High-Pressure Air Injection on a Low-Head Francis Turbine

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Abstract. Birecik is a Turkish hydroelectric power plant located at the Euphrat River in the southeast of Turkey. During commissioning of the units, a vibration phenomenon was discovered, restricted to a small power band. The cone which supports the thrust bearing and which is braced against the turbine head cover started to vibrate at its natural frequency. Investigations showed the vibrations to be innocuous to the lifetime of the machine. Exhaustive vibration measurements on site pointed to hydraulic source for the vibration. Detailed flow simulations by means of computational fluid dynamics (CFD) were carried out. They permitted the detailed analysis of a variety of transient flow phenomena happening inside the machine. They revealed the presence of interblade vortices in the power and head range where the vibrations occurred. As a consequence, it was suggested to inject air downstream of the wicket gates through the head cover. In 2012, one unit of the Birecik power plant was equipped with such an air injection system. As soon as the air injection was turned on, the machine operated calmly in the small power band where vibrations had been observed before. The necessary air volume was considerably smaller than expected to be necessary for a calm operation.

1. Introduction

Birecik is a run-of-the-river hydroelectric power plant located at the Euphrat River in the southeast of Turkey, linking the two provinces Gaziantep and Sanliurfa. It is a “build-operate-transfer” (BOT) project financed by the Birecik Company, and operated by the Austrian Verbundplan company. In 2016, the power plant will be turned over to state of Turkey. The plant has 6 Francis units with vertical axes. Commissioned in the year 2001, they have an overall maximum power output of 672 MW. The gross head is about 45m, the maximum water discharge 320 m^3/s per unit. The rotational speed is 107.14 rpm. The overall power production averages 2.5 * 10^9 kWh per year.

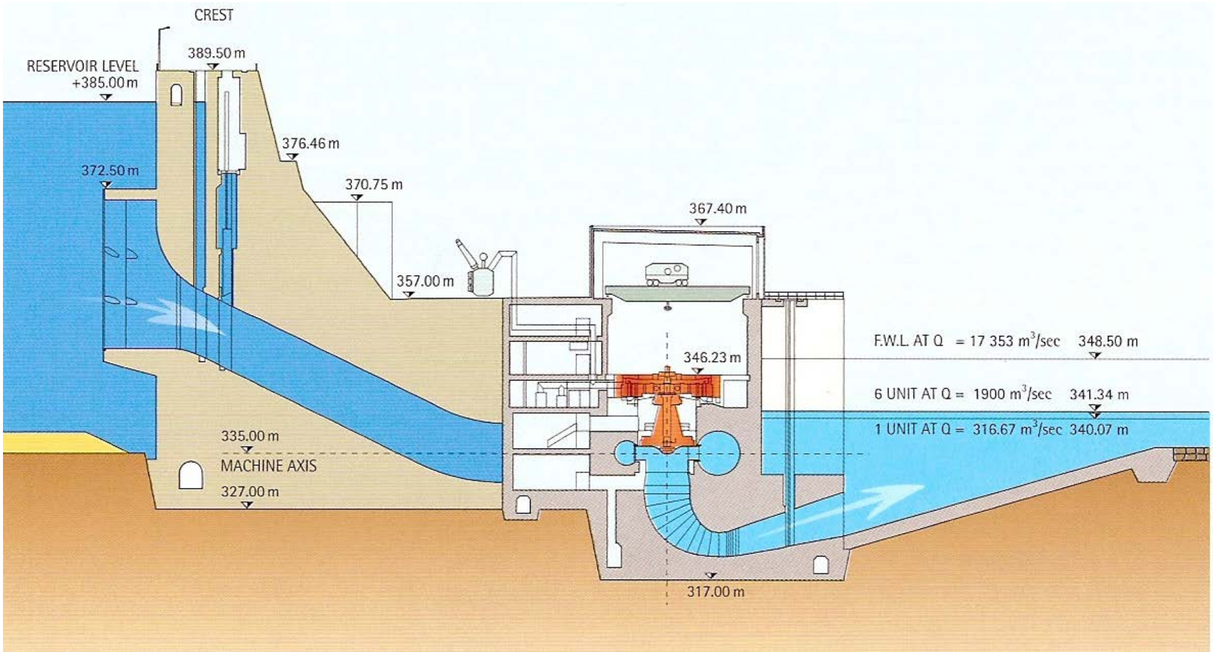

Figure 1: Cross section through the intake and the power house [1].

