Modal analysis of a river exploitation power house, with and without the turbine/generator units being in operation

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ABSTRACT: The Eglisau River Exploitation Station has been built in the years 1905 to 1910. It is located on the Rhein River on the border between Switzerland and Germany and contains seven vertical axis Francis Turbine/Generator units. The power house is under protection as a historic monument. The owner of the power station, NOK, Nordostschweizerische Kraftwerke AG, plans to exchange the existing units through new Kaplan Turbine/Generator units. FE model calculations had shown that there might be a risk of ending up in structural vibrational problems when increasing the rotational frequency to f = 1.85 Hz from the actual f = 1.39 Hz. To allow validation of the respective model, experimental modal analyses using AVT, Ambient Vibration Testing, technology were performed. As a first attempt with the turbine/generator units being in operation failed, a second successful attempt was undertaken with the units being shut off. The paper discusses the reasons for the failure and success respectively.

1 THE STRUCTURE

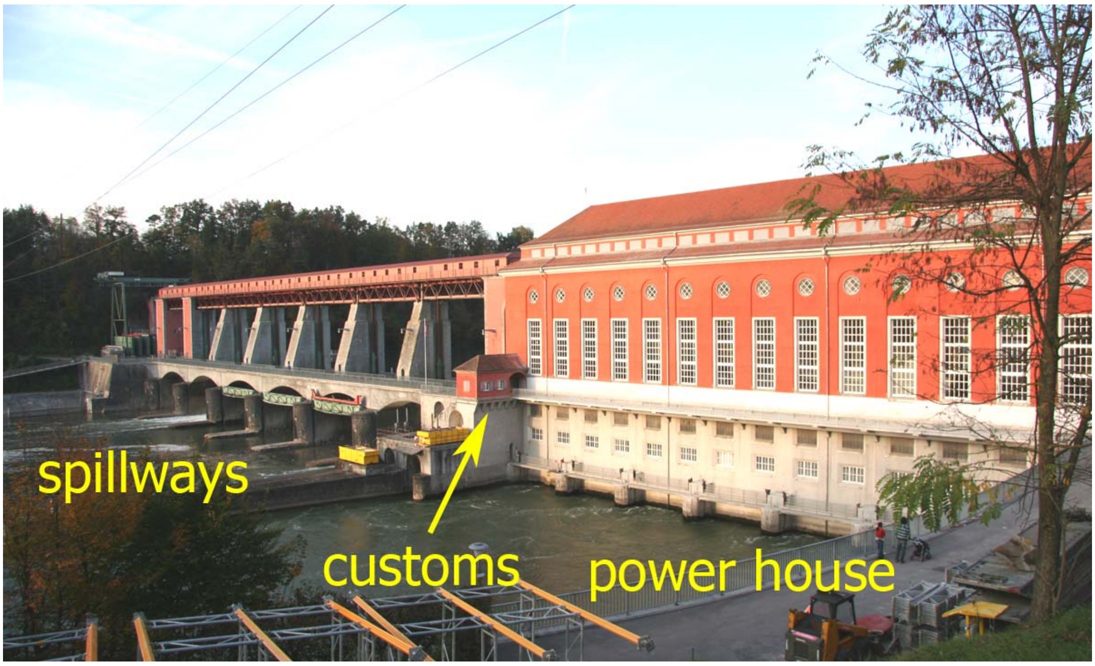

Figure 1 : The Eglisau Power Station from the downstream side. The old customs building is out of operation today.

The Eglisau power house is a reinforced concrete structure of about 90 m in length, 17 m in width and 45 m in total height (Fig. 1). It contains seven vertical axis Francis turbines and generators. Figure 2 gives a view into the machine house. We call the visible floor "machine floor" and the visible roof the "roof floor". What we can see on the machine floor are the covers of the seven generators. Underneath the machine floor, there is the so-called "turbine floor" which the top of the turbines is fixed to. The turbines themselves are located below the turbine floor where the power house is founded in rock (Fig. 3).

