Kaplan Turbine Upgrade - Case Study

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INTRODUCTION

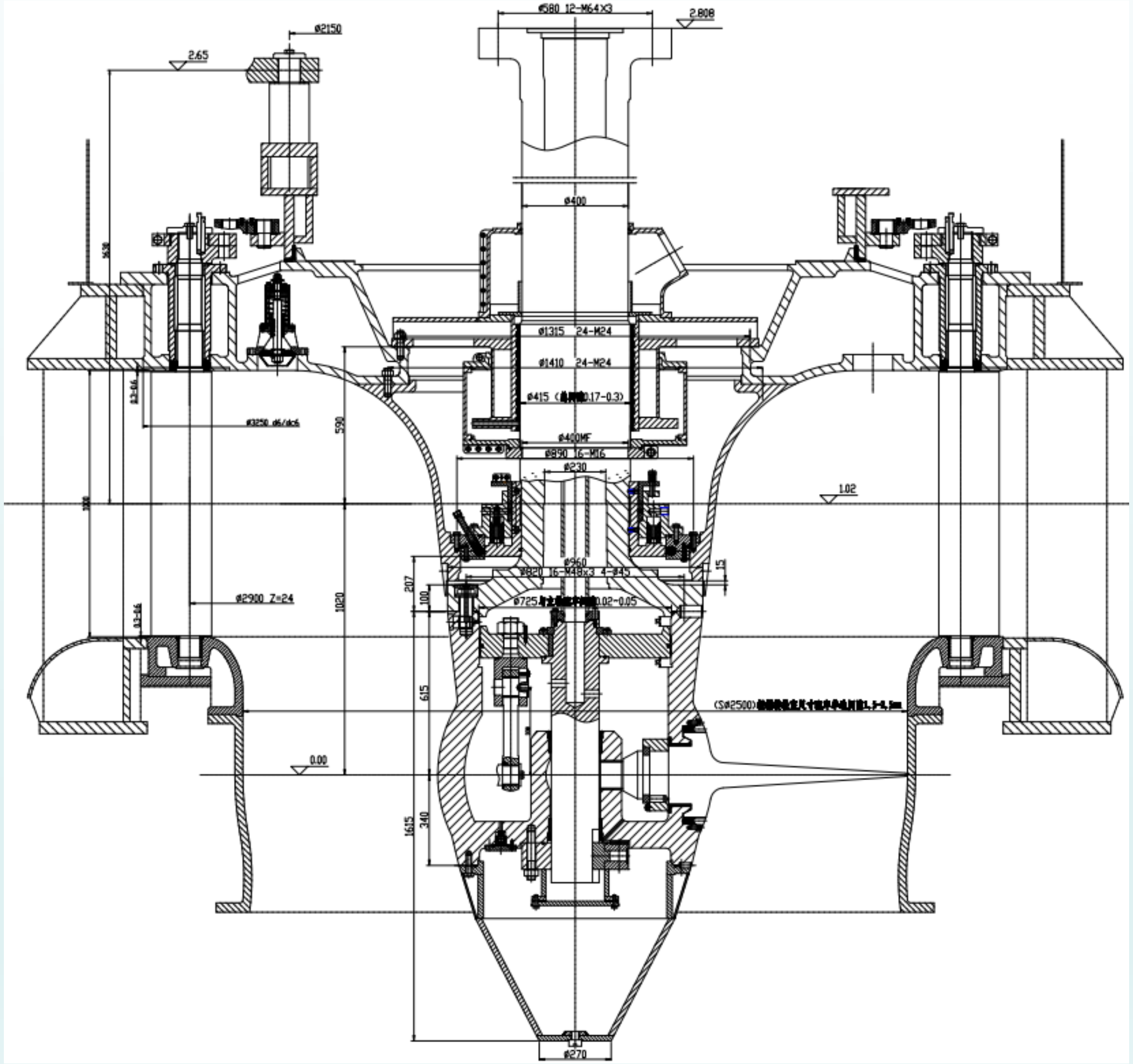
Most modern power stations were build more than 30,40 years ago since last century 80’s reform in China. Turbine refurbishment market is huge.

Some power stations suffer problems including lack of power, low efficiency, cavitation, cracks, vibration, noise, and sediment erosion. Some of them may have a single problem, while others may have multiple problems simultaneously.

