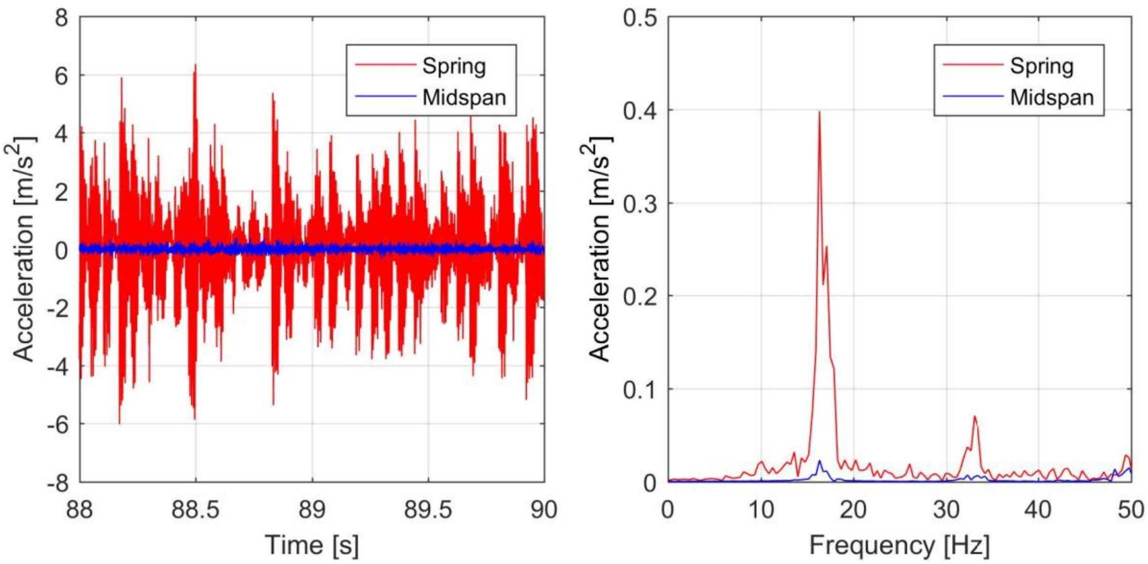

Figure 9: Acceleration signal (left) and frequency analysis (right) of the vibration measured on the seal system (red) and midspan (blue) of the roller gate.

Figure 9 shows the measured vibrations of the gate. In the frequency domain, it can be seen that the dominating frequency of roller gate and seal system are identical, on average 16 Hz. The amplitude of the signal is considerably higher at the seal system than at the roller gate itself. This indicates a main vibration of the seal system. The significantly lower amplitude of the roller is also an effect of resonance. The vibrating seal system forces the roller to vibrate, but the large difference in mass damps the amplitude.

Since there were no vibrations before renewing the construction, it is obvious, that at least one of the influencing factors changed through renewal. From visual inspection, it seems that the new springs are less stiff and have less pretension than the old ones. Lower pretension would lead to lower contact pressure on the sealing surface whereas lower stiffness would generate lower resonance frequency of the system. Incorrect assembly of the system could be also a source of malfunction. This case is a typical example for the loss in knowledge about operating old gates. Many gates from the first half of the 20^{th} century are still operating well, so there is no need to replace them. With losing knowledge about the operation and adjustment of those gates, problems like this will arise more and more.

4. Video Analysis of Vibrating J-seal

J-seals are used as side and bottom seals on miter gates, but they are also applied as bottom seals of radial gates (see 3.2) or top seals for filling valves (see 3.1). Petrikat (1980) investigated pressure fluctuations on solid gate edges and found varying frequencies, depending on the opening width of the gate. The vibration of the seal will be strongly coupled with the pressure fluctuation in the surrounding flow field. Naudascher (1991) described this phenomenon as 'movement induced excitation' (MIE), which involves strong feedback from the vibrating structure to the flow. As mentioned in chapter 3.1., J-seals tend to vibrate with a frequency of 35 to 50 Hz. Petrikat (1980) described the vibration during small openings as an ovalling deformation of the note head, caused by the upstream water head, until the seal hits the opposite sealing surface (Figure 10). Elastic restoring forces bends the seal back and the process repeats.

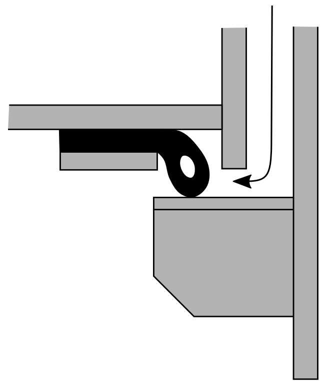

Figure 10: Sketch of a deforming J-seal. Reproduced from Petrikat (1980).

