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LARGE CAPACITY BULB TURBINE AND GENERATOR

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I. INTRODUCTION

With the sharp increase in the cost of petroleum in recent years, the industries in the world are being keenly interested in the development of low head hydraulic energy with water head of less than 20 m.

Recently, large capacity bulb turbine has been developed. This development has opened a way to the development of economical low head hydraulic energy.

This report is intended to explain the features of the recent large capacity bulb turbine and generators, particulary the 34 MW large capacity bulb turbine and generator which is now operating in the Akao Power Station of the Kansai Electric Power Company and the two 16.8 MW bulb turbines and generators which are also operating in the Sakuma No. 2 Power Station of the Electric Power Development Company.

We are under manufacturing 8 units of 17.2 MW bulb turbines and generators for Lower Mettur Power Station, India which have 6.25 m runner diameter and one 40.9 MW bulb turbine and generator for Shingo No. 2 Power Station, Tohoku Electric Power Company and so on.

Table 1 shows the main data of our major bulb turbines and generators which are supplied or under manufacturing.

II. TREND OF BULB TURBINE

Fig. 1 shows the trend of the unit capacity of bulb turbines in the world.

Since 1970, the unit capacity of bulb turbines has shown a remarkable increase; for example, the bulb turbine of the Rock Island Power Station of USA has an output as large as 53 MW.

Table 1 Main data of bulb turbines and generators

	Akao	Sakuma No. 2	Western Yamuna canal	Lower Mettur	Shingo No. 2	Yamazato No. 2
Unit	1	2	8	8	1	1
Maximum Output (MW)	34	16.8	8.56	17.2	40.6	23.7
Head (m) Maximum	17.4	15.5	12.8	9	22.45	15.93
Rated	14.4	12.3	12.24	6.5	19.25	13.58
Maximum Discharge (m^3/s)	220	153	74.29	271	200	170
Speed (rpm)	128.6	125/150	187.5	75	136	125
Runner diameter(m)	5.1	4.49	3.15	6.25	5.0	4.75
Bulb diameter (m)	6.3	5.0	3.5	7.2	5.9	5.9
Number of Guide Bearing	3	2	2	2	3	3
Runner Vane	5	4	4	4	5	5
Output of Generator (MVA)	36	17	8.89	16.67	40.9	24.1
Voltage (kV)	6.6	6.6	6.6	6.6	6.6	6.6
Frequency (Hz)	60	50/60	50	50	50	50

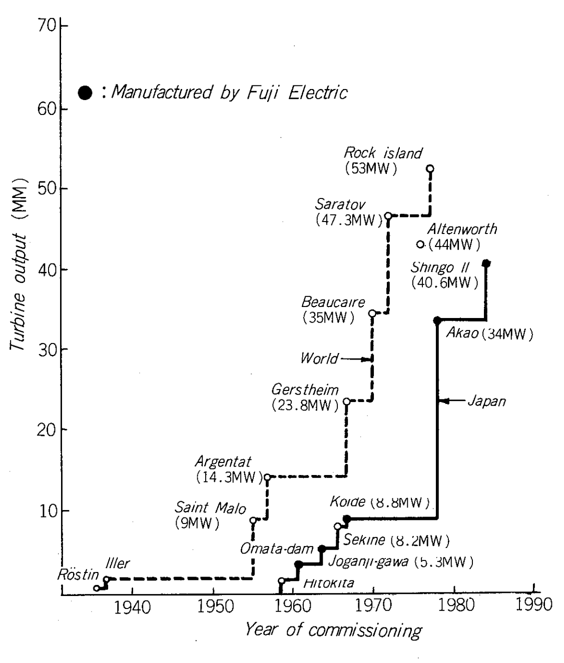


Fig. 1 Trend of unit capacity of bulb turbine

Table 2 Large capacity bulb turbine

	River	Unit	Output (MW)	Head (m)	Speed (rpm)	Runner Diameter	Operation Year
Rock Island	Columbia	8	53	12.1	85.7	7.4	1977
Saratov	Volga	2	47.3	15.0	75	7.5	1972
Altenwörth	Donau	9	46.7	18.07	103.4	6.0	1976
Sablon	Rhône	4	40	12.5	93.8	6.25	1977
Beaucaire	Rhône	6	35	10.7	93.8	6.25	1970
Akao	Sho	1	34	17.4	128.6	5.1	1978
Sauveterre	Rhône	2	33	9.4	93.8	6.9	1973
Caderousse	Rhône	2+4	32.5	9.1	93.8	6.25/6.9	1975
Gervans	Rhône	4	30	12.0	93.8	6.25	1971
Strasbourg	Rhein	6	29	14.4	100	5.6	1970
Iffezheim	Rhein	4	28	11.7	100	5.8	1977

