Vibration fault processing experiment and analysis of hydropower unit

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Abstract

To find the truth of unit vibration fault more accurately and timely, mathematical model is led in archetypal test analysis. The measuring point of vibration is selected reasonably. The caution of vibration fault is judged preliminarily according to the change of the vibration in each measuring point as changing speed, exciting voltage, load and phase modulation operation test. The parameters in sample are chosen on the basis of the vibration fault characteristic and then the mathematical model is established based on fuzzy analysis. The membership grade of vibration characteristic parameters is gotten by the ascended half Cauchy distribution function, the fuzzy relational matrix is gotten from the experience of experts evaluation by fuzzifying the relationship between vibration fault characteristic parameter and fault type, then the membership grade matrix of vibration fault type is composed by the membership grade of vibration character parameter and fuzzy relational matrix. Vibration fault causation is confirmed through the data in the membership grade matrix of the vibration fault type and the disposal measure is chosen. For the example of a certain unit whose upper guide bearing vibrating exceeding standard, the cause judged preliminarily is imbalance of mass in the unit. The swing indexes in the rated speed and rated exciting voltage are regard as sample, and then the imbalance of mass and excessive gap in upper guide bearing are judged as the major causation of the hydroelectric generating set based on the membership of the vibration fault type. Because the vibration fault of unit doesn't eliminate when the upper guide bearing overhauling, the station decided to conduct experiment of dynamic balance. After the disposal, the fault problem is radically solved.

Keywords: hydro-turbine generating unit; vibration fault disposal; the scene test; model analysis; fuzzify; membership.

1 Introduction

Destructive vibration fault in hydro-turbine generating unit seriously affect normal operation in hydropower station. Water power, mechanical and electromagnetic force are the causes of unit vibration fault. In general, the draft tube vortex strip can lead to the most vibration fault type, and dynamic unbalance in the unit can lead to the most destructive, especial vertical mixed flow unit [1]. At present, hydropower station is main added air supplying device and attenuates or eliminates draft tube vortex strip by change framework. The measures can obtain significant effect. Dynamical unbalance in the hydro-turbine generating unit is reduced as far as possible through balance test and improving installation technology level.

In installation, unit centre line, rotating centre line and principal axis centre line are adjusted until the three lines are superposed. That is the static state, but the three lines aren't superposed when the unit operates limited to installation technology level, and the dynamic unbalance may exceed standard after each part in unit is running-in. If the unit is halted, then checked and repaired and installed, manpower and material resources and financial resources would have wasted. So the experimental research of unit is very necessary.

Model test is done on the model testing machine, and more easily change correlative parameters, working conditions, structure. But model test main clarifies a few waterpower vibration sources, and it is difficult to imitate electrical, mechanical and other partial waterpower vibration sources, natural vibration characteristic and dynamic response of unit. Archetypal test can correctly measure vibration parameters. But archetypal test concerns many aspects, and its cycle is long, furthermore it affects normal production because the archetypal test needs installed sensors. Therefore, before the formal operation unit should do archetypal test in order to find the vibration sources fast and exactly [1-2].

A multitude of research findings indicates that during the test or formal operation vibration unit emerging exceed the standard or alarm. The method looking for vibration causes grouped into two classes: one is that the operating personnel judge on the basis of their operating experience from the running or testing data recorded[3-10], which is limited operating experience, two is that the vibration fault types are confirmed through the mathematical model of establishment and after the complex computing process according to the characteristics of vibration fault [10-19], which needs fully accurate test data and puts forward a very high request to the test data.

The paper introduced a method of combine experimental data and mathematical model. The true cause of unit vibration fault tried hard to find by adding correct mathematical model analysis method to test analysis and vibration fault was disposed drastically. It provides reference for the more units because it can quickly and accurately find out the vibration causes when vibration fault appears.

2 The scene test method and the analysis process

The unit scene test is that vibration situation of unit vibration is measure in the case of not dismantling unit in order to measure vibration quantitatively and then the vibration causes are analysed and the vibration part is find out. The vibration measuring system is shown in FIGURE 1, which

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has measuring device, signal processing equipment, analysis equipment, display and recording equipment and so on. The measuring point distribution of vibration is shown in FIGURE 2, which covers the main components of unit as far as possible and can reflect the characteristics of vibration.