Figure 2 : View on the power house machine floor.

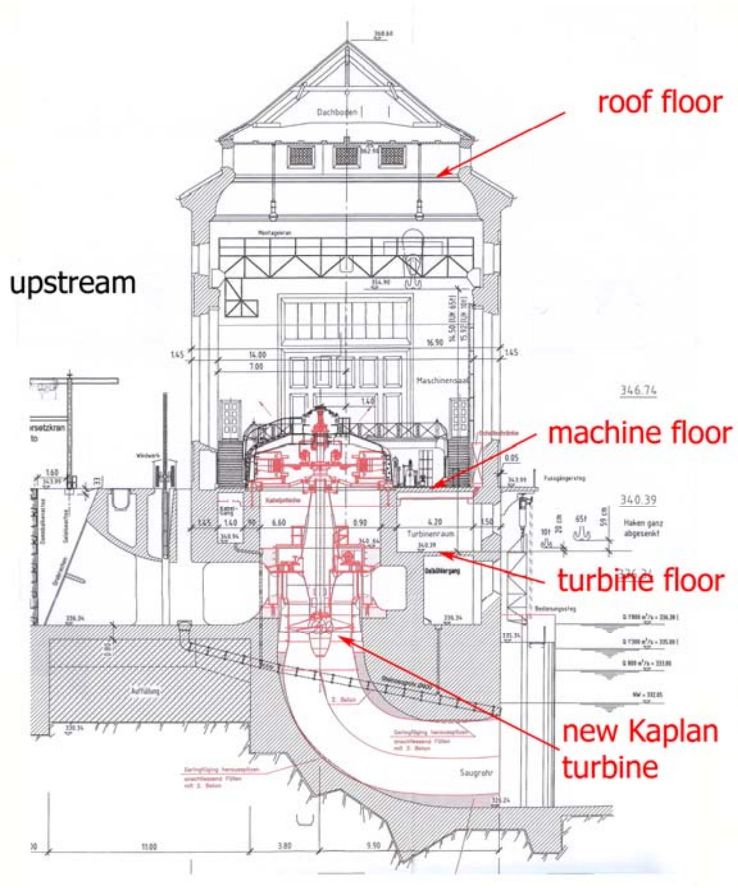

Figure 3 : Eglisau power house cross section (schematic).

2 INSTRUMENTATION

A global and a local ambient test were planned to identify the structure's natural vibrations. The global test was concentrated on the power house global behavior whereas the local test was concentrated on the region of units G7 and G6. Due to space restrictions the local ambient test cannot be discussed here. It can however be mentioned that this test was performed with the turbine/generator units shut off and that the results were of very good quality.

Figure 4 shows a plan view of the instrumentation layout on the machine floor level. G1 to G7 indicate the position of the seven generators. It also shows the fact that there are two vertical joints from top to bottom dividing the power house into three parts: Between units G6 and G5 and between units G3 and G2. It was one of the basic goals of the investigation discussed here to identify the effect of these joints on the structural dynamic behavior of the power house. Therefore, a measurement section was located on both sides of these joints. The roof floor and turbine floor were instrumented in the same way as the machine floor.

This resulted in a total of 36 measurement points or 72 degrees of freedom. It was decided to concentrate on the horizontal behavior of the power house for global identification. The local identification, as mentioned above, was performed with using three-dimensional measurement points.