During commissioning of the units, a vibration phenomenon was discovered. It was restricted to a small power band of around 95 to 105 MW, at high heads. In this band, the cone which supports the thrust bearing and which is braced against the turbine head cover, started to vibrate at its natural frequency of 65 Hz. Investigations showed the vibrations to be innocuous to the lifetime of the machine. Already in 2007, each unit had experienced at least 0.5 x 10^9 load cycles of the 65 Hz vibrations, meaning the units had reached the fatigue endurance limit without any damage caused by the vibrations. Still, the origin of the vibration phenomenon was not understood.

Over the years, several measurement campaigns and studies were carried out by the manufacturer of the turbines as well as independent consultants. Various possible sources of the vibration phenomenon were discussed, but no study was conclusive. Since the vibration occurred only in a small power band at high head, the investigations pointed to the hydraulic system as source. One possible cause for the vibration was found in the stay vanes, which shed Von Karman vortices from their trailing edges. A modification to the trailing edges removed this possibility, but did nothing to changing the vibration problem. However, all studies pointed out that the vibration was not harmful to the machine and no failure was to be expected.

In an attempt to investigate possible excitation sources in the hydraulic system with modern simulation tools, extensive flow simulations with state-of-the-art computational fluid dynamics (CFD) were carried out. A number of transient flow phenomena could thereby be investigated in detail. Meanwhile, a cleverly conceived series of vibration measurements was conducted on the prototype machine. The combination of the two studies then allowed the formation of the most comprehensive picture of the vibration problem to date.

2. CFD Simulation

To better understand the flow behavior in the turbine which could lead to vibrations, a number of transient flow simulations by means of computational fluid dynamics (CFD) were done. The commercial CFD software package CFX 11 was used for all flow simulations. All simulations were done for an incompressible, mono-phasic fluid. Flow phenomena that were investigated in particular were the interaction of the runner with the wicket gates (a well-known source of vibration problems, mostly on high-head machines), Von Karman vortex-shedding from the stay vanes and wicket gates, and interblade vortices. The part-load vortex rope in the draft tube could be ruled out as source of excitation, as its frequency is usually around 1/3 of the rotational speed and therefore much below the excitation frequency looked for [2].

2.1. Rotor-Stator Interaction

The CFD simulations of the rotor-stator interaction between wicket gates and runner showed feeble excitation amplitudes with frequencies outside of the 60 – 70 Hz range in question, both for points in the absolute frame of reference, as well as for points in the rotating frame of reference.

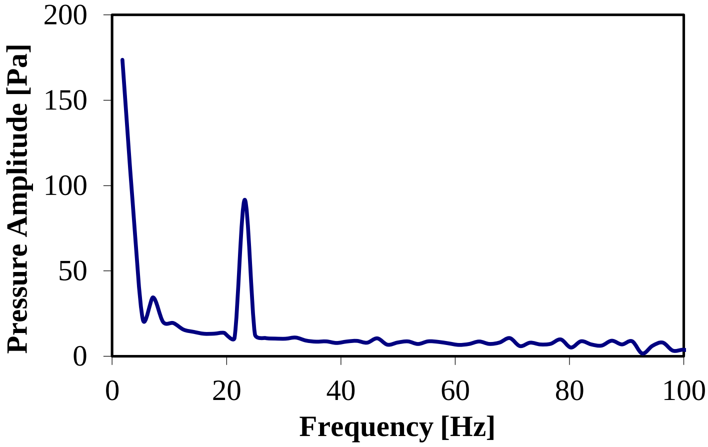

Figure 2: Frequency and amplitude of the rotor-stator interaction in the stationary frame of reference.

2.2. Von Karman Vortices

Von Karman vortex-shedding from the stay vane and wicket gate trailing-edges could be a source of excitation for vibrations [3]. Transient CFD analysis showed considerable vortices being shed from the trailing edges. The frequency of the Von Karman vortices being shed from the wicket gates were shown to be around 220 Hz and therefore much higher than the excitation frequency sought for.