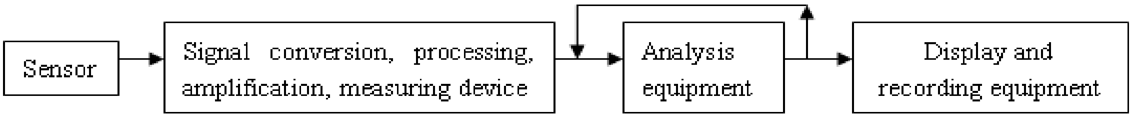

FIGURE 1 Measuring system of vibration test

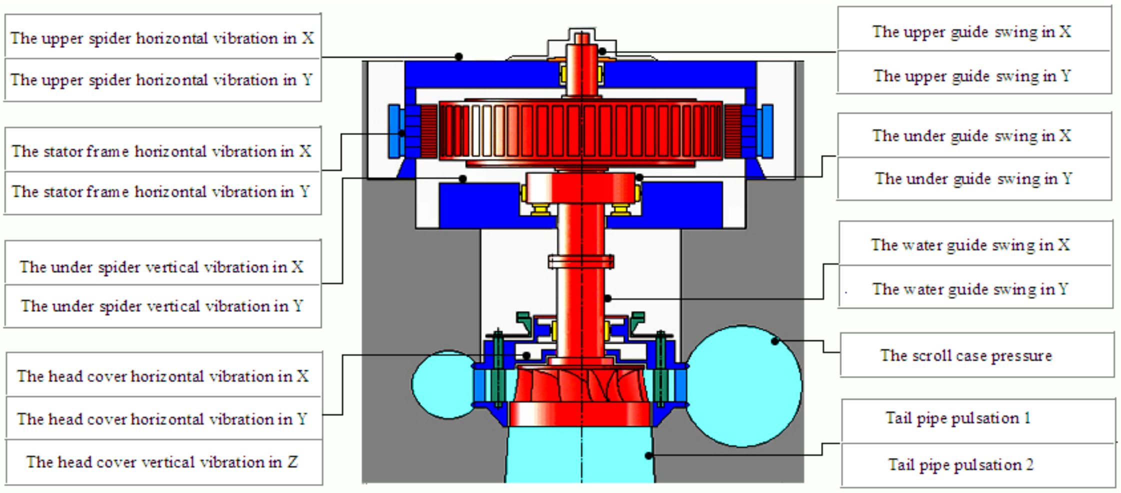

FIGURE 2 The measuring point distribution of each part in hydraulic generating unit when vibration tested

Normally, vibration cause is found out taking advantage of variable speed, variable excitation voltage, variable load and phase modulation operation test t and is judged based on the operation experience.

Variable speed test is to measure the mass imbalance existed in unit. When tested, unit no-load (active power p=0) and the rotor of the generator without excitation voltage （u=0） starts from stable minimum speed n (r/min). Every increase more than 10% of rated speed nr is chosen one operating point, up to 100%, sometimes up to about 120%. The amplitude A（μm） and frequency f (Hz) condition of vibration measuring point in every working condition are gotten and draw the double amplitude A=f(n) and frequency f=f(n) relationship curve which are changed along with the speed n. In the test, if the amplitude A is always very large, the relationship between amplitude A and speed n is no close, the vibration frequency f and speed value n is basically the same, vibration fault may be caused by mechanical structure factors. If the amplitude A is proportional to the speed n, frequency is approximately equal to the rotation frequency, the vibration fault may be caused by the mass imbalance of rotor. The unbalance mass of rotor will produce centrifugal force when the unit operating. Thus， not only the unit shaft system emerges swing, but also it will cause vibration and damage to bearings and other supporting structure. Usually, the imbalance can be reduced to the lowest degree by means of adding balance weight method. If the generator rotor is disc, one point trial weight method can be used. If the generator rotor is column, three point or two trial weight method need to be use.

Variable excitation voltage test is to ascertain the unbalanced magnetic force existed in unit. When tested, unit is no-load and started from the condition while rotor of generator is without excitation voltage. Every increase more than 10% of the rated excitation voltage is chosen one operating point, up to 100%. The amplitude A(μm) and frequency f(Hz) of vibration measurements distribution in every operating point are gotten and draw the amplitude A along with excitation voltage u relationship curve A=f (u). If the amplitude increases along with the increase of excitation voltage, the unbalanced magnetic force is the main reason of vibration fault. At this time, the unit needs check including as follows: whether or not the gap in the stator cavity and the outer circle is well-distributed, whether or not the pole coil has turn-to-turn short circuit, whether or not the air gap in the magnetic pole and the magnetic yoke arises, and so on.