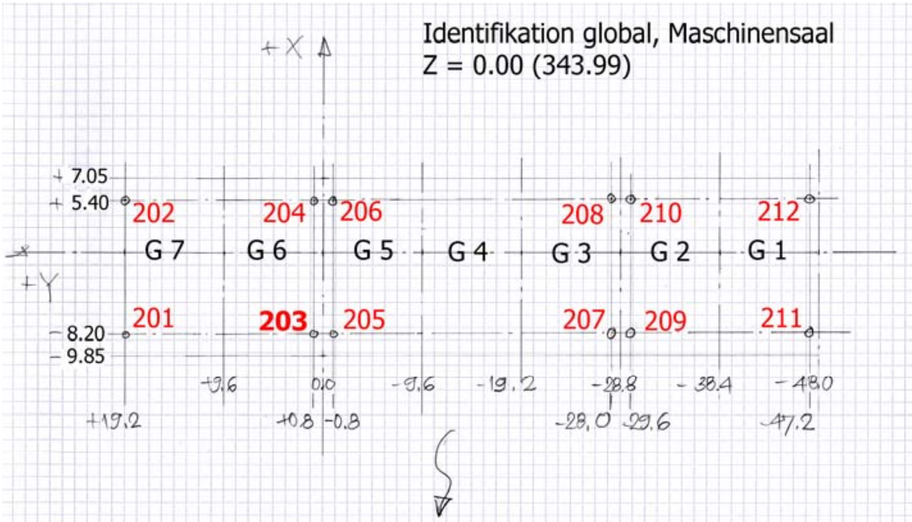

Figure 4 : Plan view of the instrumentation on the machine floor level for the global test. 203 is the reference point. Dimensions: m.

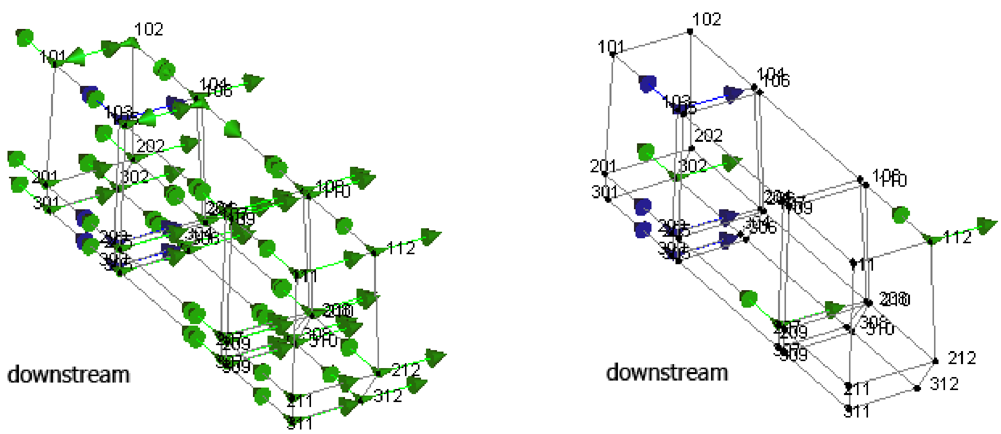

Figure 5: All measured degrees of freedom (left), and DOF's measured in setup 2 (right, references in blue). The levels "roof floor", "machine floor" and "turbine floor" can easily be identified. (The DOF's had to be adjusted to reality, the sensors not always having been installed in the planned horizontal directions.)

3 DATA ACQUISITION AND PROCESSING

As can be seen from Figure 5, 12 DOF's were acquired in each setup with six DOF's being references and six being rovers. The number of reference DOF's seems to be quite generous but it was felt that the two horizontal directions should be referenced on all of the three measurement levels. Basically, there can hardly be too many references. The total of 66 roving DOF's was worked through with 11 setups.

The accelerometers used were of the PCB 393B31 type (10 V/g sensitivity) and the data was acquired using an LMS Pimento frontend (24 bit resolution) and a laptop computer (Fig. 6).

Figure 6: A 2DOF- Sensor support (left) and the measurement center (right).

The sampling rate was set to s = 200 Hz, the length of the time window per setup was chosen to 1'800 s (30 minutes). The latter was chosen to roughly 2'000 times the period of the lowest frequency involved, f = 1.39 Hz, T = 0.72 s, which would be 1'400 s. As many problems with data processing were to be expected, the length of the time window was chosen as to definitely be not too small.