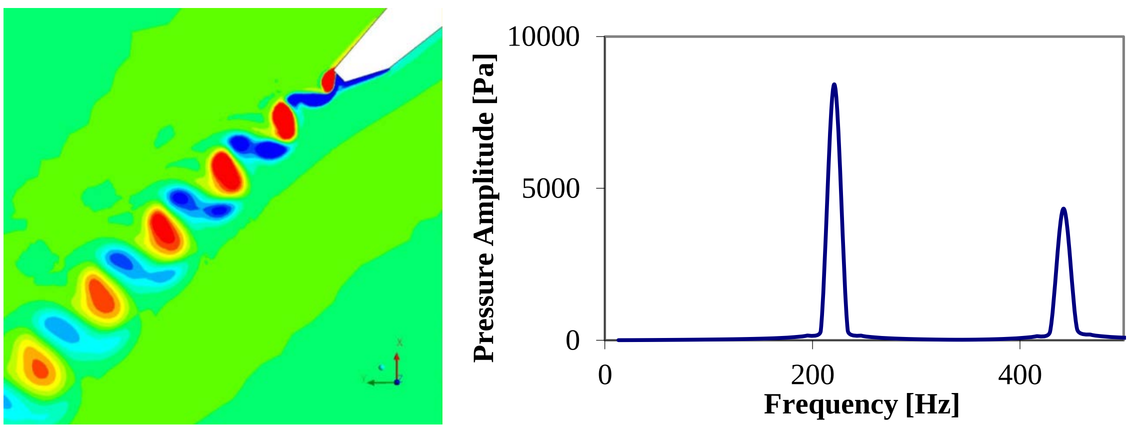

Figure 3: Von Karman vortex-shedding from the trailing edge of a wicket gate, with a frequency around 220 Hz.

The analysis of the stay vanes, however, revealed Von Karman vortices being shed with a frequency around 85 Hz, close to the critical frequency around 65 Hz and within the precision range of the frequency prediction by CFD [4]. Taking into account some calculation inaccuracies, as for example a finite mesh resolution, this could very well have been the source of the vibration problem. An extension to the existing stay vanes brought about a considerable reduction in the amplitude of the vortices. In fact, there is no predominant frequency anymore. After their modification, the stay vanes could be excluded as source of the vibration. But still, the problem of the vibration on the thrust-bearing support cone persisted.

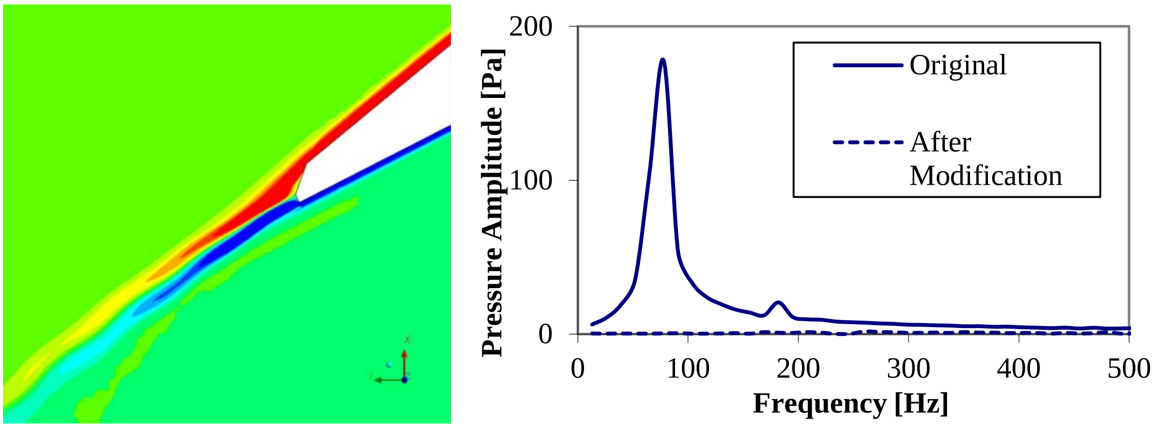

Figure 4: The trailing edge of a stay vane before and after modification. After modification the Von Karman excitation is eliminated.

2.3. *Interblade Vortices*

A transient CFD analysis of the whole hydraulic system of the turbine, from spiral casing to draft tube, was then done to get a comprehensive picture of the flow phenomena occurring in the turbine [5]. This analysis revealed that interblade vortices were present in a large part of the operating range. This had partly been known from the cavitation observations done on the test rig.

Interblade vortices are a common flow phenomenon in hydraulic Francis turbines, especially for low head machines like Birecik. At the optimum, the water flow is perfectly aligned with the blade. At low discharge, or at heads far away from the optimum, the water makes a circling motion inside the blade channel, which usually starts close to the leading edge. Depending on the pressure level, the core of such a vortex can cavitate, which makes it possible to easily observe its behavior in the hydraulic laboratory. By its very nature, such a vortex is not stable and it can easily be imagined to cause a vibration. If this vibration hits the excitation frequency in the 60 – 70 Hz range, it can excite the thrust bearing cone and be the root cause of the vibration.