Variable load test is to ascertain whether or not the vibration fault of unit caused by the hydraulic imbalance of water system. When tested, unit is rated speed. At this time, the vibration amplitudes of every measuring parts under more than 10% of the rated load is measured, and then the amplitude A and unit load p relationship curve A= f (p) or the amplitude A and servomotor travel l relationship curve A= f (l) is driven. If the measuring parts amplitude A increases along with servomotor travel l, and the amplitude A on the water guide change is more sensitive than on the upper guide, furthermore the amplitude vibration A is greatly reduced as phase modulation operation, the vibration fault is caused by the hydraulic imbalance in the runner. If the vibration amplitude is very large in 40% ~70% load but obviously reduced in other load working condition, and the vibration frequency is less than half of the rotation frequency, vibration is caused by the vortex pulsation in the draft tube. At the time, the unit needs check including as follows: asymmetrical hydraulic forces is formed owing to the design problem of runner blades or the guide vanes spacing and shape, or the hydraulic design problem of spiral case, whether or not the runner rotation is eccentric, whether or not the water seal clearance range is homogeneous because of the runner crown and ring have defects, and so on.

Phase modulation operation test can confirm vibration fault of unit caused by hydraulic, mechanical or electrical imbalance force. When tested, unit is in power system, first the water guide mechanism gradually is closed, second air is supplied and water is pressurized, thus the unit is phase modulation operation. If the vibration is reduced or disappearance in the phase modulation operation, fault is due to the hydraulic imbalance, otherwise, is due to other causes.

3 Analysis of fuzzy mathematical model

To find the cause of vibration fault, common methods are fuzzy clustering, fuzzy nearness degree, neural network, wavelet theory, grey correlation, and so on [5-10]. All of the algorithms are very complex and need for programming. Neural network method is the most studied for the good dispersion conclusion, but it is too slow convergence and poor generalization ability and the conclusion may be the local optimal solution. The fuzzy comprehensive evaluation theory has been developed commendably and it has very good dispersion too, further more the calculation process is very simple [11-13]. The fuzzy theory about comprehensive evaluation applied to vibration fault diagnosis need choose sample of vibration fault feature, and then the membership of vibration fault feature is obtained. The membership of vibration fault feature is assumed to be matrix V, and the membership matrix B of vibration fault type is obtained by means of fuzzy operation from the matrix V and the fuzzy relation matrix R. The fault type of vibration will be found from the data in the matrix B.

Membership degree matrix V of vibration fault characteristic parameters is gotten with the help of fuzzy membership function from the parameters of the sample data after processing. Parameters in the sample as the analysis object can be selected according to the experience or the established parameters. The sample data should be from the scene in order to make the feature parameters of unit vibration fault have very good performance. The membership function is determined through the fuzzy statistical method, grey correlation method [11], and so on. In the vibration fault diagnosis of hydropower unit，the membership function often adopts normal, trapezoidal, the ridge shaped, the ascended half Cauchy and other forms distribution function. The ascended half Cauchy distribution function is often used:

$$\mu_V(x)=\begin{cases}0 & when\ \ x=0\\ \dfrac{kx^2}{1+kx^2} & when\ \ 0<x\leq\infty\end{cases}. \tag{1}$$

In the formula: x is the initial value of sample parameters, mm; k is undetermined parameters, and the k value is different with different research object, ordinarily the k is gained from the membership degree of the allowable value of unit swing.

The fuzzy relation matrix R can try to establish through analyzing the collected data. A common and simple and effective method is the expert assignment method [12].

The main factors causing vibration can largely determine according to the scene experience from the parts of vibration exceeding standard and the vibration characteristic parameters. The defects or fault of the thrust bearing or upper guide bearing, the no perpendicular of unit axis, the change of the unit centreline, and so on, the upper frame vibration obviously causes by all of them. The uneven opening of guide vane, the uneven line-type or gap or opening of running, the hydraulic imbalance, and so on, those may cause vibration obviously of water guide bearing. The unit axis misalignment, the guide bearing not homocentric or partial abrasion, which may often happen the swing of guide bearing obviously increasing but the flange and water guide less. Those are the vibration part or vibration characteristics of unit used to determine the vibration fault type. Based on field experience, the membership number related factors causing vibration is larger but unrelated is smaller, which is shown in table 1. The table is fuzzy relation matrix R of vibration fault.