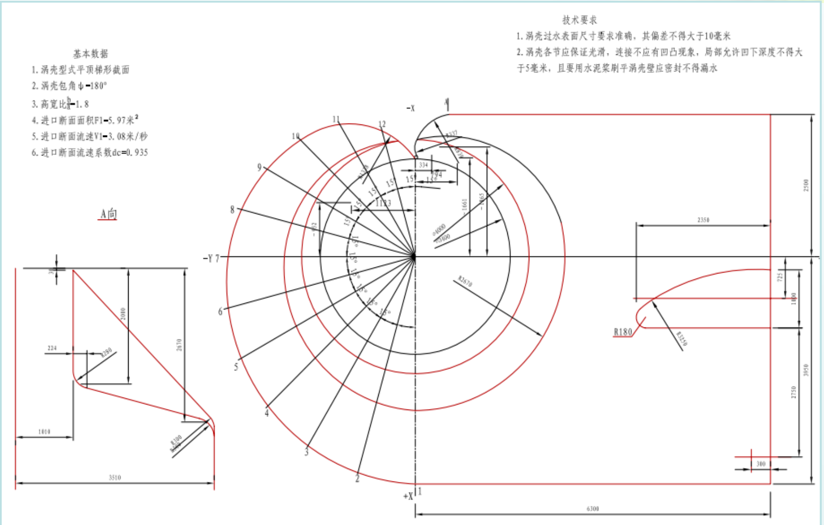
Kaplan turbine is a run-of-the-river power station located on the Xiangjiang River in Hunan Province, China. The original design output of the unit was 3,200 kW, and the hydro turbine was a vertical, double-regulated, 4-blade Kaplan type. The station was commissioned in March 1987 [1].

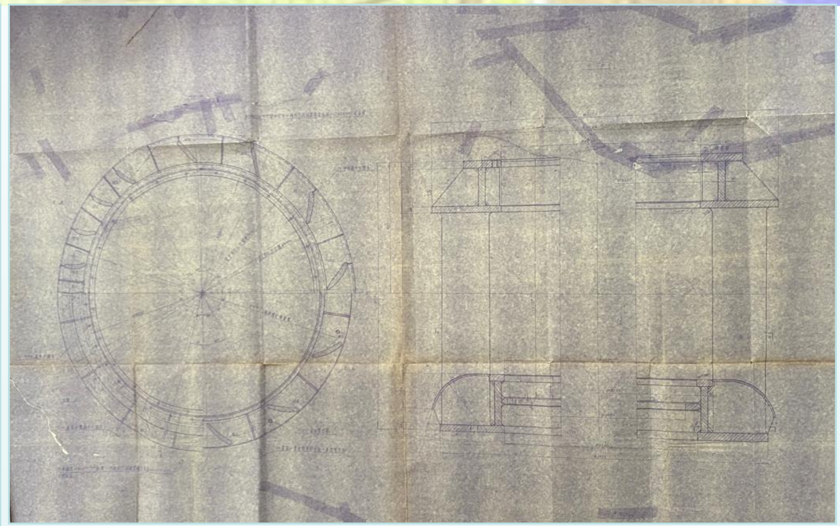
OPERATING PARAMETERS

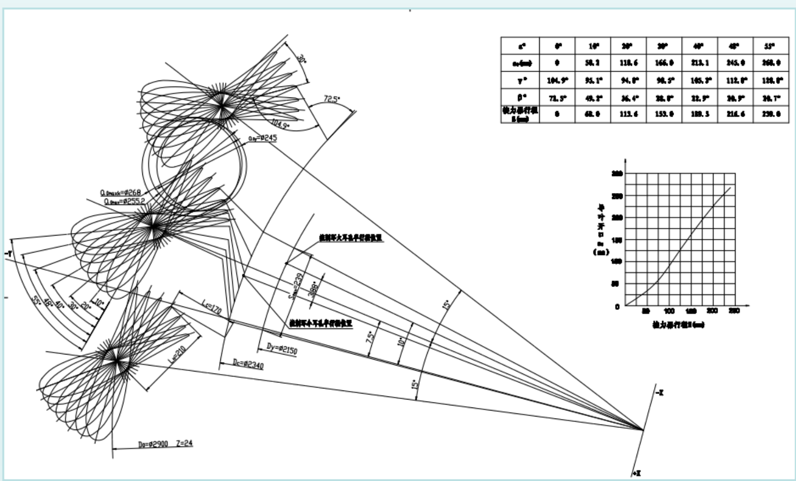
The technical specifications of the turbine after the first refurbishment were as follows:
Turbine model: ZZ550D – LH - 250 (nominal diameter D1 = 2500 mm, concrete spiral case, vertical Kaplan)
Maximum Head: 13.30 m
Minimum Head: 5.45 m
Rated Head: 10.90 m
Rated Discharge: 41.93 cms
Rated Speed: 187.5 rpm
Turbine Rated Output: 4040 kW
Runaway Speed: 437 rpm
Suction Head: +0.30 / -0.95 m (TWL to Runner Center)
Runner Center EL: 104.0 m
Gate Center EL: 105.02 m