The CFD analysis showed interblade vortices starting from the leading edge, very close to the hub. The simulation did, however, not reveal any dominant frequencies linked to these vortices. This might be due to the fact that the simulation was done mono-phasic, i.e. without a cavitation model. Streamline visualization showed that air injected on the head cover would be drawn into the vortex and would consequently attenuate the vibrations in the vortex core. Based on these observations, it was suggested to test air injection through the head cover to mitigate the vibrations in the thrust bearing cone.

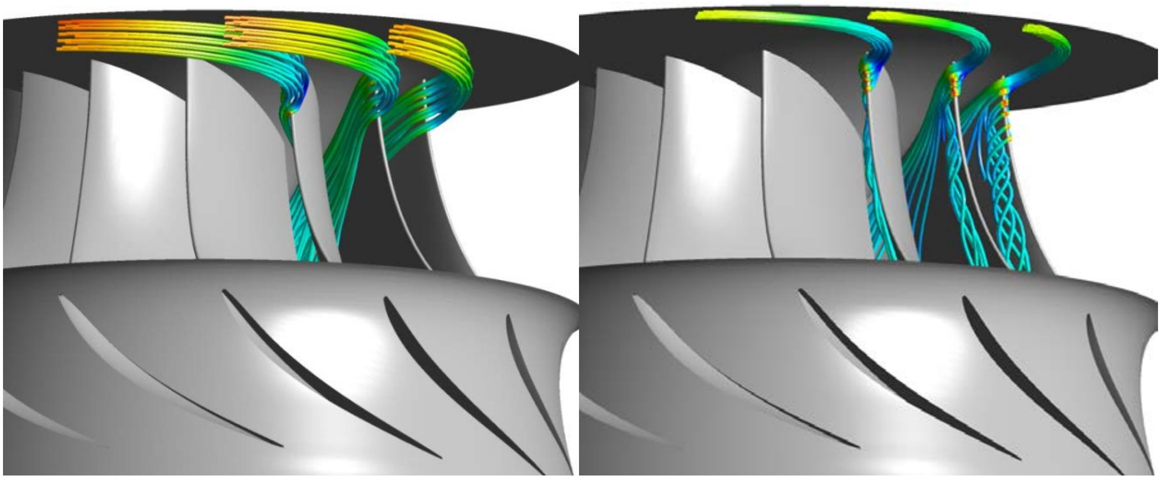

Figure 5: Streamlines in the Francis runner: for the optimum operating point (left) and the vibrating operating point (right). The interblade vortices are clearly visible on the right.

3. Vibration Measurements

Parallel to the CFD investigations, an exhaustive measurement campaign was conducted on one of the prototype machines. It permitted the formation of a comprehensive picture about the vibrations occurring on variety of locations in the machine. Measurement probes for pressure, vibration and strain were installed on the head cover, the thrust-bearing support cone, on the wicket gate stems and levers, and on the draft tube cone. The machine was then operated at different operating points, from part-load to full-load, and the signals of the various probes were recorded.

The measurement campaign confirmed the impression that in a small power band the machine shows high vibration amplitudes. The high amplitudes very most notably measured on the thrust-bearing support cone. It showed vibrations up to 10 mm/s (RMS) in the zone where the cone vibrates at is natural frequency of 65 Hz. The same vibration was also measured on the combined bearing and on the head cover, though with lower amplitudes.