TABLE 1 Fuzzy relationship matrix list of unit vibration fault

Type of unit vibration fault	**The upper guide**	**The lower guide**	**The water guide**	**The upper frame**	**Turbine head cover**
Mass unbalance	0.51	0.04	0.03	0.43	0.01
The upper guide shaft and bearing misalignment or bearing clearance big	0.5	0.09	0.02	0.38	0.01
The water guide shaft and bearing misalignment or bearing clearance big	0.01	0.01	0.55	0.08	0.35
flange partial abrasion	0.15	0.55	0.03	0.25	0.02
blade fracture	0.01	0.03	0.40	0.04	0.52
turn-to-turn short circuit in rotor winding	0.30	0.03	0.01	0.55	0.01
the inhomogeneous air gap of the stator and the rotor	0.20	0.01	0.20	0.55	0.04
Axis misalignment	0.20	0.55	0.20	0.04	0.01
The guide vane uneven opening	0.02	0.03	0.40	0.02	0.53
The big stator ovality	0.30	0.08	0.01	0.60	0.01
Carmen vortex	0.15	0.10	0.40	0.05	0.30
The stator Combined joint loosening	0.30	0.08	0.01	0.60	0.01
not good blade type line	0.02	0.05	0.38	0.02	0.53
structure and gap of sealing ring inappropriate combination	0.01	0.04	0.60	0.05	0.30
Negative sequence current	0.30	0.08	0.01	0.60	0.01
The vortex flow	0.02	0.02	0.43	0.03	0.50

A vibration fault type set B=[B1, B2,…, B15] is membership matrix of vibration fault type established by collect all the common faults type of hydropower generating unit. The quantities in the set are: B1 is mass unbalance, B2 is the misalignment between upper guide shaft and bearing or big bearing clearance, B3 is the water guide shaft and bearing misalignment or bearing clearance big, B4 is flange partial abrasion, B5 is blade fracture, B6 is turn-to-turn short circuit in rotor winding, B7 is the inhomogeneous air gap of the stator and the rotor, B8 is axis misalignment, B9 is the guide vane uneven opening, B10 is the big stator ovality, B11 is Carmen vortex, B12 is the stator combined joint loosening, B13 is not good blade type line, B14 is structure and gap of sealing ring inappropriate combination, B15 is negative sequence current, B16 is low frequency vortex tube in tail pipe.

The calculation process about membership of vibration fault types is the fuzzy synthetic operation process to the membership on vibration fault features, that is B= R·V. In the fuzzy synthetic operation method, M [·, ∨] is more suitable for the vibration fault characteristic of hydropower unit because of the prominent main factors, delicate and utility multiplication operation. The cause of vibration can be found from the data in the matrix B.

4 The example analysis

For an example, a power plant unit in Lishui River Valley of Hunan, the Hydroelectric generating set is vertical mixed flow unit, hydraulic turbine type is HLF161A0-LJ-400, the generator type is SF60-38/9070, the rated speed is 157.9 r/min, and the rotor′ s weight is 197300kg. After the unit is put into operation formally, the swing value of upper guide is gradually increased from 300µm or so to one level alarm value about 500µm, and is more and more frequently, sometimes exceeded 600µm which is the two alarm value.

In the maintenance of the station, after disassembly and assembly processing the upper guide bearing, the problem is found that the largest gap between 3# and 4# tile of the upper guide is 0.76mm without any external constraints. After dismantling the rest of guide bearing cover, conducting electric barring, the upper guide is found the swing value exceeded the standard. The most value is 39mm far beyond the requirement of the international standard 10.8mm. It seems that the measures of structure processing can not solve fundamentally the vibration fault.

The power station hopes to analyze and judge the real reason and eliminate vibration fault through other ways in order to ensure the safe operation of the unit. The station mainly is to do variable speed test and variable excitation voltage test. For variable speed test, unit is stable 2~3min at the four point of 25%, 50%, 75% and 100% of the rated speed, at the same time recorded the vibration and swing amplitudes in each measured point. For variable excitation voltage test, unit is stable 2~3min at the four point of 25%, 50%, 75% and 100% of the rated excitation, at the same time the vibration and swing amplitudes in each measured point are recorded. The curves about the swing and vibration amplitudes of the vibration part along with relative speed are drawn and shown in the figure 3 and figure 4. The curves about the swing and vibration amplitude of the vibration part along with relative excitation voltage are drawn and shown in the figure 5 and figure 6.