The SVS ARTeMIS software suite was applied to process the data. To process the data of the test with the turbines being in operation (TUon), the FDD (Frequency Domain Decomposition) procedure offered by ARTeMIS Extractor could be applied only. For TUoff, EFDD (Enhanced Frequency Domain Decomposition) could be applied. Therefore, for TUon, no damping coefficients could be estimated. This fact was one of the main reasons for not accepting the TUon test results. The background question here was if resonance problems were to be expected and damping is a decisive factor when dealing with problems of this kind.

4 TEST PROGRAM

The test equipment was installed Monday, October 1st, 2007. Distributing the cables from the measurement center located close to unit G6 on the machine floor to the roof and turbine floors, such that there was enough cable length available to cope with all 11 setups was the time consuming part here. The global test with the units running and subsequent change of the instrumentation to "local" was performed Tuesday. Tuesday evening, data analysis yielded that the data quality was not good enough to allow identification of the structure's normal modes.

Wednesday morning, negotiations with the power station management yielded that they could shut off the units, but only once. According to the original planning in case the units would have to be shut off the local test would have been performed on day X and the second global test on day X+1. This had to be changed. The shut off process being completed after 1 hour and a half, the local test was performed Wednesday between 10 am and 5 pm, the second global test was ready 7 pm and finished 1 am, and the whole operation was finished 4 am Thursday morning. Restarting of the units is even more time consuming than shutting them off: about 4 hours. It can be added here that all seven units had been shut off exactly once in the power station life time: during the flood of 1999, when the Rhein River contained so much wood that the spillways had to be opened and the power station had to be closed down.

5 RESULTS

5.1 SVD Diagrams

With the sampling rate s = 200 Hz, the Nyquist frequency lies at f = 100 Hz. The 0…100 Hz SVD diagrams (Singular Value Decomposition) for both global tests are presented in Figure 7. It becomes clear that the structural response for TUon is dominated by the vibrations forced by the units rotating at f = 1.39 Hz (and including all harmonics) and that for TUoff, the main energy of the response is concentrated in the range below f = 10 Hz.

Concerning the rotation of the units: There is no synchronisation problem here because all the seven units are driven through the frequency required by the power network (50 Hz). Reduction of this frequency to f = 1.39 Hz is a consequence of the number of pole shoes located at the generator circumference (36). And this driving frequency is taken from the network. Therefore, all seven units rotate with exactly the same frequency, which, at least, is nice.

For the continuation of the discussion the f = 0…10 Hz range will be taken into consideration only. Figure 8 gives the same SVD diagrams as Figure 7 but for f = 0…10 Hz and with the picked modes indicated. For TUon it is easy to see that small signs of natural structural vibrations can be distinguished between the peaks representing the turbine's rotation. For TUoff almost all peaks represent physically meaningful modes. For some peaks, where no mode indicator line is given, damping estimation using EFDD was not possible. Damping estimation using EFDD requires manual estimation for all modes and all setups. Problems arise in cases where a mode exists in some of the setups but not in all of them.