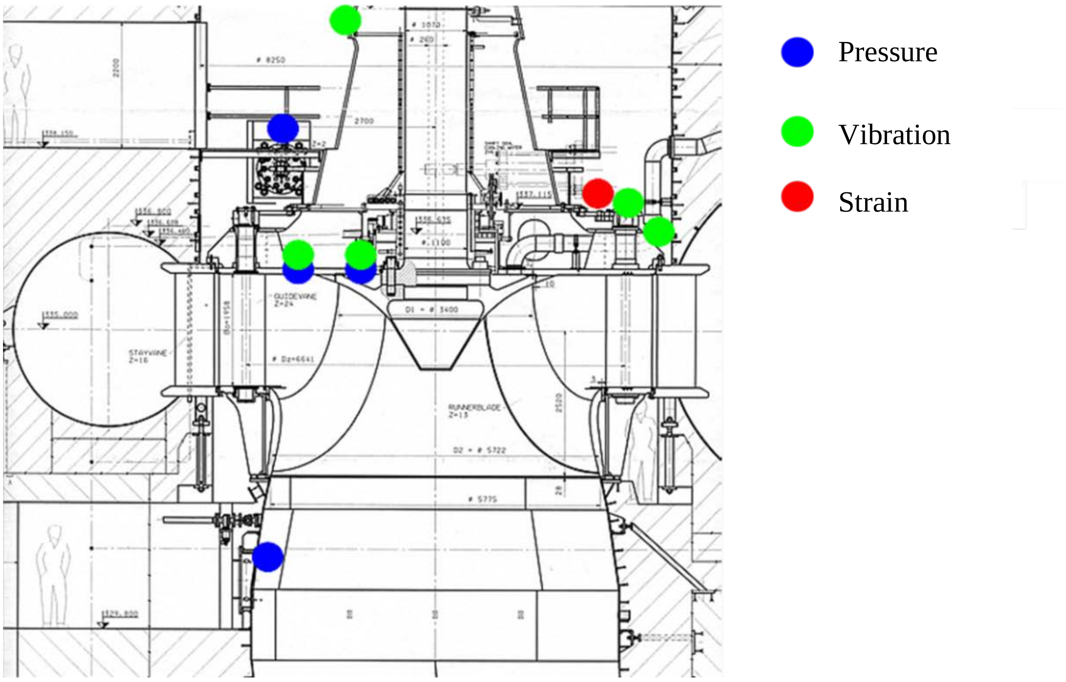

Figure 6: Turbine cross section and locations of the sensors for pressure, vibration and strain.