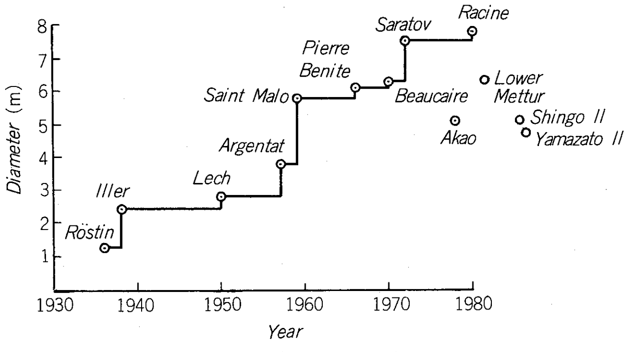


Fig. 2 Trend of runner diameter of bulb turbine

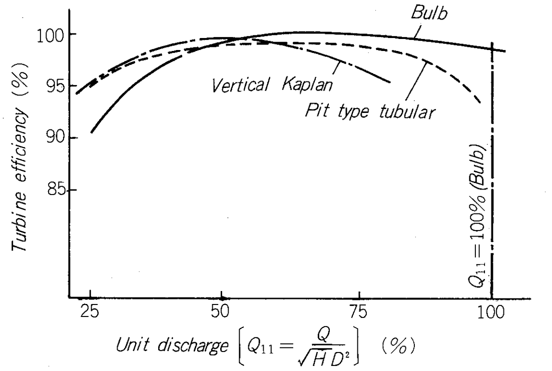


Fig. 3 Comparison of model turbine efficiency

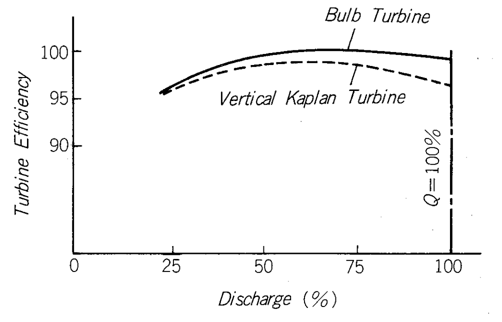


Fig. 4 Comparison of prototype turbine efficiency

Fig. 2 shows the trend of the runner diameter of bulb turbines.

The runner diameter of the bulb turbine of the Racine Power Station of USA, which is expected to start operating in 1980, is as large as 7.7 m.

The bulb turbines provide high efficiency as compared with other types of tubular turbines; in addition, large capacity bulb turbines require less maintenance. For this reason, a number of large capacity bulb turbines and generators, in place of vertical shaft Kaplan turbines, were installed on the Rhône River, Donau River and Rhein River in the Europe.

Table 2 shows the main data of the large capacity bulb turbines operating in the world.

III. COMPARISON OF BULB TURBINE AND VERTICAL SHAFT KAPLAN TURBINE

1. Efficiency

In order to reduce the size of turbine, the low head turbine requires a large unit flow rate ($Q_{11} = Q/D^2\sqrt{H}$, Q: flow rate, H: effective head, D: runner diameter).

The velocity energy at the draft tube inlet is high as 50% of the effective head. Accordingly, a bulb turbine with a cone type draft tube has a higher efficiency than a vertical shaft Kaplan turbine at a large flow rate (large Q_{11}) since the cone type draft tube has a higher velocity energy recovery efficiency. As shown in *Fig. 3*, the loss of bulb turbine efficiency is very small even at a large flow rate, so the maximum unit discharge of a bulb turbine is about 20% as large as that of a vertical shaft Kaplan turbine. Because of this, when an effective head and maximum flow are given, the bulb turbine's runner diameter become about 90% of the runner diameter of a vertical shaft Kaplan turbine.

Fig. 4 shows the relationship between the discharge and efficiency of a prototype bulb turbine where its runner diameter is selected to 90% of the runner diameter of a vertical shaft Kaplan turbine.

From the figure, it can be understood that the bulb turbine has an excellent efficiency over the entire range of the flow rate.

2. Specific speed

In a bulb turbine, the unit speed ($n_{11} = nD\sqrt{H}$, n: speed, H: effective head, D: runner diameter) can be increased about 10% higher than that of a vertical shaft Kaplan turbine.

Therefore, the bulb turbine's specific speed ($n_s = \frac{nP^{1/2}}{H^{5/4}} \propto n_{11}\sqrt{Q_{11}}$, P:Output) can also be increased about 20% higher than the vertical shaft Kaplan turbine.

Fig. 5 shows the relationship between the specific speed and effective head of recent large capacity bulb turbines. From this figure, it can be understood that the specific speed of recent bulb turbines is 10 to 20% higher than the limit of the specific speed of vertical shaft Kaplan turbine prescribed by JEC 151.

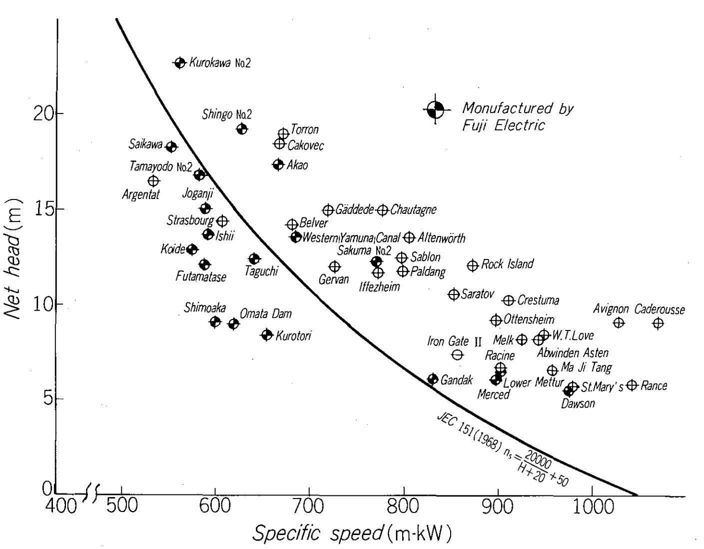


Fig. 5 **Specific speed of tubular turbine**

3. Cavitation performance

The relation between the cavitation coefficient and the unit discharge of a bulb turbine is similar to that of a vertical shaft Kaplan turbine. As stated previously, the maximum unit flow of bulb turbine is larger than that of vertical shaft Kaplan turbine, so the plant cavitation coefficient of the bulb turbine is also larger than that of the vertical shaft Kaplan turbine.

However the bottom of the water passage of a bulb turbine is shallower than the bottom of the draft tube of a vertical shaft Kaplan turbine. Hence the amount of excavation is relatively small.