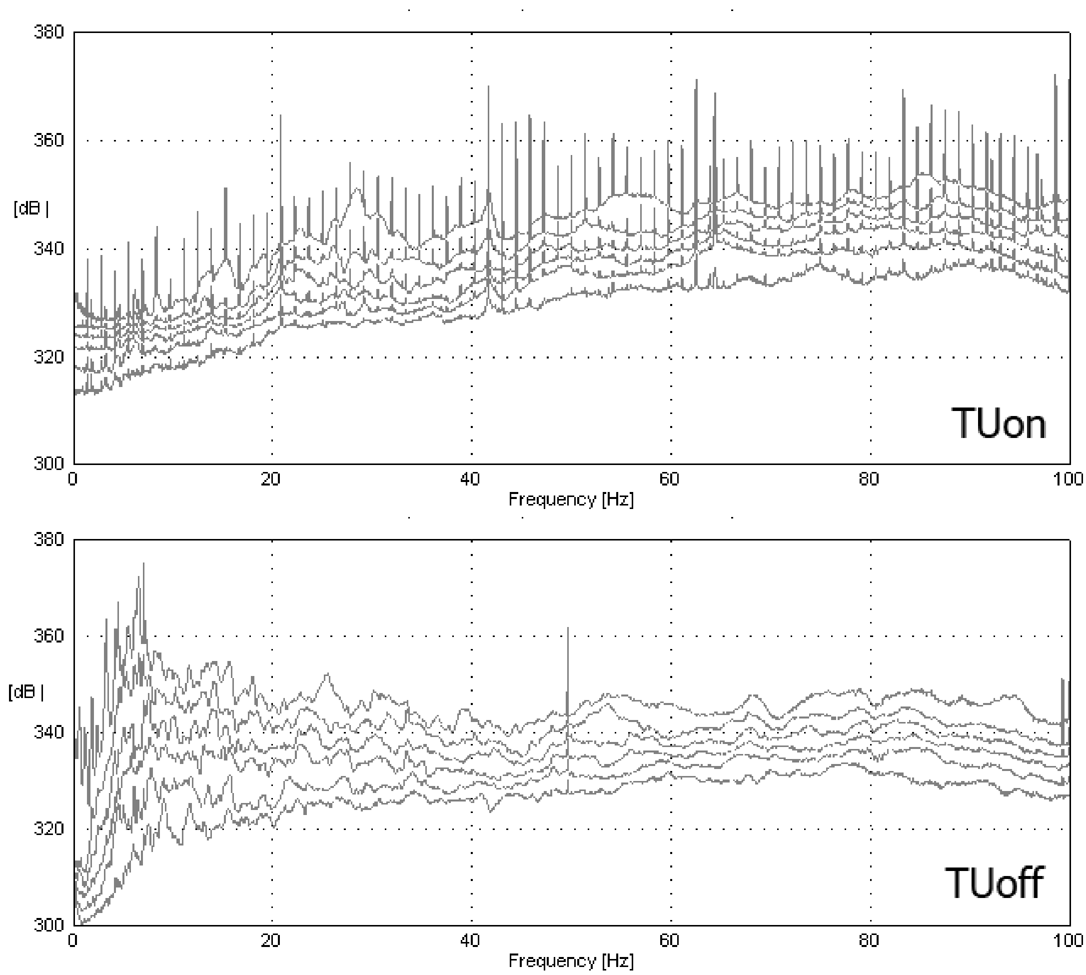

Figure 7 : SVD Diagram (Singular Value Decomposition) for all 11 setups for TUon and TUoff .

