Axial check valve behaviour during flow reversal

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Abstract. An ideal check valve is supposed to have a zero pressure loss when the flow rate direction is positive and a negative flow rate is not possible. A real check valve has a low pressure loss and it is possible to suppress negative flow (especially when the check valve is new) under steady conditions. The transition between the steady positive flow and zero flow is often connected with a water hammer, here called check valve slam. An experimental investigation of behaviour of the axial check valve disc during the flow reversal is described in this paper. A high-speed camera was used for the disc position observation and pictures are compared with pressure pulsations and the flow rate.

1. Introduction
Check valve is an important part of pumping systems. A special care of the design of this pipeline system element can avoid many troubles in the future. There are many types of check valves: ball check valve, swing check valve, lift check valve, split disc check valve and so on. Different construction, properties and price is typical for each type. Basic requirements on the check valve properties are described in [1].

The check valve properties can be divided into static (pressure loss, tightness, reliability, durability,. . . ) and dynamic (disc stability, closing delay, sensitivity to pressure pulsations,. . . ). All of them must investigated by manufacturers and researchers to improve quality of this element. E.g. optimized pressure loss of the swing check valve using Adjoint Solver [2]; noise and vibration connected with cavitation, which can appear in the hydraulic system with a high flow velocity [3]; [4], [5] and [6] describe the dynamic characteristics of various check valves.

The dynamic characteristics shows maximal reverse flow velocity through the check valve before it shuts as a function of the flow deceleration. The higher reverse flow velocity, the higher pressure surge appears in the system. This phenomenon is called "the check valve slam" and there is a risk of the hydraulic system (or at least the check valve) damage. [7] performed a statistics of the check valve failures in the nuclear power plants. Also authors of presented paper have dealt with the check valve slam [8].

The experimental investigation of the check valve slam is rarely presented, but you can find for example papers [9] or [10].

1.1. Check valve slam
The pumping system consists of a bottom tank, a pump, a check valve, a control valve, a discharge pipeline and an upper tank. In the pump operation the liquid flows in a positive direction through the open check valve. When the pump trip occurs, the flow starts decelerating.
The deceleration depends on the system properties (length, head, pump inertia...). When the flow velocity reaches zero, the check valve is supposed to shut, but there is a delay, which varies with the check valve design, so the flow velocity can reach negative values before the check valve shuts.

When the negative flow velocity is high enough, a noticeable pressure peak (the check valve slam) appears in the system. The check valve slam is quite common problem of pumping systems and can be predicted only by known dynamic check valve characteristics. Examples of dynamic characteristics are described for example in [6], [9] or [11]. Generally, check valve producers do not offer the dynamic characteristics of their products so you need a special hydraulic circuit to measure it. The experimental investigation of behaviour of the axial check valve disc during the flow reversal is described within this paper.

2. Experiment
The experiments were performed on a special hydraulic circuit (see Fig. 1), where the flow can change its orientation to simulate conditions in a real pumping system during the pump trip.

![Experimental circuit](image)

Figure 1. Experimental circuit.

The pump is driven by a dynamometer and sucks water from the suction tank of 10 m$^3$. The water flows through the tested check valve to the small tank (2.5 m$^3$), which is pressurized by the compressed air. When the pump stops, the flow decelerates and changes its orientation. The deceleration rate can be controlled by the pressure in the small tank and by the dynamometer (pump deceleration). The steady flow can be controlled by the butterfly valve downstream the small tank. The steady flow is measured by an electromagnetic flowmeter. The pressure sensors allow the unsteady flow rate evaluation during the whole event by the Gibson (time-pressure) method. The pipeline diameter is 100 mm, the length is 12 m and material is steel.

The tested axial check valve is custom-made with inspection windows to see the position of the disc. Inspection windows are on the both sides of the body. The disc was spotlighted through one of the windows and recorded by a high speed camera through the other one.

High speed camera pictures and pressure records were synchronised via LED trigger. The trigger was recorded on camera as light and, in other data acquisition, as voltage measured on the LED.
3. Methodology

Individual frames from the high speed camera were processed, see Fig. 2 and Fig. 3. The pictures show the valve disc from the side and the spring is also visible. The disc edges position were evaluated based on the light intensity changes as is shown in Fig. 2. Outputs of this software analysis are files with positions of these edges inside the area of our interest (blue rectangle). These files were further processed. The area of interest was chosen as close to the axis as possible, to allow the disc position evaluation in the whole stroke. (It was necessary to avoid the spring, which would make the evaluation much more difficult).