4. Cost of turbine and generator

As explained above, the bulb turbine has a smaller runner diameter and a higher speed than the vertical shaft Kaplan turbine, the weight of the bulb turbine is lighter than the vertical shaft Kaplan turbine.

However, the bulb turbine is complex in construction and its generator requires a water-tight structure. Therefore, the bulb turbine and generator is a little costly as compared with the vertical shaft Kaplan turbine and generator.

5. Civil cost

The major feature of the bulb turbine is substantial reduction of civil cost of a power plant.

In the case of the vertical shaft Kaplan turbine, the water passage has a width about 3 times the runner diameter, while, in the bulb turbine, it is about 2 times as large. Since the bulb turbine's runner diameter is about 90% of the vertical shaft Kaplan turbine's runner diameter, the width of the water passage for the bulb turbine is about 60% of the vertical shaft Kaplan turbine.

Fig. 6 shows the comparison of power house dimensions. With the bulb turbine, the power house width can be substantially reduced and the water passage structure can be simplified. Accordingly, the civil cost for a bulb turbine power house is much less than that for a vertical shaft Kaplan power house.

6. Maintenance and inspection

The large capacity bulb turbine permits maintenance personnel easy access to the inside of the turbine and generator through an inspection passage. As for the turbine runner which is important in the sense of maintenance, the bulb turbine can be maintained much easier than the Kaplan turbine.

7. Stability

In order to minimize the loss of the water passage, the bulb turbine generator is such that the generator stator has a diameter about 60% of the outside diameter of the stator of the vertical shaft Kaplan turbine generator. Because of this, the inertia constant ($T_j = GD^2 \cdot n^2/364$ kVA) of the rotating part is about 1/3 that of the vertical shaft Kaplan turbine generator. When the bulb turbine generator is connected to a power system, the system stability must be considered. This can be achieved by the use of PID governor and power system stabilizer (PSS).

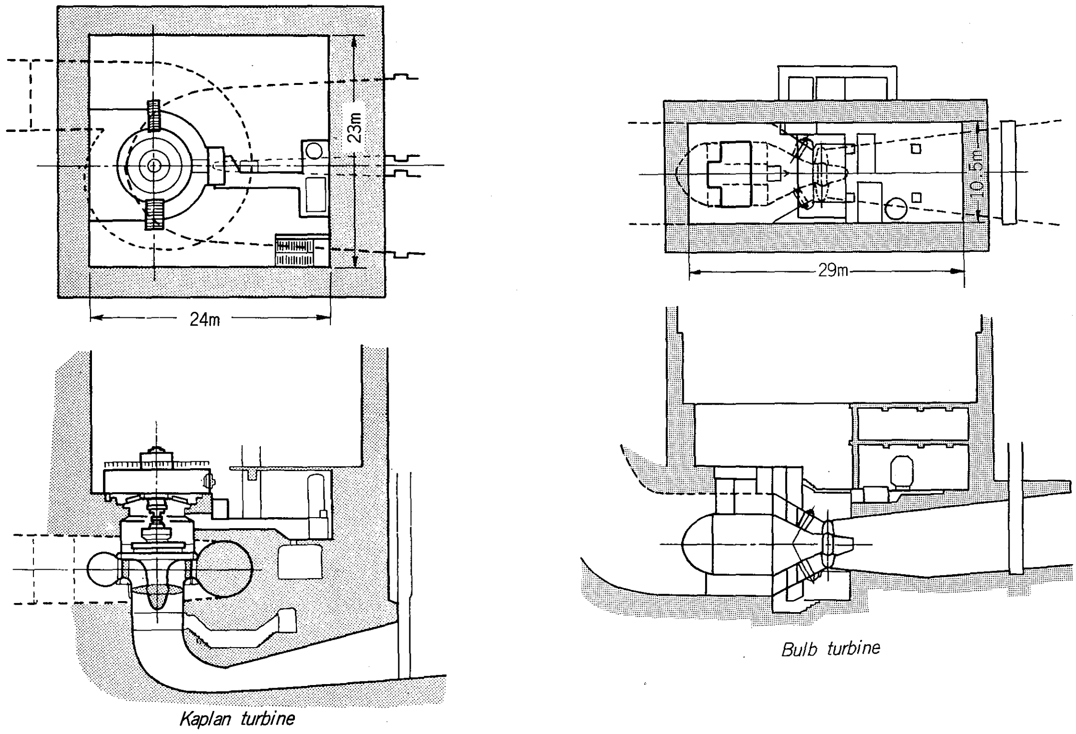


Fig. 6 Comparison of power house dimensions

IV. FEATURE OF LARGE CAPACITY BULB TURBINE AND GENERATOR

1. Bulb supporting method

The bulb in which the turbine and generator are housed, is subject to static load due to hydraulic thrust, weight, buoyancy, generator torque and thermal stress, and dynamic load due to rotating parts and hydraulic pressure fluctuation. Consequently, the bulb supporting member must have sufficient strength and rigidity. It must also be designed to minimize the loss which affects the flow of water, to serve as a passage for maintenance and inspection, and to simplify the civil work to support the load.

The bulb can be supported by various methods as shown in *Fig. 7*. In the Akao Power Station, the hydraulic thrust and the generator torque were supported by two stay-vanes located on upper and lower sides. Since the bulb is supported locally, the turbine and generator is deformed easily as compared with a vertical shaft type. So, the stress and deformation at each part under any operating conditions must be checked in the designing stage.

Fig. 8 shows the details of the stress and deformation analyzed by the finite element method.