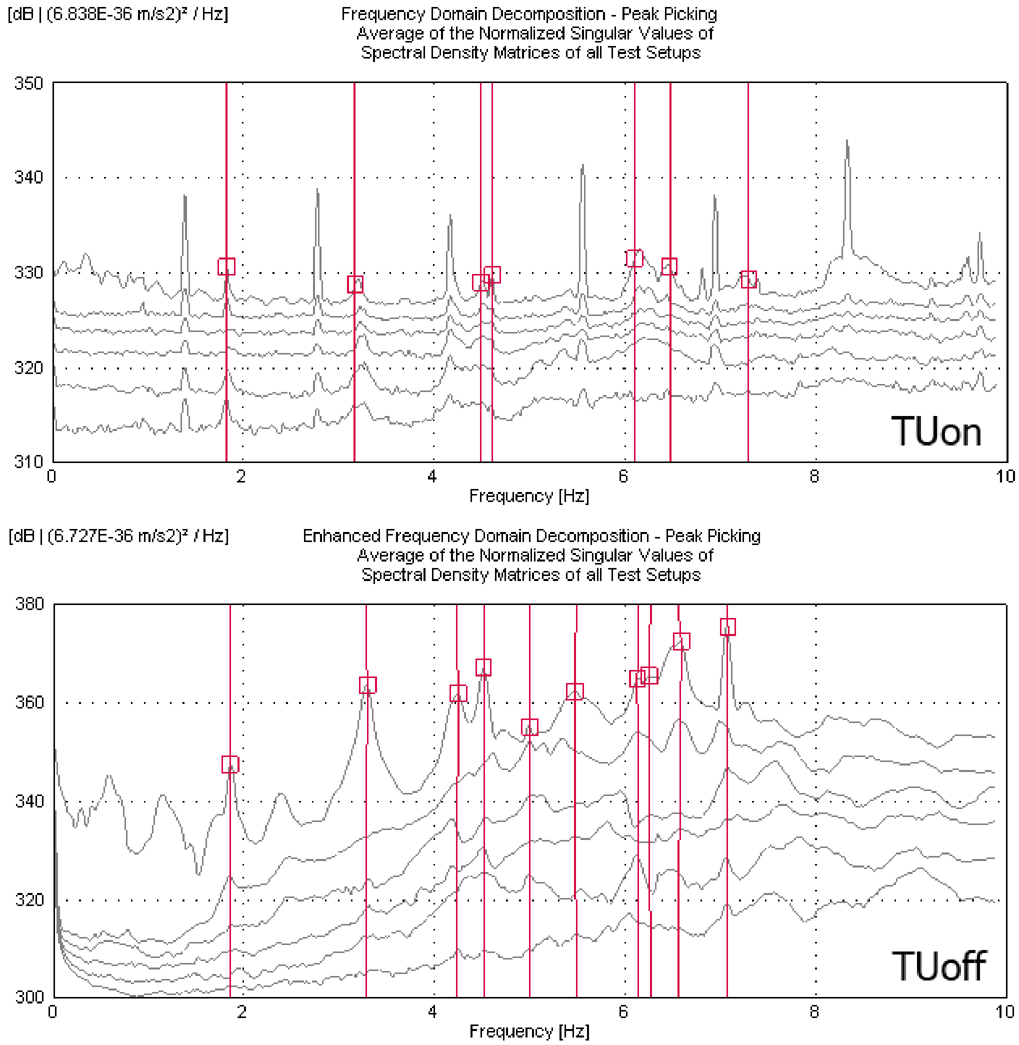

Figure 8 : SVD (Singular Value Decomposition) for all 11 setups for TUon and TUoff.

5.2 Natural frequencies and mode shapes

The modes having been "identified" according to Figure 8 are summarized concerning frequency and damping (for TUoff) in Figure 9. This figure also gives the MAC value. The related mode shapes, as far as mode pairs could be established, are given in Figure 10.

Mode pair	freq. TUon [Hz]	freq. TUoff [Hz]	damp. TUoff [%]	st. dev. damp. TUoff [%]	MAC TUon/TUoff
1	1.83	1.86	1.15	0.16	0.003
2	3.17	3.29	0.91	0.06	0.15
		4.24	1.15	0.19	
3	4.49	4.52	0.73	0.06	0.47
		4.99	0.46	0.11	
		5.49	2.16	0.32	
4	6.10	6.15	0.55	0.16	0.64
		6.27	0.44	0.16	
5	6.47	6.55	0.75	0.18	0.82
6	7.30	7.07	0.31	0.03	0.51

Figure 9 : Natural frequencies as determined for TUon and TUoff plus damping values for TUoff.