Experiences show that even J-seals with a bigger head diameter d (see Figure 1) tend to vibrate. There are J-seals with no hole inside and even those can show vibrations. In this case, a deformation of the note head like illustrated in Figure 10 does not seem likely. A laboratory experiment was conducted to gain more knowledge about the excitation mechanism. The goal was to identify the vibration mode of a J-seal and to get an idea on the critical opening widths. Therefore, a vertical plate with thickness t = 3cm was placed in a 0.6 m wide and 18 m long glass flume. Two variations of seal arrangements were tested. Figure 11a) shows a configuration, where the seal was fixed on the downstream side of the bottom edge of the gate. Figure 11 b) shows a second configuration, where a horizontal plate was added at the bottom edge of the gate on which a J-seal was mounted. The length L of the bottom side of the gate was 0.13 m and the seals head center was placed in the middle. J-seals of two different sizes were tested. In all test series, the tailwater level was raised to reach fully submerged conditions. The water head ΔH was held constant at around 0.2 m throughout the experiment. The experiment was filmed with a frame rate of 1000 fps.

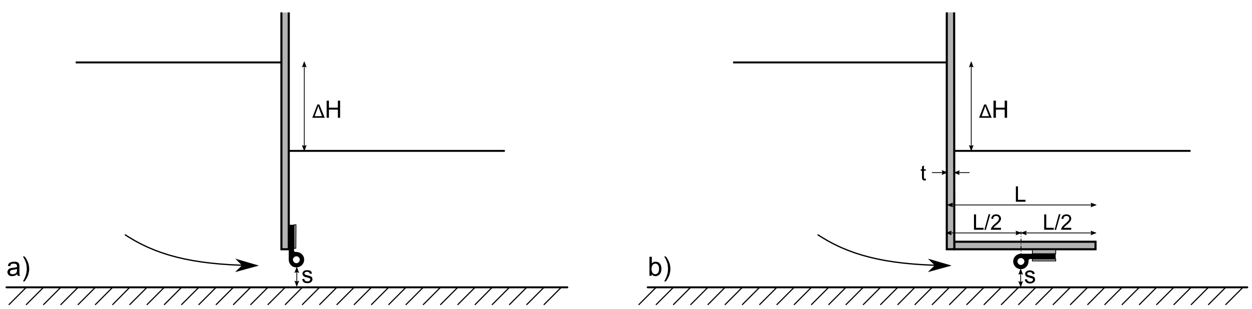

Figure 11: Sketch of the laboratory model.

In configuration a) the seal showed slight ovalling vibrations with negligible amplitudes. In configuration b) the seal showed vibrations during openings between $s = 1{,}5\ d$ and $s = 2.5\ d$ (Table 1 and 2). The dominating deformation was a bending mode (Figure 12). Although the vibration amplitude was between 1 and 2 mm, which corresponds to $1/10$ of the seal diameter, the vibrations were clearly to hear and to feel on the upper part of the gate. Overall, the vibrations described in chapter 3.2 could be reproduced. It is unclear if this effects the gates steel construction, but an elastic fatigue of the seal is probable. It can be concluded, that J-seals should only be used at hydraulic gates where no gap flow occurs, such as flood barriers or lock gates that open and close only when the water levels are equalized. Leakage should be omitted in any case. At weirs, valves or gates with underflow, flat rubber profiles are preferable as mentioned in many recommendations (Petrikat 1980, Naudascher and Rockwell 1994, U.S. Army Corps of Engineers 2000, Lewin 2008).

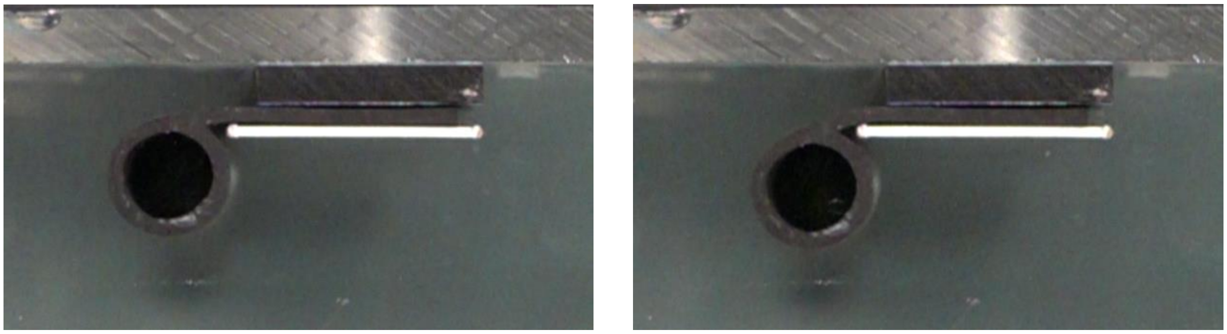

Figure 12: Highest (left) and lowest point (right) of the vibration cycle of a J-seal. The diameter of the note head is 12 mm.