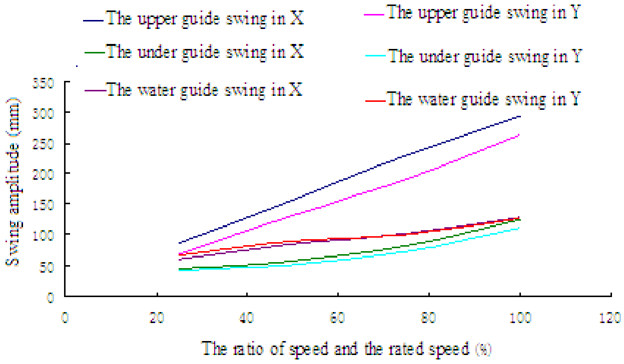

FIGURE 3 Swing amplitude of all the measuring point along with relative revolution (%)

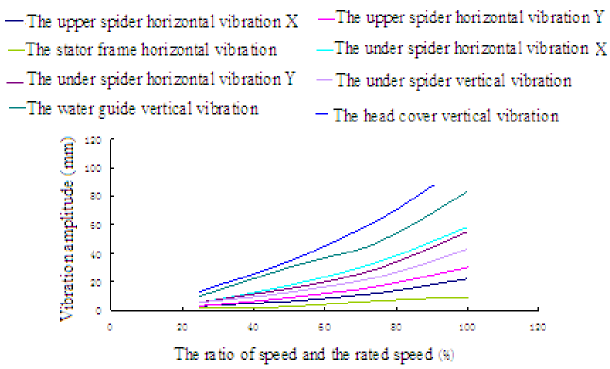

FIGURE 4 Vibration amplitude of all the measuring point along with relative revolution (%)

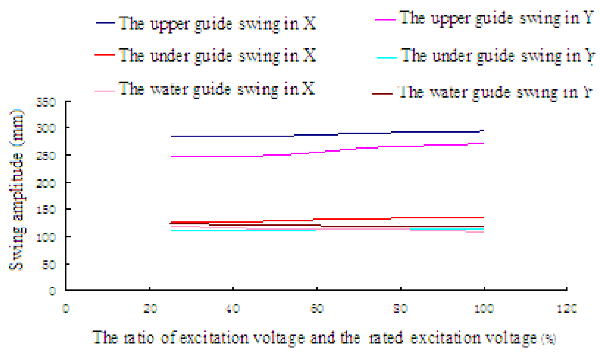

FIGURE 5 Swing amplitude of all the measuring point along with relative exciting voltage (%)

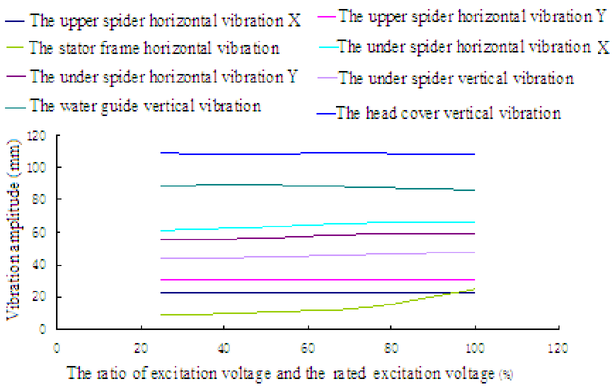

FIGURE 6 Vibration amplitude of all the measuring point along with relative exciting voltage (%)

From the figures 3~6, the vibration and swing amplitudes increase evidently along with the increase of unit speed but changed indistinctively along with the excitation voltage. The unit has mass unbalance preliminary identified. At the same time, the swing of upper guide, lower guide and water guide bearing are too large especially at rated speed and rated excitation voltage according to the figures 3~6. All the swing values about guide bearings at rated speed of each measuring point are selected as the parameters data of the sample in the table 2.

TABLE 2 Initial data of sample set (mm)

swing of the upper guide	swing of the lower guide	swing of the water guide
0.294	0.125	0.129

The swing allowable value of water guide bearing 0.50mm is chosen to substitute into the formula (1) and gotten k=1/250000. So the membership of the vibration characteristic parameters is: $\mu_A = \begin{pmatrix} 0.2569 \\ 0.0588 \\ 0.0624 \end{pmatrix}$.