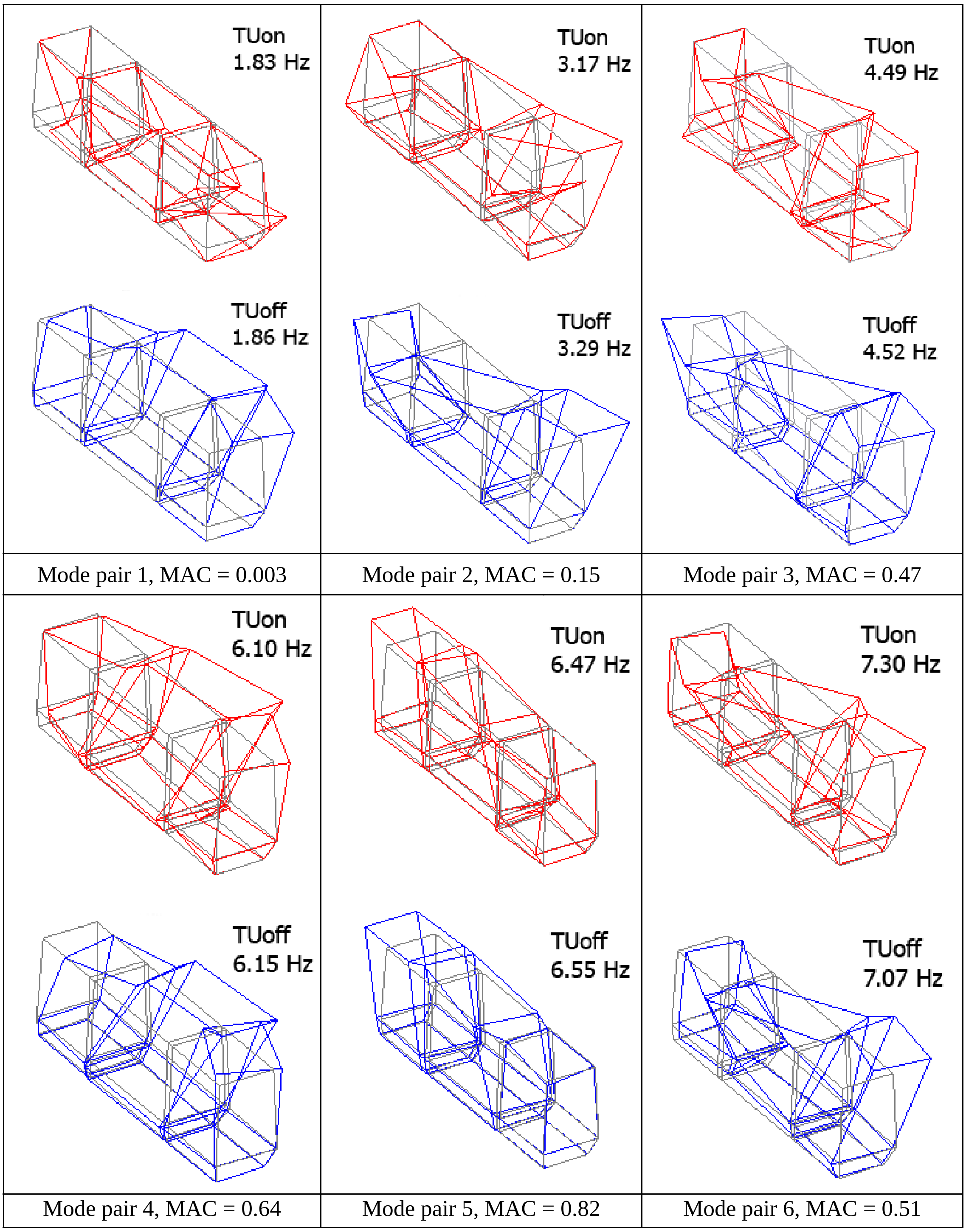

Figure 10: Mode shapes as determined for TUon and TUoff. Also indicated are the MAC values.

The MAC-value (Modal Assurance Criterion) gives a number between Zero and One for the degree of coincidence between two mode shapes. It is interesting to see that this value lies between 0.003 and 0.82 for the six mode pairs discussed here. What can not really be seen in Figure 10 is the fact that, in the cases of MAC being below MAC = 0.45, the mode shape is dominated by the rotational movement of the machine floor. This can however be seen when having a look at the animated mode shapes (if not available: please order at rci@rcidynamics.ch).

