Recent Technology of Water Turbines

Shoichi Yamato
Yukio Murata
Ken-ichi Suzuki

1. Introduction

Recently, the development of hydropower has shifted to the development of medium/small capacity sites and the replacement of existing turbines, because most of the economically advantageous large capacity sites have already been developed. Thus a large number of medium/small capacity units have been designed, manufactured and put into operation.

According to the Fifth Undeveloped Hydropower Investigation conducted by MITI in 1986, it was reported that undeveloped general hydropower sites in Japan numbered 2811, with total output at 13,010MW and annual power production at 49,700GWh. The average output per site approximately 4,600kW, indicating a trend towards the development of medium/small capacity hydropower plants in the future.

Medium/small capacity hydropower plants require relatively high civil costs despite their smaller capacity. Thus, unit construction cost tends to be higher. For this reason, various new technologies need to be applied to improve overall plant economy. Fuji Electric has long been developing and applying numerous technologies in order to cost decrease and simplify equipment in response to the coming era of medium/small capacity hydropower plants.

In this report, turbines commissioned in the last five years are outlined, focusing mainly on their technical characteristics (**Table 1**).

2. Research and Development

In the research and development of a turbine, the main activities are performance prediction by numerical analyses on the turbine's internal flow, performance checks, and improvement of performance by model tests. For numerical analyses, programs have been developed enabling the optimization of a design in a short period of time.

In recent years automatization of experimental measurements and data processing, as well as the air test stand, have been introduced. These developments have enabled a

Table 1 Main turbines put into operation in the last 5 years

Type	Power plant	Specification			Date in operation
		Output (MW)	Head (m)	Speed (r/min)	
Francis turbine	Chiew Larn	92	83.5	177	1987. 4
	Hondoji	77	143.3	273	1990. 6
	Akiba No. 3 (unit 1)	46.5/45.6	47.1	129/107	1991. 9
	King	147.9	188	273	1992. 2
Bulb turbine	Lower Mettur	17.2	7.53	75	1987. 11
	New Martinsville	20	6.4	64	1988. 8
	Yamazato No. 2	23.7	15.93	125	1992. 7
Kaplan turbine	Lucky Peak (unit 1)	11.5	72.85	450	1988. 6
	(unit 2, 3)	46	72.85	257	1988. 7
	Shinhatasato (unit 1)	7	30.4	400	1988. 9
	Sasado	9.7	42.95	277	1989. 6
Pelton turbine	Bradley Lake	63.1	335.3	300	1991. 9
	Ohzaso	12	215.55	375	1991. 4
	Kitamatado	24.9	256	360	1991. 11
S-type tubular turbine	Michiyabara	1.9	19.39	429	1988. 3
	Kokusei No. 2	2.5	21.64	400	1992. 5
	Kokusei No. 3	1.6	14.16	327	1992. 5

Fig. 1 Computer room

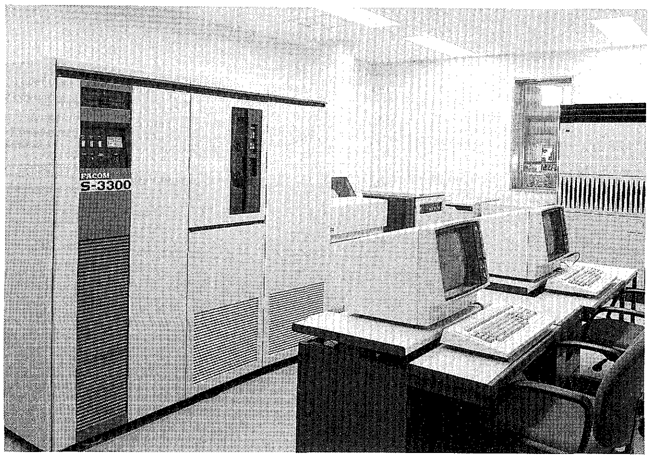

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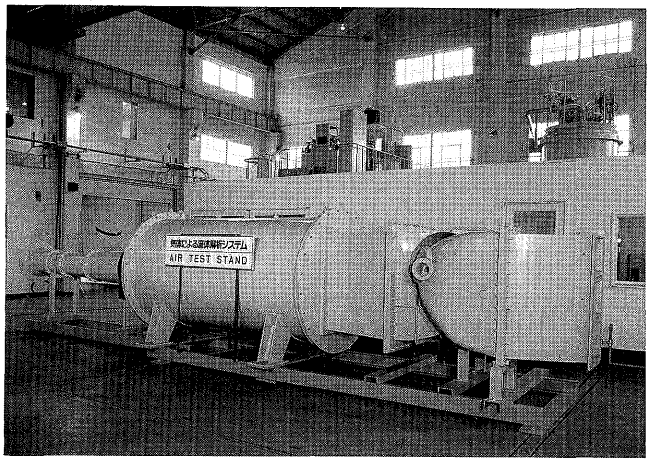
Fig. 2 Air test stand