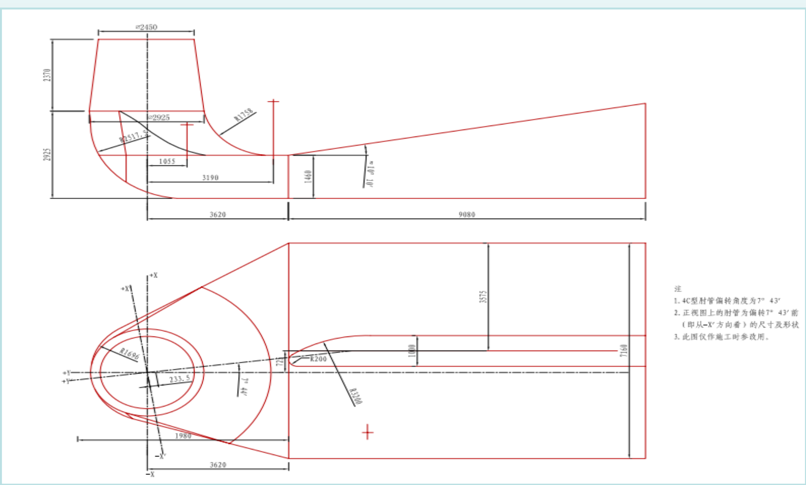


FLOW PASSAGES DATA







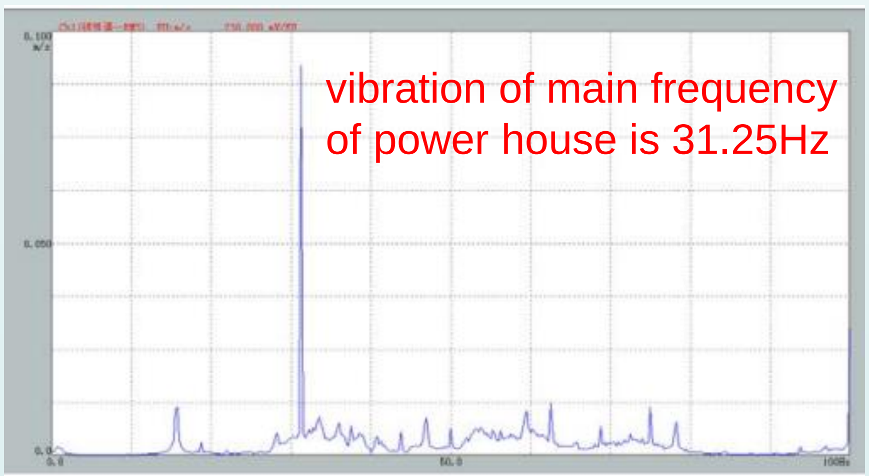


Note: design limitations

PREVIOUS UPGRADE

In 2016,first time upgrade with 5 blade turbine was completed. The power reached 3900kW(21.9% increase over the original turbine).

However, the updated turbine experienced several problems, including severe vibration, loud noise, load shedding, cavitation, and resonance with the power plant. These issues posed significant safety hazards.

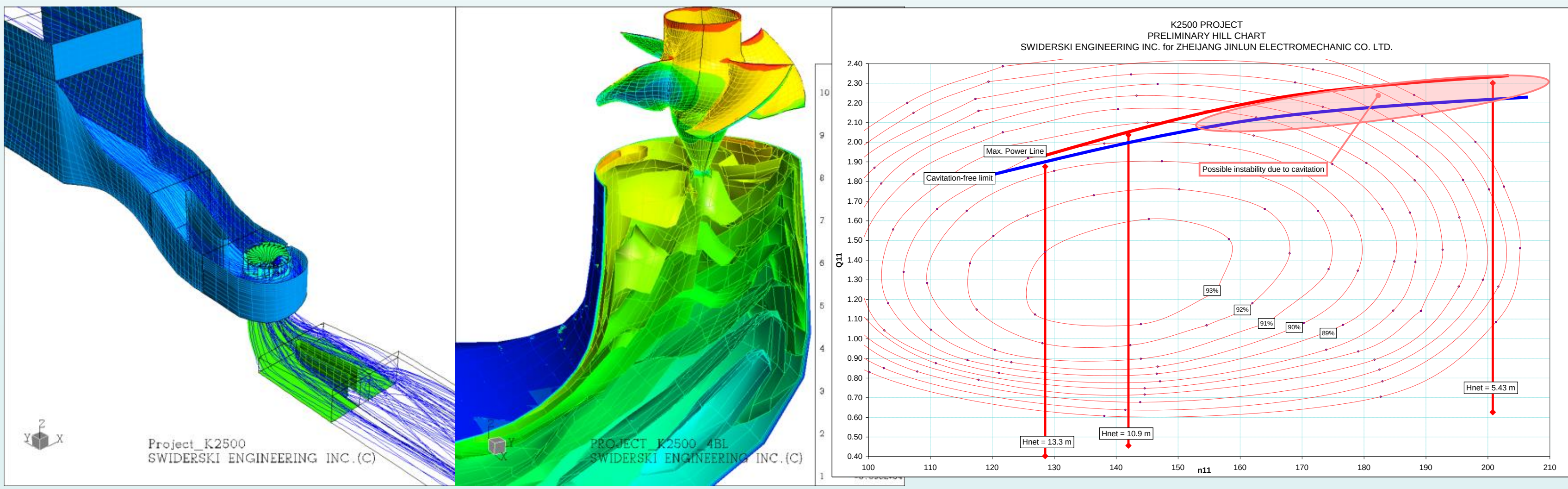


resonance with the power plant(2*5*3.125=31.25Hz)