The turbine/generator related rotational movement is present in all mode shapes. This applies however for the regions of G7/6 and G2/1 only (Fig. 4). It is open to speculations why the power house middle part does not really rotate with the units running. Anyway, the rotational movement of the outer power house parts does not dominate in all cases. It is definitely destroying the shapes of the TUon modes related to mode pairs 1 and 2 (Fig. 9 and 10). From mode pair 3 on, the movement of the main structure is strong enough to cope with the machine floor rotation.

Some questions arise upon having a look Figure 9. With TUoff, 10 modes have been identified in the f = 1…10 Hz range, but only 6 for TUon. Let's go through the list of the "lost" modes:

a) What happens to the TUoff mode at f = 4.24 Hz when the units are running? It simply disappears behind the rotational movement with the unit's third harmonic at f = 4.17 Hz. b) The TUoff mode at f = 4.99 Hz shows a very weak performance. No wonder it doesn't show up significantly at the TUon spectrum. c) The TUoff mode at f = 5.49 Hz is simply a victim of the unit's fourth harmonic at f = 5.56 Hz. d) The remaining "lost" mode at f = 6.27 Hz is very close to the mode pair 4 TUoff mode at f = 6.15 Hz. There is no explanation for this one and next time we would delete this from data processing in time.

6 SUMMARY AND CONCLUSIONS

A river exploitation power station is going into a major renovation. The question arose whether or not structural vibrational problems were to be expected when exchanging the turbine/generator units. One of the related consequences will be an increase of the unit's rotational frequency from f = 1.39 Hz to f = 1.85 Hz. Ambient vibration tests were initiated to acquire an experimental basis to allow updating of an FE model of the existing structure. Based on the updated and therefore validated FE model, the consequences of the unit exchange can be studied with a good chance of being close to reality.

It was clear from the beginning that trying to identify the structure's natural vibrations with the turbine/generator units running (TUon) would be a ride on a very sharp blade. Although all necessary precautions were taken (high sensitivity sensors, a large number of reference DOF's, very long time windows per setup) the results of the TUon analysis were clearly not acceptable: No way to identify mode shape and damping of the lowest modes, unfortunately being of largest interest. Repeating the analysis with the units being out of operation (TUoff) and comparison with the results of the analysis with the units in operation yielded some interesting results:

- No useful results could be gathered for the two lowest modes (1.83 Hz and 3.17 Hz) with TUon although there is a significant distance to the closest frequencies of excitation, the first and second unit's rotational harmonics (1.39 Hz, 2.78 Hz). The unit rotations dominate the structural mode shape completely.
- For higher modes, the structure's natural modes are strong enough to not being drowned in the rotational movement, unless they are directly hit by a unit rotational harmonic. As a consequence, four out of seven structural modes in the range f = 4.5…7 Hz could formally be identified with the TUon test, the respective Modal Assurance Criterion being MAC = 0.47…0.82. Still, damping values could not be extracted.

Summarizing: Identification of a river exploitation station's natural modes should be based on ambient vibration tests with the turbine/generator units being shut off. Excitation through the unit's rotational movement destroys every structural natural movement. This is true for low frequencies (f = 1…3 Hz in the case under discussion here) and is true also for higher frequencies (f = 3…10 Hz) if one of the unit's rotational harmonics hits the structural natural frequency very closely. It came as a surprise that four of the seven structural modes in the frequency range f = 3…10 Hz could be identified with MAC = 0.45…0.82 even with the units running.

In addition, this experience showed that there are very nice ambient excitation sources for a power station with the units shut off. As the upstream river level has to be maintained in very narrow limits (at least for the Eglisau station), the water usually flowing through the units has to be de-routed over the spillways. This is obviously a very nice broad-band source of ambient excitation for the power house.