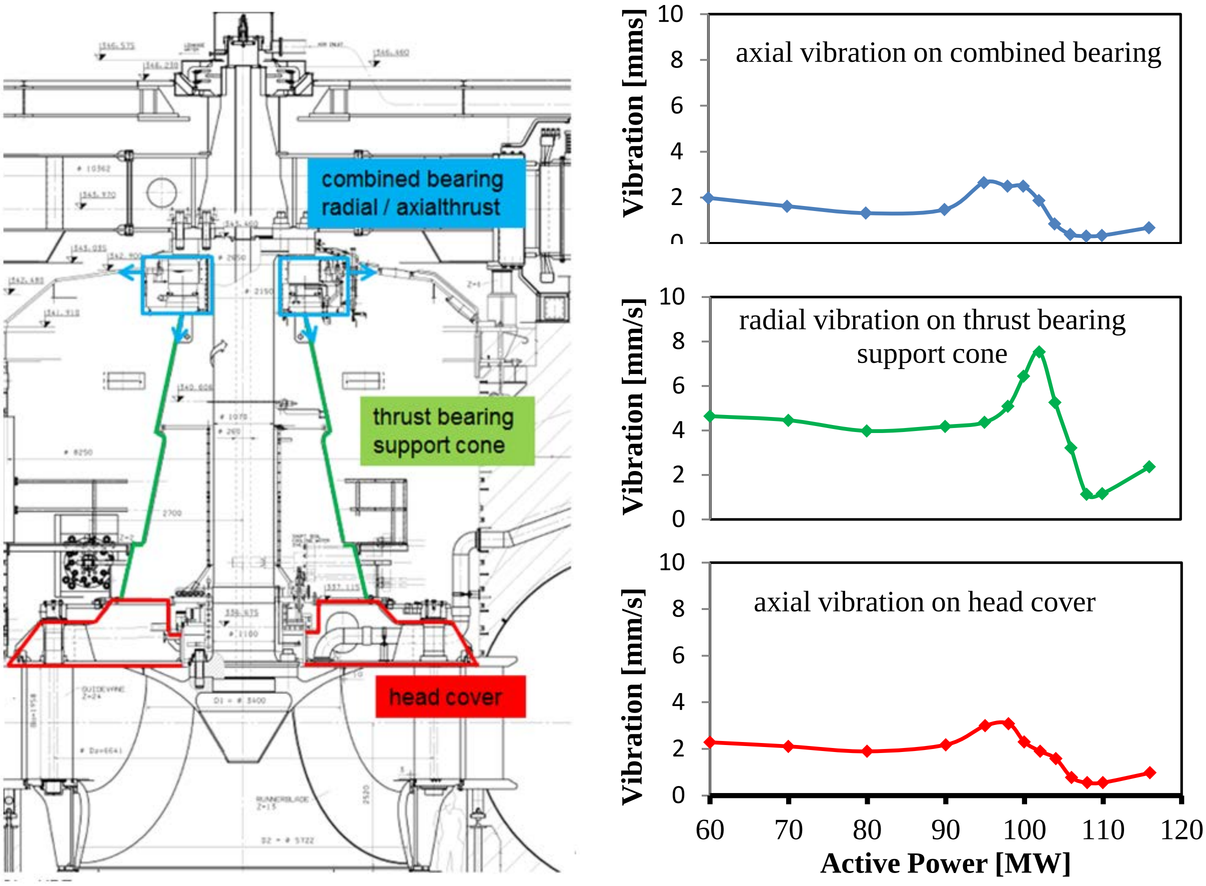

Figure 7: Turbine cross section and results of the vibration measurements for different sensor locations.

The prototype measurements showed that the vibration phenomenon could easily be reproduced. However, it did not permit to pinpoint the source of the excitation. As an easy test, it was suggested to use the air relief pipe, which is usually used to de-aerate the unit after synchronous condenser mode, to inject air into the head cover, and from there into the runner channel. This simple makeshift arrangement proved to have an enormous effect on the vibrations. As soon as the air had filled the runner side-chamber and entered into the runner channel, the vibrations on the thrust-bearing support cone were drastically reduced. This was taken as proof for the theory that the interblade vortices are the source of the vibration phenomena, and that air injected into the core of these vortices would solve the vibration problem.

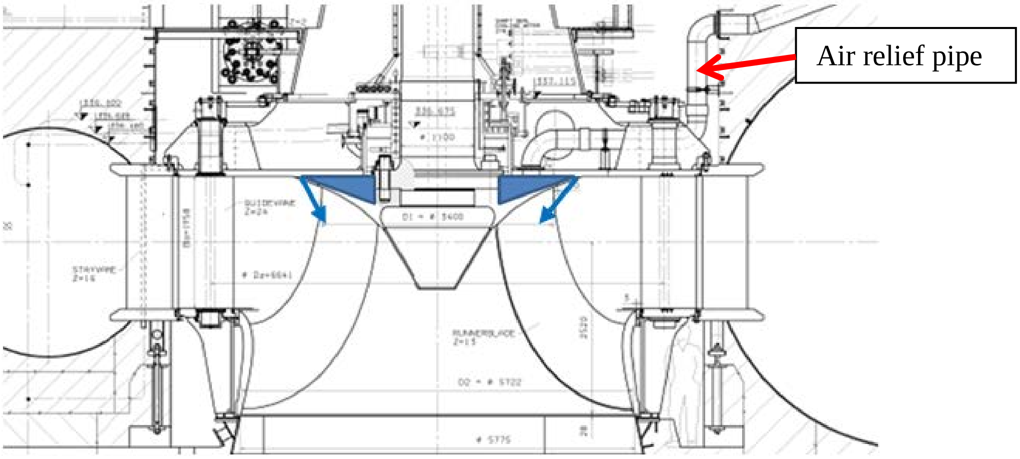

Figure 8: Location of temporary air injection for measurements.