cavitation

ACTUAL UPGRADE

In March 2022, the owner of the power plant decided to carry out a second refurbishment to resolve these problems. In May 2023, the customer issued a public tender invitation. The Canadian company Swiderski Engineering Inc. (SEi), as technical support, partnered with a Chinese Company and finally won this project. SEi proposed a technical approach based on numerical flow simulation by means of Computational Fluid Dynamics (CFD) analysis.



CONTRACTUAL CONSTRAINTS

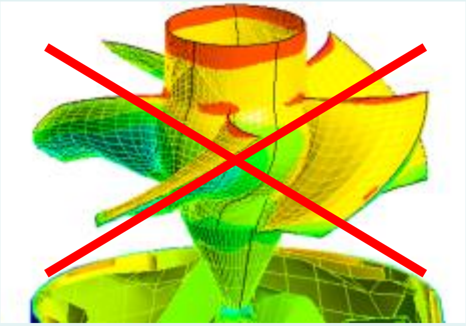
In the general contract, *performance guaranteed* as the following:

1) power not less 3900KW .

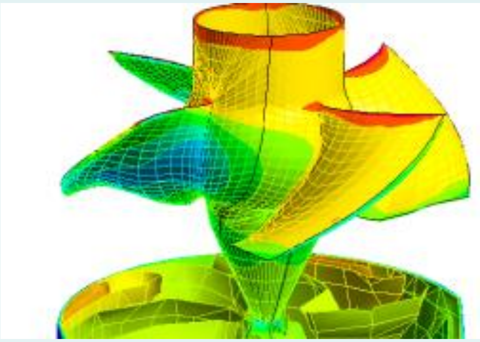
2) Vibration and noise levels must not exceed the maximum values regulated by GB or international standards, ensuring stable operation of the turbine in all allowable operating zones.

3) Free from cavitation in all operating zones.

4) The runner must have 4 blades due to resonance problems with the power plant structure.