2. Bearing arrangement and vibration

In the Akao Power Station employing high speed, large capacity bulb turbines, the three-bearing system is used. In the case of low speed, small capacity turbines, as found in the Sakuma No. 2 Power Station, the two-bearing system is used to overhang the generator rotor (*Figs. 9* and *10*).

Fig. 11 shows the relationship between the bearing arrangement, turbine output and rotating speed.

In either bearing arrangement, the natural vibrations of the main shaft and bulb must be checked accurately in the designing stage to avoid resonance, since the heavier runner is overhung.

3. Air cooling of generator

In the bulb turbine generator, the outside diameter of the generator stator must be 1 to 1.2 times the runner diameter to minimize the loss of the turbine water passage. As compared with ordinary turbine generators, the core length is relatively large for the outside diameter of the generator stator.

This not only increase the rate of the field loss in the total loss but also the rate of the core length to the pole pitch. Accordingly, special care must be taken with regard to the efficient cooling of the generator rotor.

The air cooling system of the bulb turbine generator is roughly classified into the following two types.

One is a type by which air enclosed in the generator is circulated using forced circulation blowers and air coolers, and the other is a type by which the generator is cooled actively by water flowing outside of the bulb since the bulb is fully immersed in the water channel. An example of the former type is shown in *Fig. 12*.

This air cooling system has been employed for the 36,000 kVA generators in the Akao Power Station. In this