In order to use the fuzzy relation matrix, in the table 1 the characteristic parameters of membership is amended as: A=[0.2569 0.0588 0.0624 0 0] T. The membership of unit vibration fault types through the fuzzy synthesis calculation is obtained in the table 3.

TABLE 3 The membership of vibration fault type

Type of unit vibration fault	degree of membership
Mass unbalance	0.1351
The misalignment between upper guide shaft and bearing or big bearing clearance	0.1347
The water guide shaft and bearing misalignment or bearing clearance big	0.0343
flange partial abrasion	0.0385
blade fracture	0.0250
turn-to-turn short circuit in rotor winding	0.0771
the inhomogeneous air gap of the stator and the rotor	0.0514
Axis misalignment	0.0514
The guide vane uneven opening	0.0250
The big stator ovality	0.0771
Carmen vortex	0.0385
The stator Combined joint loosening	0.0771
not good blade type line	0.0237
structure and gap of sealing ring inappropriate combination	0.0374
Negative sequence current	0.0339
The vortex flow	0.0028

From the table 3, the possible reasons for vibration fault of the unit are “mass unbalance” and “the misalignment between upper guide shaft and bearing or big bearing clearance”， so the two reasons can be proceeded from. Because the plant has been carried out maintenance of the upper guide bearing and can not solved the problem of vibration fault, the possibility of“the misalignment between upper guide shaft and bearing or big bearing clearance” can be ruled out. Adding the test record, the cause of vibration is determined basically as the "mass imbalance". The dynamic balancing of the unit can be considered.

Dynamic balance process, the test quality of weight block is chosen appropriately according to the centrifugal force produced by the block, which is the 0.5~2.5% of generated rotor. Estimation formula is:

$$m_0 = (0.005 \sim 0.025)\frac{Mg}{R\omega^2} = (4.5 \sim 22.5)\frac{Mg}{\pi^2 R n_r^2}. \quad (2)$$

In the formula: m0 is quality of trying to add, kg; M is the weight of the rotor, kg; nr is the rated speed of unit, r/min; R is the radius of adding mass focus when tested. In the plant R is chosen 3.297m and by the m0=12~59 kg the test chooses 40 kg of test weight block.

The first trial weight test, the block is placed in the turning point of No.6. M30 screw is selected and welded on the rotor arm, and then the test weight block is connected on the screw and spot welding. The test weight block is close to the rotor arm external end after welding. In this way the centrifugal force generated by the test weight in the unit during operating is tried to fall the rotor arm, and then the screw is not influenced from centrifugal force caused by the shearing force of test weight. After welding test weight, the vibration and swing amplitude of the measuring point is recorded in rated excitation voltage when the unit is in static condition. After the unit started up, the speed of the unit is slowly increased. When the vibration judged has no harm to the unit, the speed of the unit is increased to rated speed slowly. The vibration and swing amplitudes are measured while the unit is stable at rated speed and rated excitation voltage in the table 4 and table 5. According to the vibration situation, the second trial weight block is decided to place at the No.4 turning point.

Cut off the test weight block and it is welded on the No.4 turning point, then repeated the process of the first trial weight test. When tested, vibration and swing amplitudes of the measured parts is measured and shown in table 4 and table 5.

The original test weight mass is 40kg. From figure 3, the maximum swing value of the upper guide which can be red out is 295μm and 269.15μm after the first trial weight test. That is to say, the maximum swing value is down 24.85μm. The estimation formula of final test weight mass is as follow:

$$m_1 : m_2 = \mu_1 : \mu_2 . \quad (3)$$

In the formula: m1 is the final balance weight mass, kg; m2 is the original test weight mass, kg; μ1is the swing value of the upper guide after the final balance weight eventually hoped to be reduced, μm. The power station hoped swing value of the upper guide bearing in the unit operation is more below than the value in the operating directive rules, which is dropped 110μm. μ2 is the reduced value of the upper guide swing after the original trial weight test, that is 24.85μm. After calculation, the balance weight mass is m1=177.06kg, and is selected 180kg.

By analyzing the data in the table 4, the second trial effect is worse than the first, so the 180kg balance weight block is welded on the location of the No. 6 toward No.7 turning 20°. After that the unit is decided to do retest in order to verify the final effect of balance weight test. After adding balance weight block, the vibration and swing situation of each measuring point is recorded in the condition of 10MW, 40MW and 56MW when the unit is stabled at rated speed and rated excitation voltage shown in the table 4 and table 5.