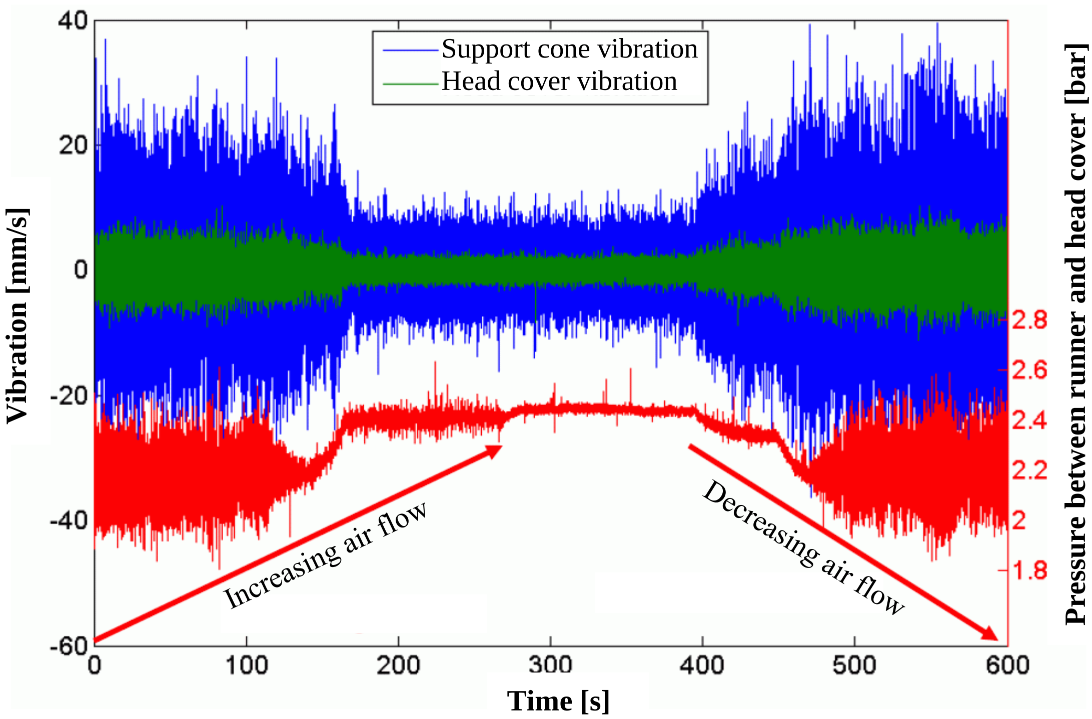

Figure 9: Measured influence of temporary aeration in the operating point which shows a strong vibration on the support cone.

4. Air Injection

Air injection is a common measure to reduce pressure fluctuations and vibrations originating from the hydraulic system of a turbo machine [2], [6]. After the improvisational test with air injection through the air relief pipe had proven to be a success, a proper air injection system was installed. One unit was equipped with a compressor and 24 air injection spots on the head cover, one behind each wicket gate. Each individual air injection was equipped with a ball valve to test the effect of opening and closing it. With this setup, the necessary air amount and number of air injection spots needed could be determined.

The unit was kept running at the same operating point during the tests, that is, at the operating point with the highest vibration level on the thrust-bearing support cone. The amount of air injected through the head cover and the number of injection spots were varied.

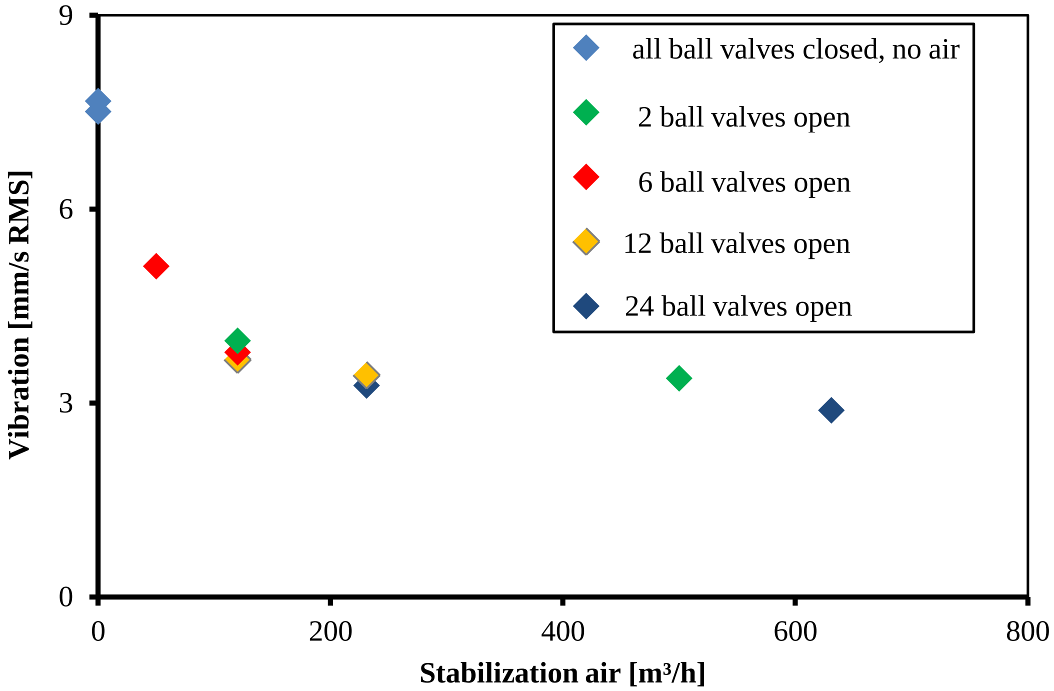

Figure 10: Measured influence of temporary aeration in the operating point which shows a strong vibration on the support cone.