Experiments were made for different conditions; such as different flow rate, pressure head and deceleration rate. Some of the high pressure pulsations during operation resulted in cavitation. Cavitation causes troubles with data processing, because it forms a great number of little bubbles, which create false edges as shown in Fig. 3. Detected edges in the cavitation mode appear as random jumps of disc position. For this reason the false detections have to be filtered out. The solution of this problem dwells in a verification, if the chosen points are creating these edges. Since the points should ideally form a vertical line, the standard deviation can be computed and compared with properly chosen threshold value. Samples which are not in compliance (partial detections or curves detected on bubbles, eventually randomly detected points in cavitation cloud) are dropped out, so the processing uses only physically correct data.

![Figure 2](image_url) **Figure 2.** Example of disc edges detection. Detected edges are highlighted with green and purple colour. The blue rectangle demarcate the area of interest.

![Figure 3](image_url) **Figure 3.** Misdetected edges on cavitation bubbles (green lines). These edges do not form straight lines. The blue rectangle demarcate the area of interest.

![Figure 4](image_url) **Figure 4.** Position of the valve disc evaluated from two edges. Correct position is highlighted by the blue line.
Beside the possible cavitation creation, the problem with size of observation windows occurs. Since the inspection window on the check valve limits the observing capabilities, both edges are not visible for the whole time. One edge is not visible, when the valve is fully open and other edge is not visible, when the valve is closed. Thus, tracking of different edges in time is needed. Problem lies in finding out when to change the tracking from one edge to the other and what criteria to use. If the positions of both edges are converted to general position of the disc, they should align at some moments. (This is the moment when both edges are visible as shown in Fig. 2). The choice of the criteria is based on comparing the standard deviations of positions composed of a few consecutive edge positions. This simply means that the criteria prefer line with smoother transition without any sudden jumps. When one of the edges hides, software detects same transition in light intensity somewhere else, hence the sudden jump of this edge position appears. Correct edge positions are then assembled so they form a line of check valve disc positions in time, see Fig. 4.

Since the disc position tracking is based purely on image processing, a high quality of images is required. Picture resolution is one of the main parameters of recording. It should be high enough to precisely capture the experimental data with sufficiently high detail without errors caused by the aliasing. The real position is calculated from coordinates of boundary positions and real disc tracking. Image tracking 500 px and real disc tracking 30 mm give the resolution of 17 px/mm, which is precise enough for our purposes. The camera sampling directly affects the precision of tracking. Generally, the higher sampling, the more precise tracking of the valve position. Although demands on the light intensity and processing power of camera has to be kept in mind. In our case the sampling frequency of camera was 257 Hz.

The dynamic behaviour of LED was also taken into account. Ideally light turns off when the voltage drops. But this drop, due to non-zero capacitance of conductor, is not instant. Operating voltage is 4.3 V and minimal operating voltage needed for the LED to emit visible light is (1.8 – 3.3) V. This minimal voltage depends on the colour of light. Since the voltage drops from the operating state under minimal voltage needed in just one sample at sampling rate of 3 kHz, the error is negligible. Greater error is created by camera, where the largest synchronisation time error is one sampling period (less than 4 ms), which is still small enough for our purposes.

4. Results

Figures 5 and 6 show pressure close to the check valve as well as the disc position during the closing process. The run with the low deceleration exhibits low pressure peak as the low reverse flow velocity evolves. The run with the fast deceleration causes fast movement of the disc, which bounces from the seat. The higher velocity of the disc the bigger reopening was visible. The reopening was up to 50% in some cases. The closing with the higher deceleration rate is shown also in the Fig. 7 together with the pressure difference at the valve ($p_4-p_3$).

The Fig. 8 shows the flow rate with the disc position for the case with the greater deceleration. The faster closing and bigger reopening is visible. The flow rate was computed by the time-pressure method and the negative flow rate when the disc shuts and the positive flow rate during the reopening can be seen. The non-zero flow rate between closing and reopening is caused by growing and collapse of the cavitation bubbles.

An interesting observation is apparent in the Fig. 5. A speed change of valve closing results in longer closing time. This phenomenon occurred more or less in every measurement and we were not able to connect this behaviour with any hydraulic property. The phenomenon is not visible in the Fig. 6, where the closing speed of the valve does not change when it reaches maximal value.

The change in the disc velocity is quantified in the Fig. 10. When the disc position is extrapolated by the linear function according to Fig. 9, it is possible to find an expected closing time $t_E$ and compare it with the real closing time $t_R$. 

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5. Summary
The experimental measurement of an axial check valve behaviour during the flow reversal is described within a paper. The check valve was equipped with inspection windows to allow the
disc position observation and was tested in the hydraulic circuit with required parameters (head, flow rate and deceleration). The high speed camera was used for the position determination of the check valve disk in time. All these data were processed to show the dependencies between the disc position and other observed parameters such as pressure and flow velocity. Variations in the disc velocity during the closing were observed as well as a rebound of the disc from the seat.

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