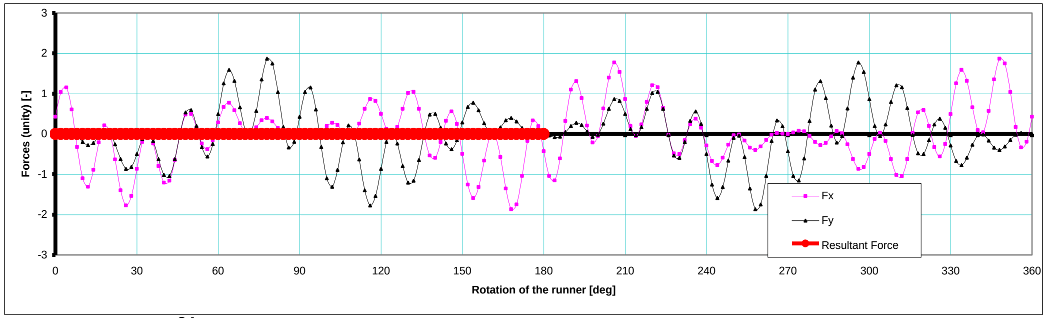
No 5 blades design



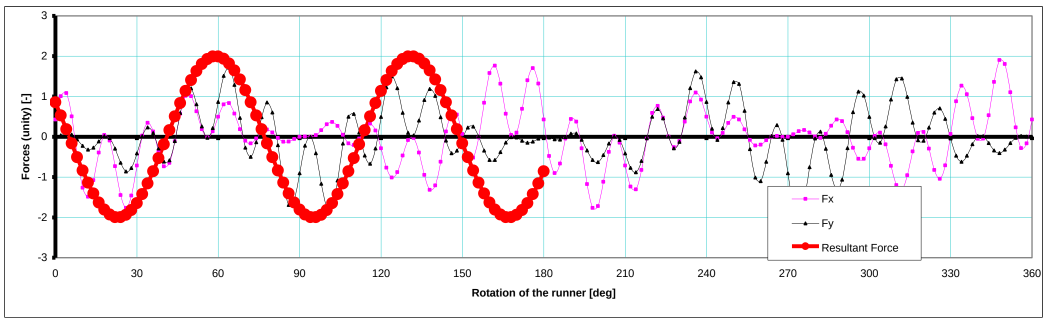
must have 4 blades design

STABILITY EVALUATION

Number of Wicket Gates = 24
Number of Runner Blades = 4



Number of Wicket Gates = 24
Number of Runner Blades = 5



Number of Wicket Gates = 24
Number of Runner Blades = 6

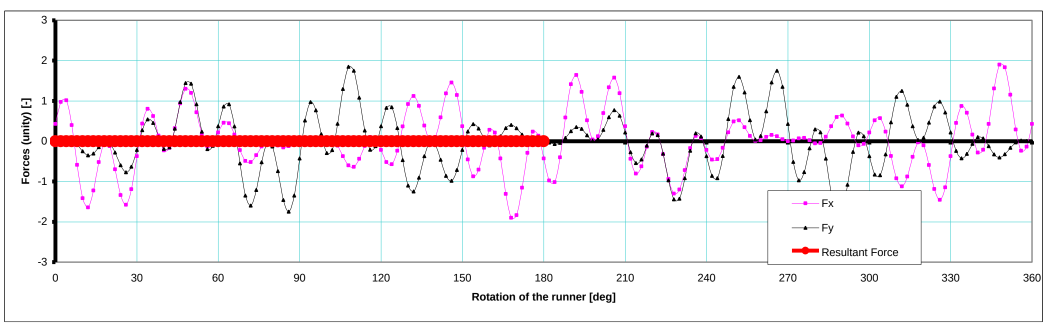
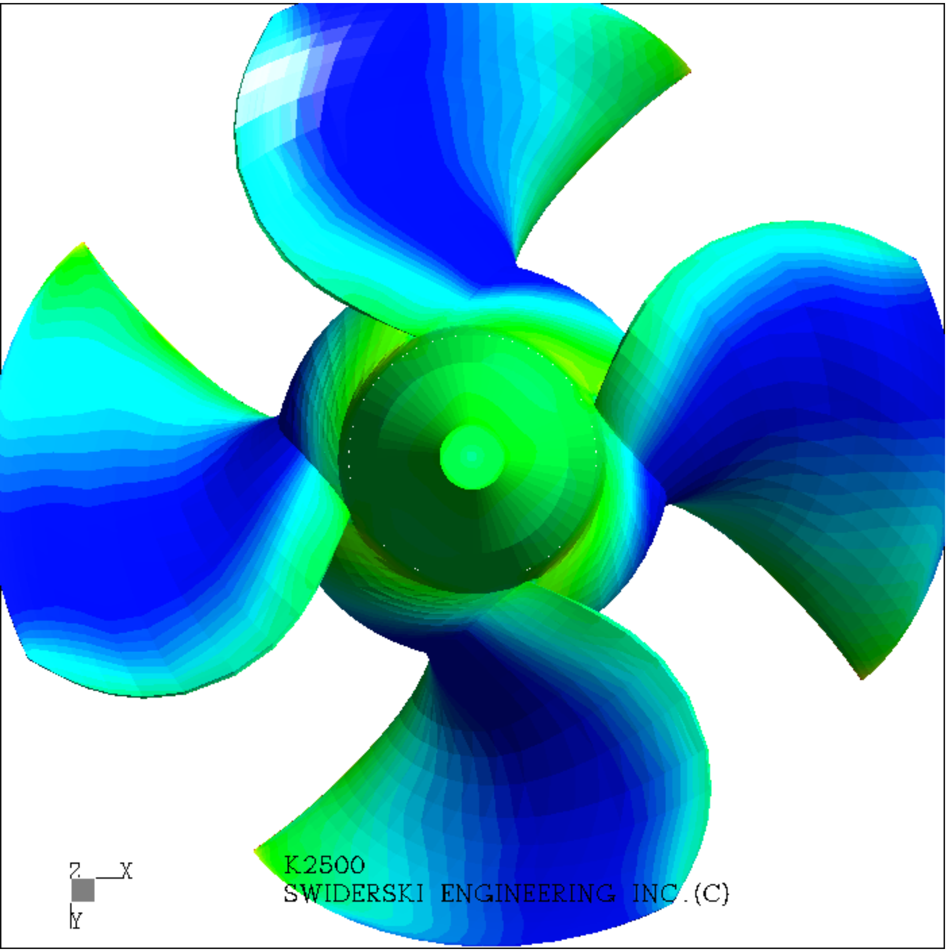
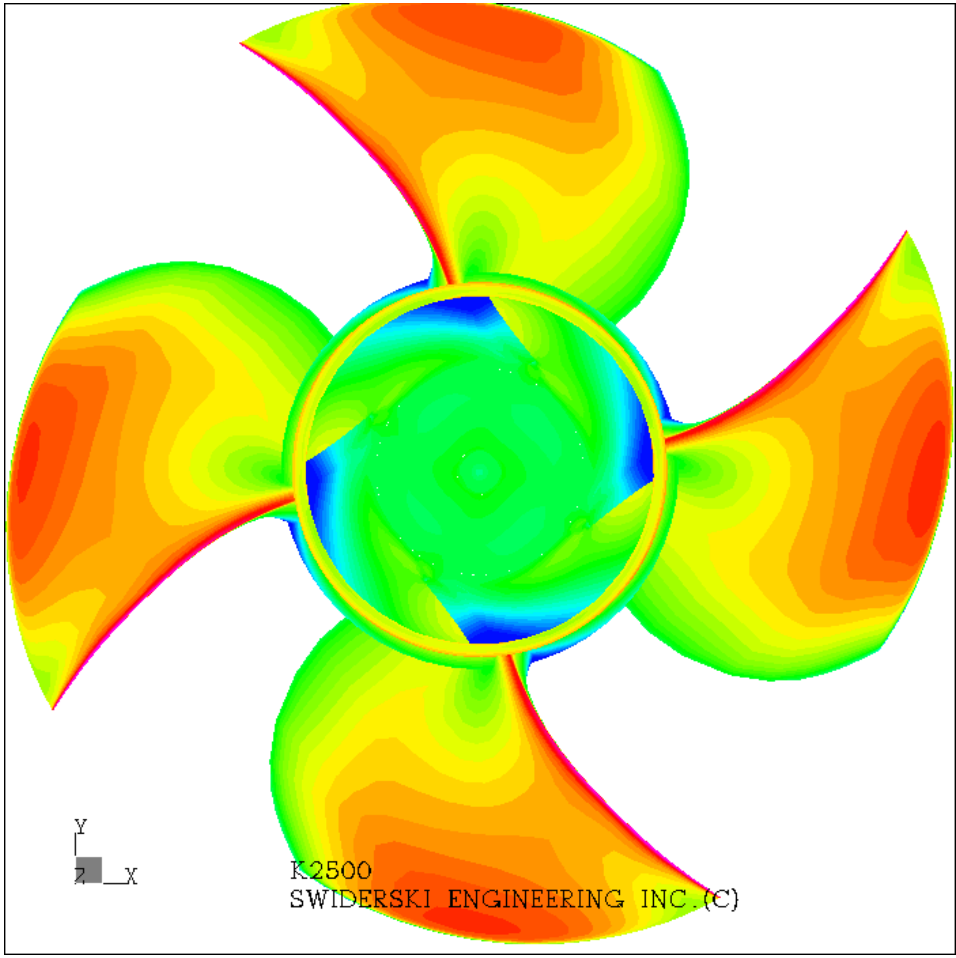