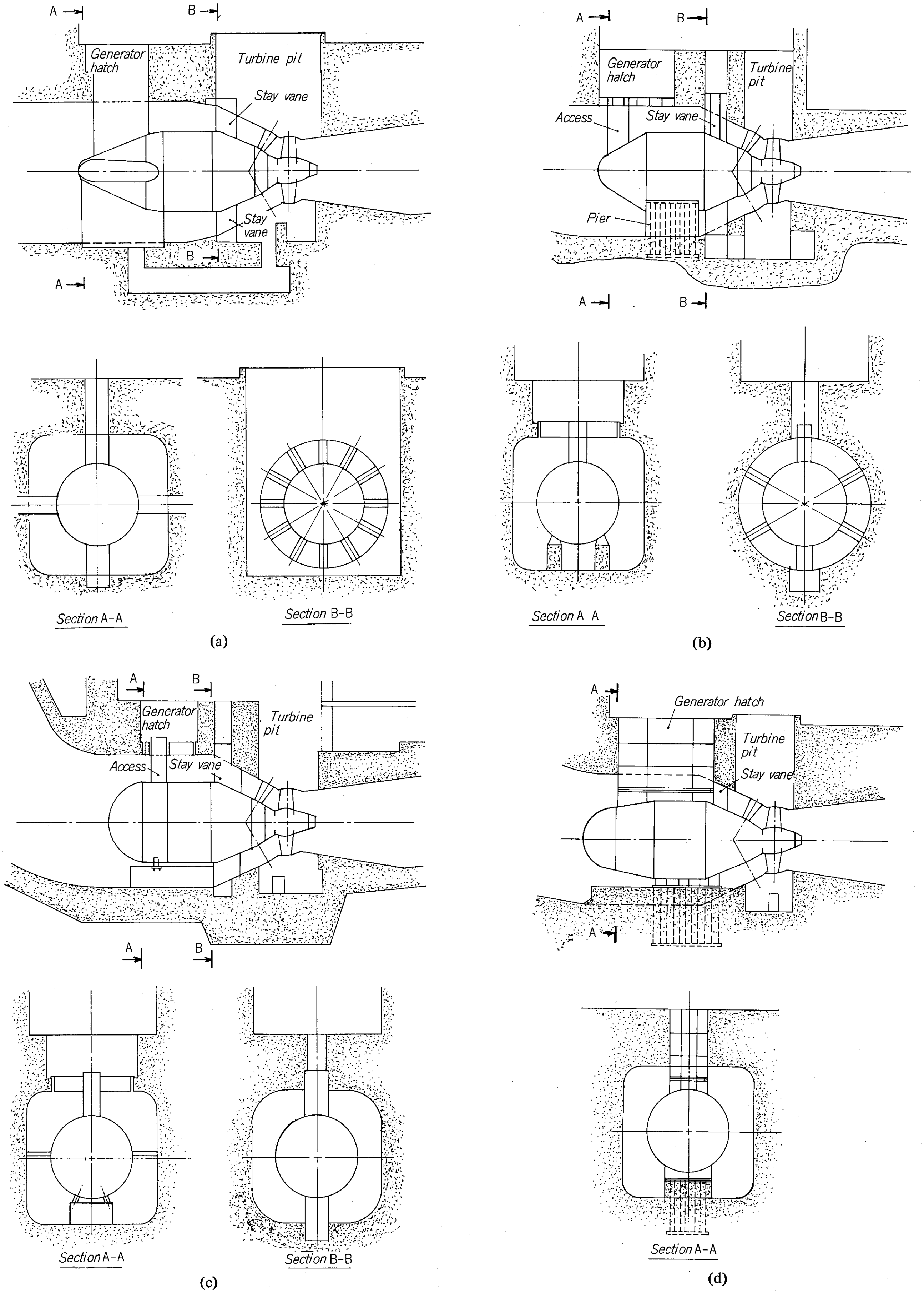


Fig. 7 **Supporting methods of bulb**

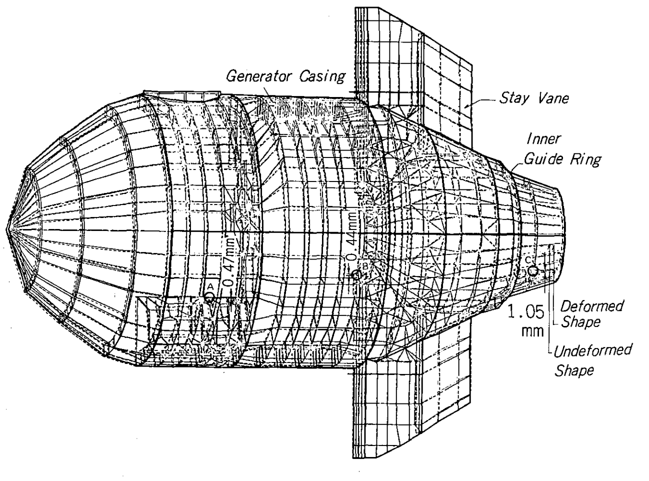


Fig. 8 Analysis of bulb deformation by finite element method

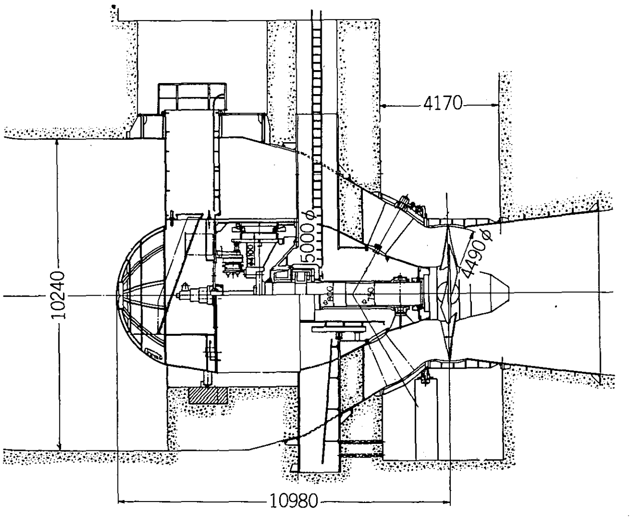


Fig. 10 Section of bulb turbine and generator for Sakuma No. 2 power station

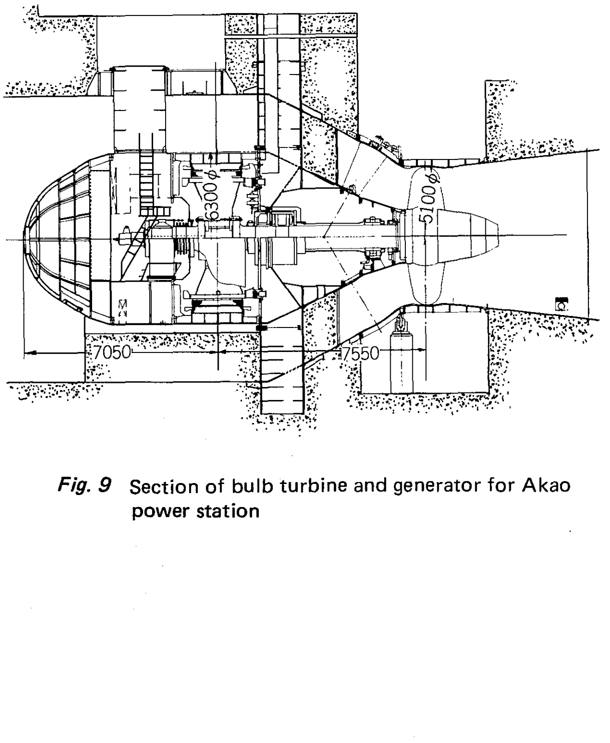


Fig. 9 Section of bulb turbine and generator for Akao power station

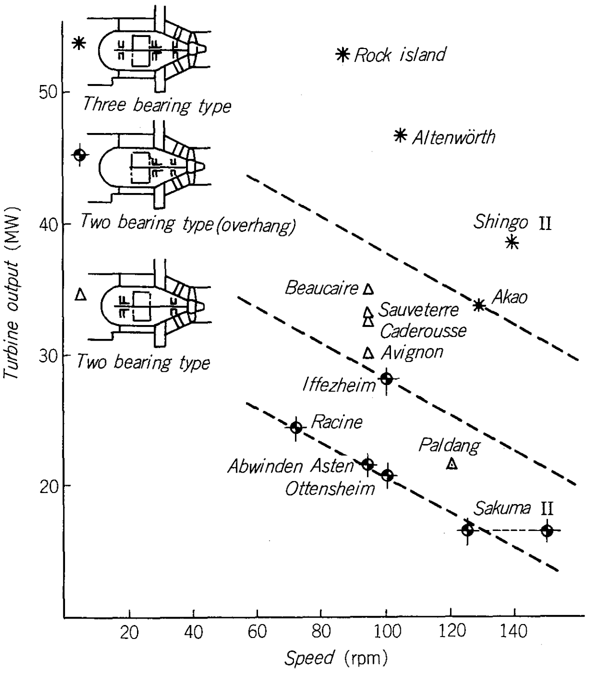


Fig. 11 Bearing arrangement of bulb turbine and generator

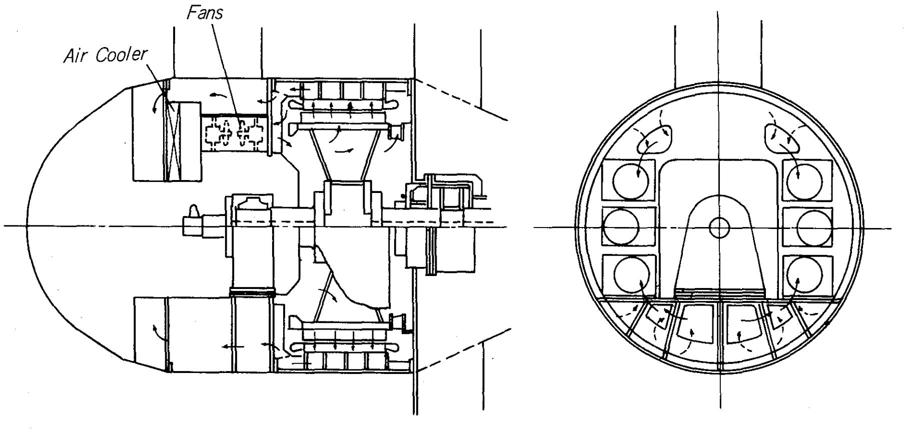


Fig. 12 Cooling system of generator for Akao power station

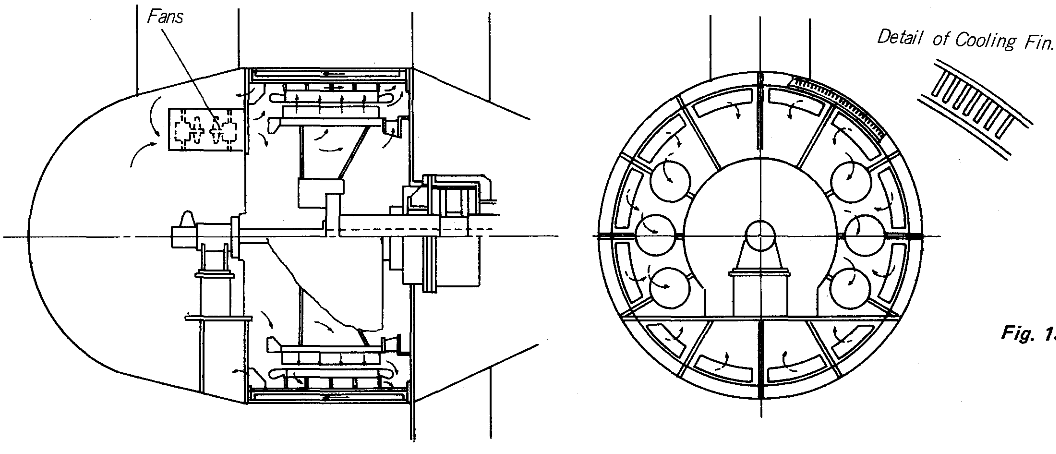


Fig. 13 Cooling system of generator for Sakuma No. 2 power station

system, the cooling air is fed into the generator by six forced circulation blowers mounted on the bulb nose. In this way, the rotor and the stator are cooled effectively by means of the auxiliary radial fan on the rotor. The cooling air then flows back to the bulb nose along the inside wall of the bulb and is again fed to the generator by the air coolers and blowers. In this cooling system, the cooling air circulation route in the bulb is isolated from the turbine chamber or the bulb nose chamber, thus permitting easy access to the interior of the bulb for maintenance and inspection of the bearings during operation.

In the latter type of cooling system by which the generator is cooled with water flowing outside the bulb, the inside wall of the bulb is provided with fins to increase the heat transfer surface and to dissipate the heat of the warmed air without using a separate air cooler. In this type, for the purpose of increasing the cooling efficiency and realizing a compact design of the machine, often the inside pressure of the bulb is increased. Selection between these two types should be studied carefully with consideration given to the economy and maintenance. Since the degree of increase in the available surface area of the bulb is smaller than the degree of increase in the loss caused by the increase in the output, this cooling system is normally used for generators with capacity of less than 20,000 kVA.