The dots in figure 10 represent the vibration measured on the thrust-bearing support cone. With the air injection turned off, the vibration level is at about 7.5 mm/s (RMS). This value drops to about 2.9 mm/s for all air injection spots open and full aeration capacity. It can clearly be seen that the vibration level decreases with increasing air flow. Surprisingly enough, closing half or more of the injection spots affects the reduction of the vibration level only very marginally.

Based on the findings of these measurements, a permanent aeration system was installed on all 6 units with only 2 air injection spots, placed opposite of each other on the head cover, and 200 m³/h of stabilization air. The power consumption of the air compressor amounts to only about 0.025% of the generated power per unit and is therefore negligible. Based on the head and the wicket gate opening, the compressor is regulated such that it is only turned on in the operating range with high vibrations. After equipping all units with such a system, the effect of the air injection was tested again on each individual machine. Although the vibration level with the aeration turned off varies for the 6 units, the effect of the aeration on the vibration level was shown to be significant for all units.

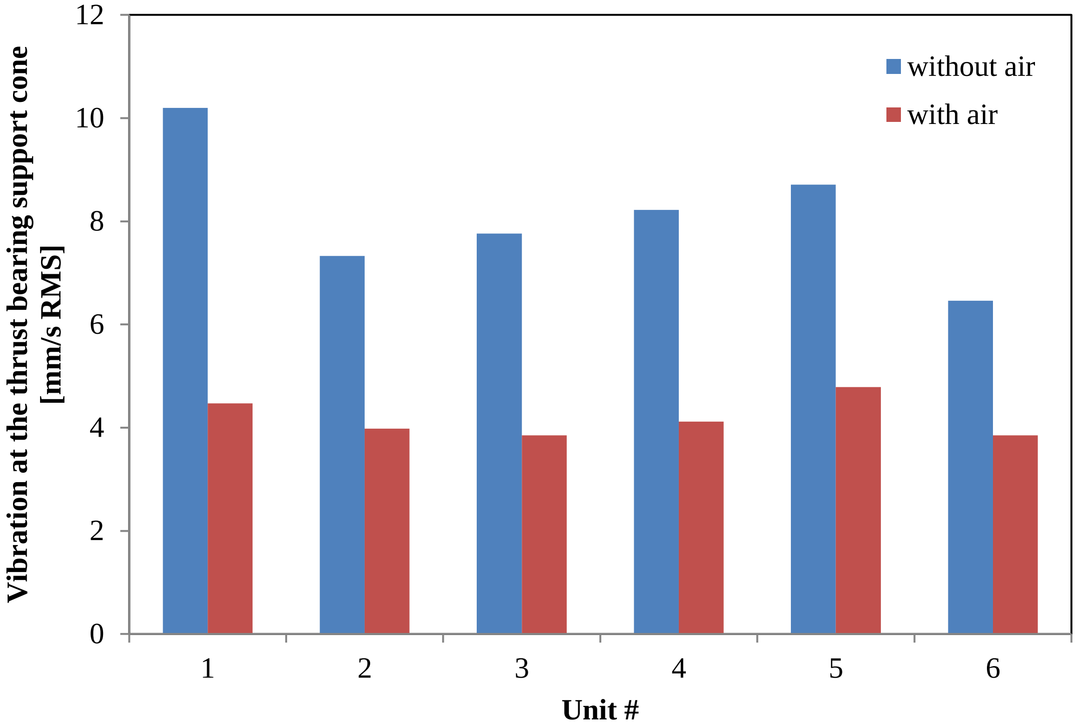

Figure 11: Example of the reduction of the vibration level. The vibration level was measured for all 6 units at the thrust-bearing support cone.

5. Summary and Conclusions

Exhaustive CFD simulations allowed the investigation of a number of unsteady flow phenomena occurring in hydraulic turbines. The interblade vortices in the runner were pinpointed as excitation source of the support-cone vibrations on the Birecik power plant. A simple test with a makeshift air-injection into the runner side-chamber proved this theory. It showed that damping of the interblade vortices substantially reduces the vibrations. A permanent air injection system through the head cover was installed and the effect of the number of air injection points and the amount of air were systematically tested. It showed that two air injection spots per machine were sufficient for calm operation. The impact on the efficiency of the machines is negligible. The same air injection system was installed on the rest of the units. All machines show significantly lower vibration levels with air injection.

Acknowledgements

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