Fig. 1 Graphs illustrating resultant pressure impulses as they get amplified by interaction between wicket gates (24) and the rotating runner for various runner blades numbers (4,5,6).

RUNNER BLADES – FINAL DESIGN



Static pressure – suction side



Static pressure – pressure side

COMISSIONING

In May 2024, the new updated runner was installed, and commissioning tests were carried out on-site.

Field Test Results

- The loading test showed that the unit reached 3,900 kW at the rated head. The machine ran smoothly, with no cavitation noise detected. Based on the peak-to-peak vibration values across the test heads (gross head 8.04 m–11.74 m) and test loads (0–4,018 kW), all results met GB and international standard requirements.
- The vibration frequency of the upper and lower frames was mainly 3.13 Hz, corresponding to the normal rotational frequency of the unit.
- The vibration of the top cover was primarily caused by the blade rotation frequency in the draft tube, measured at 12.50 Hz.
- The 15.61 Hz vibration frequency -corresponding to the natural frequency of the powerhouse structure - previously detected in tests before the second refurbishment was no longer observed.

Comissioning

<u>Loading and Stability tests (comparison between before and after upgrade)</u>

	Operation point	3950kW （ vibration unit um pressure kPa ）									
		before upgrade (3950kW)					after upgrade (3900kW)				
#	Channel Name	Vpp	F1	V1	F2	V2	Vpp	F1	V1	F2	V2
1	P.H. Hor.Vibr.	10.01	15.61	3.56	15.61	1.22	3.92	12.50	0.35	3.13	0.31
2	P.H. Ver.Vibr.	5.68	46.83	0.88	15.61	0.72	3.60	0.41	0.11	75.03	0.11
4	L.F.Hor.Vibr.	19.70	15.61	3.21	3.12	3.05	16.75	12.50	1.64	0.50	1.53
5	L.F.Ver.Vibr.	97.08	15.61	32.01	15.61	10.82	12.49	3.13	2.61	18.75	0.97
6	H.C. Hor.Vibr.	167.99	0.43	12.32	0.66	10.40	68.91	0.37	5.63	0.54	5.43
7	H.C. Ver.Vibr.	33.99	15.61	9.51	15.61	3.29	17.59	12.50	3.55	75.03	1.35
8	U.G. Throw	203.84	12.49	39.84	3.12	33.66	160.99	3.13	61.64	6.25	10.22
9	L.G. Throw	606.56	3.12	154.1	12.49	63.36	215.77	3.13	66.67	12.50	40.70
10	Tur. G.Throw	503.08	3.12	176.7	3.12	60.79	116.73	3.13	40.09	12.50	21.09
11	SP Pressure	23.84	15.61	8.32	15.61	2.86	1.08	0.65	0.07	0.69	0.06
12	DT Pr. Pul.	6.68	3.12	0.46	124.9	0.18	14.18	12.50	3.14	12.51	0.72