The pressurize fin cooling system was employed in the 17,000 kVA bulb turbine and generator for the Sakuma No. 2 Power Station.

The outline of the system is explained in the following.

1) Fin cooling

Fig. 13 shows a typical air cooling system.

Forced circulation blowers are installed in the bulb nose. The cooling air from the blowers is fed to the generator for cooling the rotor and the stator. When the cooling air reaches the barrier at the turbine chamber, it flows into the duct located between the bulb wall and the rear of the stator core. The duct is provided with copper fins which are arranged on the inside wall of the bulb at proper pitches determined by various experiments and studies. When the cooling air passes through the fins in the axial direction the heat is dissipated into the water flowing outside the bulb, thereby cooling the generator.

After cooling, the air is again fed to the generator by the blowers in the bulb nose via the sealed air circulation route.

2) Pressurize in generator

o Effect of pressurizing

In the bulb turbine generator, the rate of field loss is larger than that of the conventional turbine generator, so the size of the generator is determined mainly by the rotor. To reduce the size, the cooling efficiency of the rotor must be improved by increasing the air pressure circulating in the generator for greater heat dissipation.

That is, the heat dissipation coefficient is proportional to 0.75th power of (pressure x air velocity) and hence the cooling efficiency is improved about 1.7 times at air pressure of 1 $kg/cm^2 \cdot G$, if the air velocity remains unchanged. *Fig. 14* shows the relationship the air pressure and the output of the generator. When the generator size is reduced by increasing the air pressure, the generator efficiency is lowered while the turbine efficiency is improved, thereby increasing the overall efficiency.

o Pressurizing and air seal system

To increase the pressure in the generator, the air pressure from the compressor is fed to the generator through