Table 1: Vibration occurrence of a J-seal with head diameter d = 17 mm at different opening width.

s [mm]	16	21	26	31	36	41	46	51
s / d	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3.0
Vibration y / n	n	n	y	y	y	y	n	n

Table 2: Vibration occurrence of a J-seal with head diameter d = 12 mm at different opening width.

s [mm]	10	15	20	25	30	35	40
s / d	0.8	1.3	1.7	2.1	2.5	2.9	3.3
Vibration y / n	n	n	y	y	y	n	n

5. Numerical Simulation of Elastic Seals

For the numerical solving of FSI problems, it is possible to use two standalone solvers for the fluid and for the solid region. On the interface of the two regions, there has to be an information exchange between the solvers. In every time step, the pressure and velocity field in the fluid region is solved. The pressure and viscous forces on the interface are set as external forces on the solid region and the deflection of solid region is solved. The mesh is moved to fit according to the solid deformation and the loop starts again. This is repeated until the fluid velocity and the solid deflection rate on the surface are equal. Then the next time step starts. This method is called partitioned approach and is used in the solver package fsiFoam that can be included in OpenFOAM, a widely used open source software for computational fluid dynamics. OpenFOAM applies the Finite Volume Method (FVM) to both the fluid and solid solver. Since the coupling tends to be unstable for various conditions (e.g. small ratios of solid and fluid density) (Banks et al. 2014) and the coupling is very expensive, FSI is seldom used in real-world application and more a topic of research and development.

Numerical simulations can be useful to understand the mechanisms of flow-induced vibrations, as shown by Göbel et al. (2017) for the interaction of free surface flow with an elastically supported rigid body. By means of the interaction of flow with soft deformable structures like rubber seals, first simulations were carried out on a reduced model. The model consists of a semicircular cross section in a flow field, a simplified shape of a J-seal with a leakage gap. Figure 13 shows the deformation of the cross section.

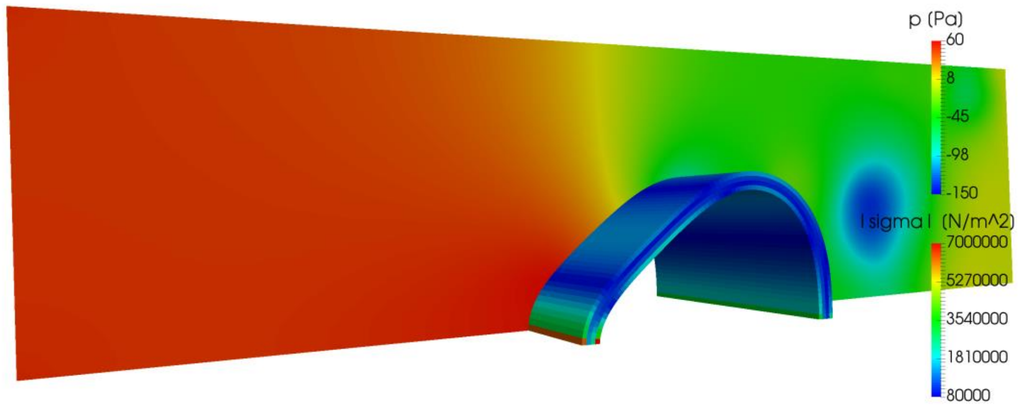

Figure 13: Deformation of an elastic semi-circle in a flow field.

The numerical experiment shows, that small scale application of FSI is possible. In general, FSI is a promising method for the future not only for academic interest, but also for practical purposes. Such applications can be the gap flow around J-seals or through small openings of underflow gates. Future goals will be the transfer on large scale models including free surface flow, such as the elastic deformation of hydraulic gates with over- and underflow. This would be not only beneficial for the hydraulic design, but also for the structural design of the gates. Additional dynamic loads are influencing the fatigue life and can be predicted using numerical models.

6. Conclusion

Despite of remarkable research in the last decades, flow-induced vibrations still cause problems in hydraulic engineering. In particular, seal vibrations are a wide spread phenomenon at existing but also at new hydraulic structures. In this contribution, examples of seal and gate vibration are described and the excitation sources detected. The difference between gate and seal vibrations is decisive for the remedy procedure.

The vibration mode of a J-seal was studied in a laboratory experiment. While other authors assumed an ovalling mode of the J-seal head, it could be observed that the J-seal moves more in a bending mode. The understanding of this phenomenon is helpful to design seal constructions which fulfill tightness, adaptability and vibrations safety. It is also shown, that FSI Simulation can be a tool to investigate FIV.

Against the background of increasing vibration incidents on German waterways, a research and development project was initiated at the BAW, in order to analyze the different vibration causes by measurements on site and by the use of numerical models. The aim is also to improve the current construction standards.

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