Comissioning

Loading and Stability tests (comparison between before and after upgrade)

	Operation point	3500kW （vibration unit um pressure kPa）									
		before upgrade（3500kW）					after upgrade（3650kW）				
#	Channel Name	Vpp	F1	V1	F2	V2	Vpp	F1	V1	F2	V2
1	P.H. Hor.Vibr.	11.05	15.62	3.32	15.61	2.02	3.60	3.13	0.33	12.50	0.32
2	P.H. Ver.Vibr.	4.32	15.62	0.65	15.61	0.40	3.04	0.51	0.09	0.59	0.08
3	L.F.Hor.Vibr.	18.90	3.13	3.59	15.62	2.41	11.14	3.13	1.72	0.52	0.64
4	L.F.Ver.Vibr.	103.4	15.62	24.4	15.61	16.86	12.09	3.13	2.47	12.50	1.26
5	H.C. Hor.Vibr.	92.52	0.52	6.49	0.51	5.27	32.65	0.59	2.66	0.54	2.26
6	H.C. Ver.Vibr.	22.47	15.62	3.83	15.61	2.59	15.67	12.50	3.05	12.51	1.90
7	U.G. Throw	119.5	3.13	11.2	0.01	10.83	154.86	3.13	60.21	9.38	8.25
8	L.G. Throw	534.5	3.13	159.	3.12	63.74	186.71	3.13	72.33	12.50	14.34
9	Tur. G.Throw	811.2	3.13	176.	3.12	78.99	92.10	3.13	37.06	12.50	8.55
10	SP Pressure	17.85	15.62	3.51	15.61	2.27	1.40	0.01	0.26	0.01	0.13
11	DT Pr. Pul.	25.45	15.62	4.48	15.61	3.47	12.37	12.50	2.18	12.51	1.40

Commissioning

Loading and Stability tests (comparison between before and after upgrade)

Operation point		1500kW （vibration unit um pressure kPa）									
		before upgrade（1500kW）					after upgrade（1500kW）				
#	Channel Name	Vpp	F1	V1	F2	V2	Vpp	F1	V1	F2	V2
1	P.H. Hor.Vibr.	8.97	15.61	2.17	15.62	2.04	3.68	99.97	0.34	3.12	0.33
2	P.H. Ver.Vibr.	3.44	15.61	0.36	15.62	0.34	2.96	0.48	0.07	3.12	0.07
3	L.F.Hor.Vibr.	14.66	3.12	3.75	12.50	1.39	8.74	3.12	1.82	0.72	1.24
4	L.F.Ver.Vibr.	64.43	12.50	8.51	15.61	8.41	14.01	3.12	2.63	0.72	1.54
5	H.C. Hor.Vibr.	4.88	0.53	0.35	0.51	0.34	29.93	0.72	2.81	0.48	2.44
6	H.C. Ver.Vibr.	6.16	12.50	0.97	12.49	0.84	14.55	12.50	1.52	1.44	1.48
7	U.G. Throw	108.33	12.50	15.16	3.12	15.10	156.99	3.12	60.54	6.25	9.74
8	L.G. Throw	480.94	3.12	138.6	3.13	35.81	210.73	3.12	73.20	0.72	19.9
9	Tur. G.Throw	424.25	3.12	102.0	0.53	36.26	125.85	3.12	35.89	0.72	16.6
10	SP Pressure	3.06	12.50	0.49	12.49	0.41	5.29	0.72	1.79	0.71	1.16
11	DT Pr. Pul.	13.51	15.61	1.34	15.62	1.26	28.93	0.72	5.09	0.71	3.29

Commissioning

Loading and Stability tests (comparison between before and after upgrade)