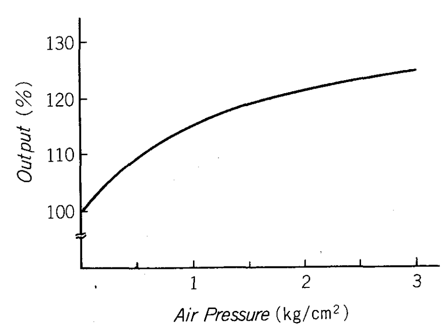


Fig. 14 Relation between air pressure and output of generator

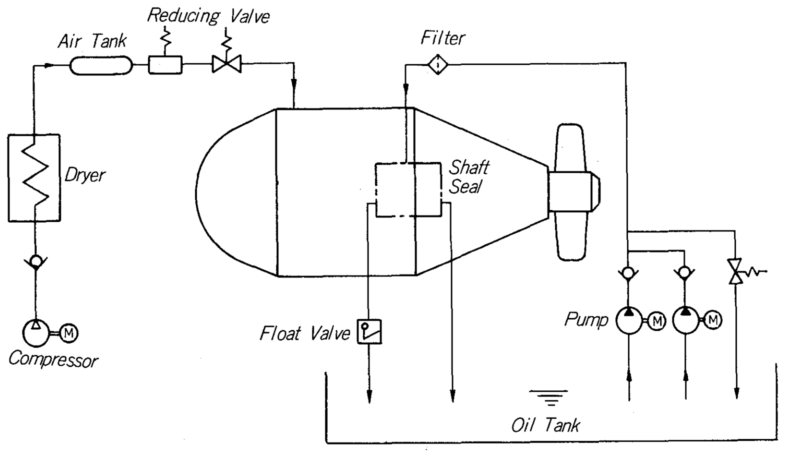


Fig. 15 Pressurizing and shaft sealing diagram

the dryer and the air tank. If, at this time, the pressure is lowered due to leaks from the generator, the compressor starts operating by the pressure switch to maintain the required pressure. In order to maintain the required pressure, the pressure chamber must be of an air-tight structure as far as possible. The turbine chamber must be opened to allow inspections of the bearings and control devices even when the generator is in operation.

That is, the air seal section is provided with a white metal lined seal ring with a slight radial gap given at the shaft to feed oil pressure a little higher than the pressure in the generator, thus preventing air leaks into the turbine chamber. The oil fed to the seal ring is discharged from the high and low air pressure sides. The oil discharged from the lower air pressure side is combined with the oil from the bearing and then returns to the oil tank. On the other hand, the oil discharged from the high air pressure side is collected in the oil tank with a float valve and then returns to the oil tank.

V. SITE TEST OF LARGE CAPACITY BULB TURBINE

The bulb turbine and generator used in the Akao Power Station is an large capacity machine. On this machine, data such as bulb deformation and vibrations of the main shaft and bulb were analyzed in detail in the designing stage. Also, various data were collected at the time of the site test to compare them with the design data so as to be used as a reference in designing large capacity bulb turbines and generators in future.

1. Deformation and stress of bulb in axial direction.

Fig. 16 shows the results of the measurement of the deformation in the axial direction at the "A" point representing the displacement of the thrust bearing casing and "B" point representing the displacement of the bulb in various operating mode such as water filling, starting, parallel running, increased load and load rejection.

Since water was first fed from the tailrace with the guide vane fully closed, the bulb was shifted to the upstream side. Water was then fed from the upstream side, so the bulb was shifted to the downstream side. During the increased load operation, the hydraulic thrust changes very little at above the minimum on-cam opening and hence the deformation in the axial direction of the bulb remains practically unchanged.

When the load is rejected, the hydraulic thrust causes a substantial change, thus vibrating the bulb in the axial direction.

The site test revealed that the deformation of the bulb in the axial direction and the stress of the stay-vane are within the allowable values, proving us with'an important data concerning the analysis of deformation and stress.

2. Movement of runner in vertical direction

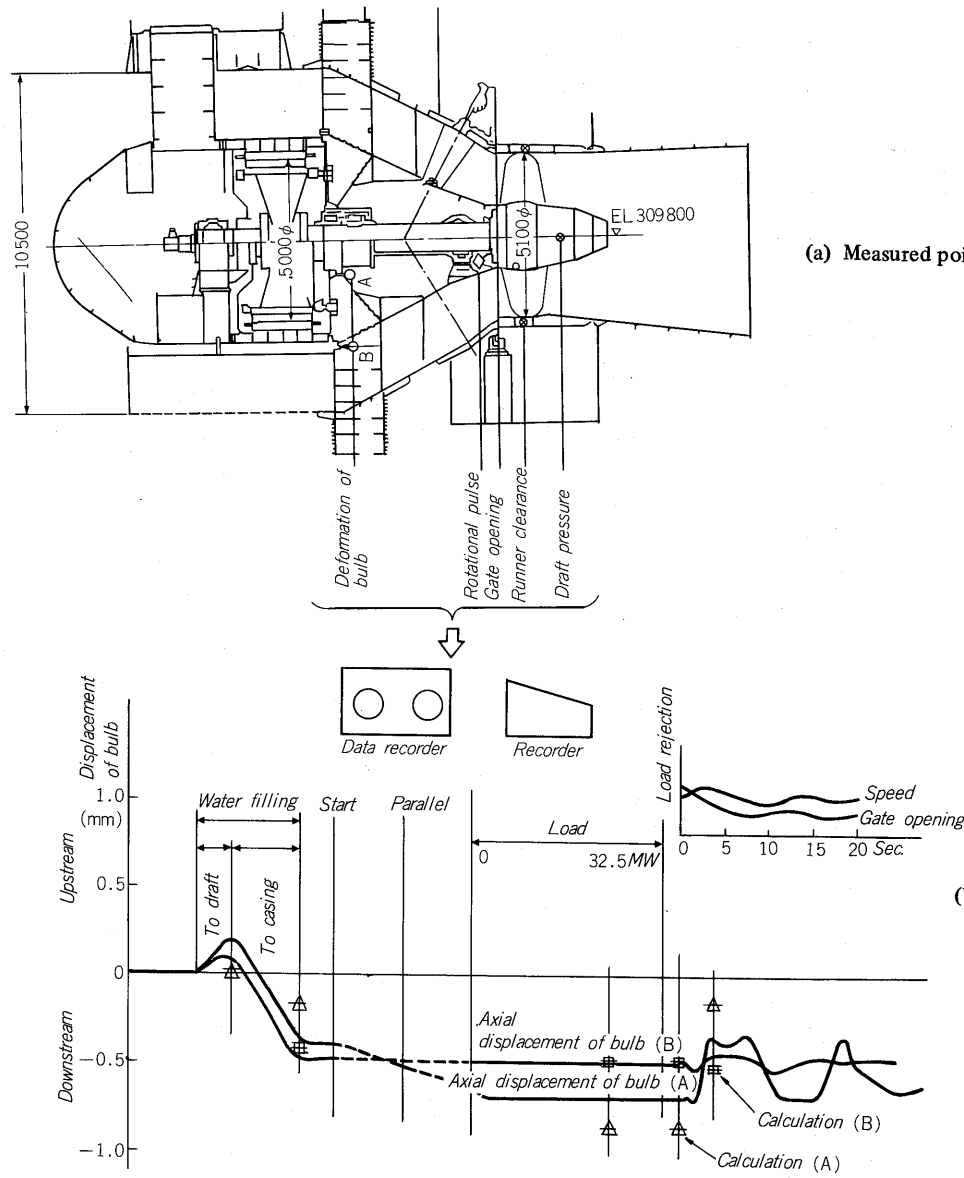
The gap between the runner blade tip and the discharge ring should be as small as possible to reduce the leakage loss and the gap cavitation. When the turbine is to be installed, the runner must be centered correctly taking account of the movement of the runner center and the deformation of the runner which may occur in any operating mode.