TABLE 4 The swing amplitude of the measuring point trial weight and balance weight test

Test project	**Relative speed Nr (%)**	**Relative speed Nr (%)**	**Active power (MW)**	**swing of the upper guide**		**the lower guide**		**the water guide**	
				Swing of X direction	*swing of Y direction*	*swing of X direction*	*swing of Y direction*	*swing of X direction*	*swing of Y direction*
The first test	100	0	0	263.71	223.46	118.80	99.86	121.31	125.01
	100	100	0	269.15	250.70	122.09	100.75	114.70	124.33
The second test	100	0	0	305.83	303.23	141.31	123.47	117.54	119.97
	100	100	0	315.20	328.70	147.96	136.44	108.65	114.64
After balance weight test	100	100	0	223.05	211.15	119.42	107.98	140.88	143.88
	100	100	0	175.22	90.05	89.89	63.44	123.32	130.58
	100	100	10	170.86	83.27	88.55	67.22	120.75	128.29
	100	100	40	159.79	95.58	87.92	70.87	99.80	107.81
	100	100	56	154.16	99.72	89.83	71.42	80.67	96.3

TABLE 5 The vibration amplitude of the measuring point trial weight and balance weight test

Test project	**Relative speed nr (%)**	**The relative excitation voltage ur (%)**	**Active power (MW)**	**upper spider**		**The stator frame**	**lower spider**			**Water guide**
				horizontal vibration of X direction	*horizontal vibration of Y direction*	*horizontal vibration*	*horizontal vibration of X direction*	*horizontal vibration of Y direction*	*vertical vibration*	*vertical vibration*
The first test	100	0	0	18.66	24.99	8.43	50.75	47.52	36.40	77.37
	100	100	0	19.58	25.68	39.43	58.11	52.01	40.82	94.78
The second test	100	0	0	23.64	32.69	7.46	59.37	51.07	41.49	75.50
	100	100	0	24.56	34.71	27.82	64.34	58.21	48.69	82.11
After balance weight test	100	0	0	13.25	18.59	6.09	42.08	39.21	28.38	76.02
	100	100	0	13.24	13.39	34.91	27.15	21.45	23.90	78.67
	100	100	10	13.28	14.31	39.75	26.41	20.59	24.63	73.14
	100	100	40	11.53	12.67	32.36	22.73	16.33	17.12	22.52
	100	100	56	11.09	12.38	24.51	22.27	15.69	14.88	29.90

From the table 4 and 5 can be seen that the swing under Y direction of the upper guide bearing at full load rated voltage is the biggest change after the dynamic balance process, which reduced about 181μm, and greatly exceeded 110μm. The horizontal vibration is improved obviously. Horizontal vibration of upper and lower frame is reduced 20~30μm. After dynamic balance processing, the plant did variable load test. The maximum vibration amplitude of each guide swing and the frame is 97.38μm, the minimum is 11μm, which indicated that the dynamic balance treatment effect is obvious. Moreover, the one-level alarm value of guide bearing swing is dropped to 375μm and two-level alarm value is dropped to 500μm, which indicated the operation quality of power plant is greatly improving.

5 Conclusion

By means of variable speed, variable excitation voltage, variable load and phase modulation operation test, unit will be shown all of the vibration characteristics in the dynamic condition. On the basis of the vibration characteristics, fault cause can be determined. Considering the fuzziness of the vibration characteristic and type, which is complex vibration and interaction coupling, fuzzy theory is adopted to fault diagnosis.

Because of the complexity of vibration characteristics in unit, only after the data analysis and theoretical research are put together adding comprehensive consideration and judgment, the causes of vibration fault can be found when the scene test. The mathematical theory analysis is combined with field prototype test because the two methods have complementary advantages and thus repeatability of work can be reduced.

When the fuzzy comprehensive evaluation method is introduced into the vibration test analysis, difficulty is the sample selected and the fuzzy relation matrix determined. When the sample is selected, not only the parameter data is chosen which can reflect the vibration characteristics of the unit, but also chosen properly from examples, which have been applied successful. The determination of the fuzzy relationship matrix is ordinarily used expert assignment method, which can be adjusted appropriately according to the actual situation.

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