	Operation point	1000kW （vibration unit um pressure kPa）									
		before upgrade（1000kW）					after upgrade（900kW）				
#	Channel Name	Vpp	F1	V1	F2	V2	Vpp	F1	V1	F2	V2
1	P.H. Hor.Vibr.	30.10	0.05	2.92	0.05	2.92	3.76	3.13	0.33	100.06	0.25
2	P.H. Ver.Vibr.	44.68	0.05	3.74	0.05	3.73	2.88	3.13	0.06	0.38	0.06
3	L.F.Hor.Vibr.	35.56	0.01	3.11	0.01	2.96	9.70	3.13	1.83	0.72	0.96
4	L.F.Ver.Vibr.	55.54	12.49	6.61	12.50	5.54	23.46	3.13	2.56	6.68	1.23
5	H.C. Hor.Vibr.	40.66	0.05	3.50	0.05	3.50	65.95	0.66	4.40	0.77	4.22
6	H.C. Ver.Vibr.	35.03	0.05	3.03	0.05	3.03	24.87	5.83	2.07	6.68	2.02
7	U.G. Throw	104.72	12.49	13.80	12.50	11.47	156.67	3.13	59.79	6.25	9.82
8	L.G. Throw	478.22	3.13	106.6	3.12	76.62	244.04	3.13	72.50	6.68	16.73
9	Tur. G.Throw	271.39	3.13	68.22	3.12	54.05	142.56	3.13	35.58	0.72	23.63
10	SP Pressure	3.95	12.49	0.53	12.50	0.43	4.53	0.72	1.23	0.73	0.53
11	DT Pr. Pul.	9.93	25.01	1.01	25.01	0.96	39.10	0.72	3.30	12.50	2.69

Pressure Pulsation Analysis

- The pressure pulsation frequency in the draft tube was mainly associated with the normal vortex band and blade frequencies.
- Above 50% load, the pressure pulsation value decreased significantly as the load increased, with the dominant pulsation frequency at 12.50 Hz (blade frequency).
- Below 50% load, low-frequency pressure pulsation caused by the draft tube vortex band was present, with a frequency of about 0.75 Hz.

HWL 117.22m				HWL 117.10m			
Output KW	97% Confidence level Kpa	F1 Hz	V1 Kpa	output KW	97% Confidence level Kpa	F1 Hz	V1 Kpa
4018	10.84	12.49	2.61	3900	14.18	12.50	3.14
3800	11.27	12.51	2.74	3650	12.37	12.50	2.18
3580	10.79	12.51	2.26	3000	11.60	12.50	2.80
3100	8.88	12.50	1.49	2500	17.76	12.51	4.86
1800	11.94	0.82	1.61	2000	22.44	12.50	4.59
1200	34.95	0.70	5.74	1500	28.93	0.72	5.09
				900	39.10	0.72	3.30

Comissioning

HWL 116.5m				HWL 115.5m			
Output KW	97% Confidence level Kpa	F1 Hz	V1 Kpa	output KW	97% Confidence level Kpa	F1 Hz	V1 Kpa
3680	11.89	12.50	2.81	3200	11.94	12.50	3.06
3500	11.03	12.51	2.42	3000	12.32	12.50	2.55
3000	9.69	12.50	2.48	2500	10.46	12.51	3.02
2500	12.51	12.50	2.67	2000	16.23	12.50	4.22
2000	18.19	0.72	3.82	1500	23.39	0.72	3.92
1500	28.50	0.74	6.53	1000	26.50	0.71	4.03
1000	40.73	11.09	6.44	600	35.66	0.72	1.97
500	37.00	0.78	1.26				

HWL 114.4m				HWL 113.5m			
Output KW	97% Confidence level Kpa	F1 Hz	V1 Kpa	output KW	97% Confidence level Kpa	F1 Hz	V1 Kpa
2700	14.23	12.50	3.80	2200	14.37	12.49	4.00
2300	20.63	12.50	6.48	1800	23.87	12.49	7.32
2000	15.80	12.50	4.81	1600	18.57	12.49	5.44
1500	20.72	12.51	5.06	1400	25.69	12.50	4.78
1200	27.60	0.72	5.50	1000	29.89	0.72	4.28
800	32.23	0.73	5.52	600	37.57	0.75	4.15
500	35.09	0.73	2.29				

Commissioning

Overspeed and Load Rejection Tests

- The overspeed protection device was set to activate at 268 rpm (140% of rated speed) and functioned accurately.
- At 50% and 75% load rejection, the unit speed did not increase significantly, and pressure rises remained within acceptable limits.
- At 100% load rejection, the pressure rise in the spiral case reached 54.46%, while the speed rise was only 23.95%, a condition that can be mitigated by adjusting the shutdown time.

Parameters	50% Load rejection	75% Load rejection	100% Load rejection
Max Speed(rpm)	192.7	214	232.4
speed rise（%）	2.79	14.06	23.95
SP pressure rise（%）	30.86	25.85	54.46

CONCLUSIONS

All tests, including the rotating dynamic balance test, were successfully passed. The new optimized runner, designed using MODOA process, which is fully based on numerical flow simulation, met all technical requirements specified in the general contract. No hydraulic laboratory tests were involved. Second upgrade was successful.

Thank you!

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