In the site test, eddy-current type proximitors were mounted on the discharge ring to measure in the runner gap, the vertical movement of the runner center, and the deformation of the runner vane in all the operating modes.

3. Natural frequency of main shaft and bulb

In testing the natural frequency, hydraulic oscillators were attached to the runner end and the bulb upstream side. The exiting frequency was changed from 0.5 to 50 Hz, and the amplitude measured at each part was recorded by a multi-channel data recorder. The recorded data were analyzed by a special computer.

Fig. 17 shows the frequency characteristic of horizontal vibration of the bulb nose and the runner cone with vibration applied to the upstream side of the bulb. The horizontal natural frequency of the main shaft and the bulb was lower than the vertical natural frequency becuase of the difference of the rigidity of the bulb support.



(a) Measured point

(b) Displacement of bulb

Fig. 16 **Measured value of axial deformation of bulb turbine**

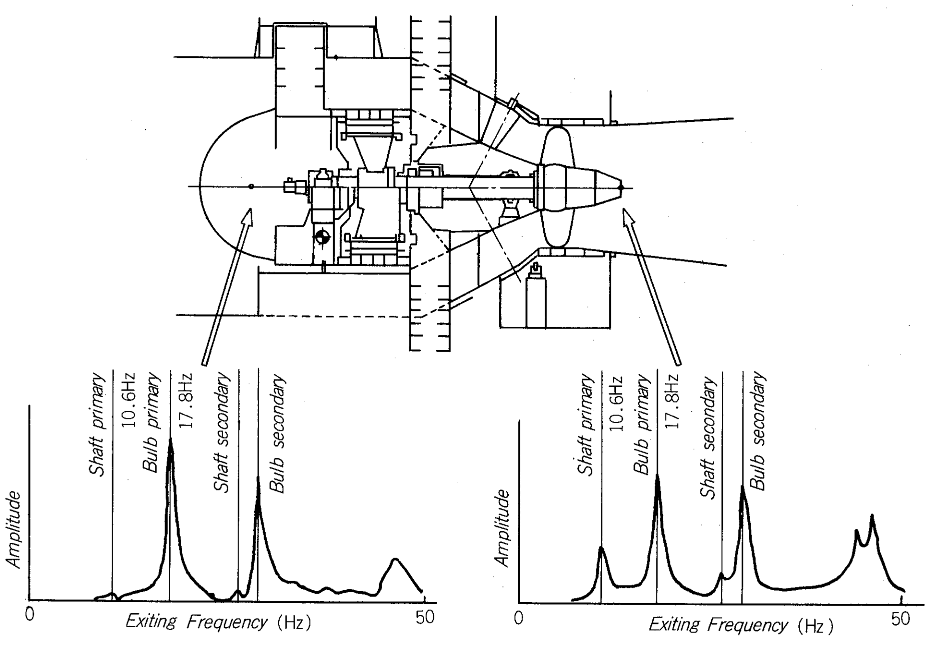


Fig. 17 **Frequency spectra in horizontal vibration**

The primary natural frequency of the main shaft is determined mainly by the weight of the runner and the rigidity of the turbine shaft and bearing.

4. Measurement of vibration

The bulb turbine and generator is less rigid in construction, so the vibration at each part tends to increase. Vibration was measured during operation. The actual vibration at each part was small, particularly the vibration of the turbine shaft during on-cam operation was below 20 μ (single amplitude).

VI. CONCLUSION

As for the bulb turbine and generator which was used in the low head field, it is assumed that the unit capacity in future will be increased with a higher head through analysis of technical problems. To attain this, it is considered important to obtain a cooperation of civil, turbine, and generator engineers.

The technology of large capacity bulb turbine and generator is also expected to be utilized in the development of new energies such as tidal power generation. In concluding this report, we wish to express our many thanks for the technical advice given by the Kansai Electric Power Company and the Electric Power Development Company.