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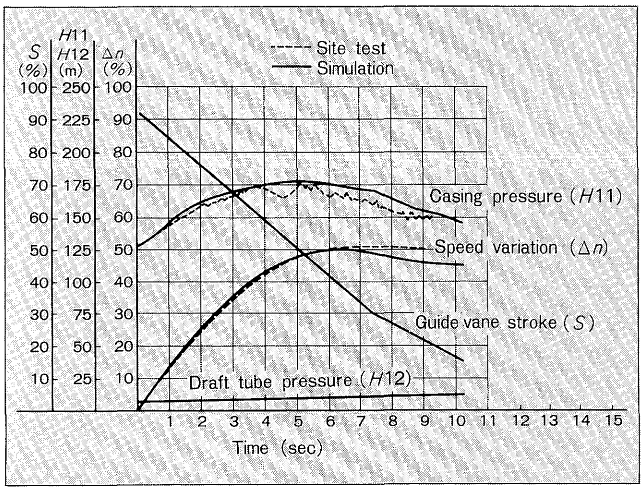
significant simplification of the testing equipment and reduction of test time. Development of the tunnel ventilation system is also being carried out with the application of the flow analysis technique, which was perfected many years ago.

This automatization of testing makes possible automatic calibration, automatic equipment operation, and automatic measurement and data processing. The computer system installed in Fuji's Hydraulic Research Laboratory (**Fig. 1**) performs testing. Various instructions necessary for testing are given, and test conditions are monitored by the site computer which is connected to a host computer. Using these improvements a considerable energy saving is realized.

Since low density air is used for the air test stand (**Fig. 2**), tests can be conducted with plastic or wooden models, simplifying the testing. Using this test stand, a model is placed in the air duct, and the same tests as those using water or those of even greater complexity are conducted. These tests include performance measurement using the pitot tube and/or laser flow meter and flow visualization, which achieves detailed analysis of the flow condition.

Fig. 3 Load rejection characteristics of Hondoji Power Station



3. Large Capacity Turbines

Among large capacity and large size turbines, a number of large bulb turbines have been put into operation in the last five years. Development of low head hydropower is also expected in such areas as China, India and Pakistan in the future.

3.1 Francis turbines

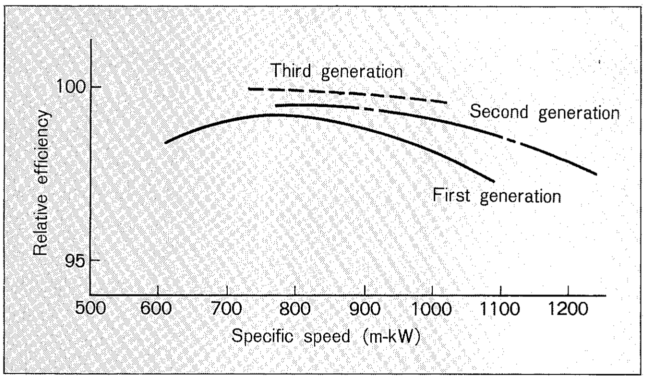
Hondoji Power Station (max. output 77MW), which Tohoku Electric Power Co., Inc.'s was put into operation in June 1990 is an underground power plant, thereby realizing a compact turbine-generator, higher turbine specific speed, and reduction in the generator's moment of inertia (J)/(kg-m^2) (1/4 of the value of the existing flywheel effect GD^2 (kg-m^2)).

Moment of inertia (J) and speed variation/(Δn) during load rejection are correlated therefore, the optimum (J) and (Δn) can be derived from the simulation of load rejection characteristics. As shown in **Fig. 3**, the site test shows results as per the design.

In September 1991, The Electric Power Development Co., Ltd.'s Akiba No. 3 Power Station was put into commercial operation. For this power plant, civil costs were reduced by installing a new water intake on the bank of an existing dam and using the existing water intake dam commonly for both the new and existing power plants. The maximum outer diameter of the runner of Unit 1 (max. power output 46.5MW) is 4,350mm and the weight is approximately 40 tons, making it one of the largest class runners (excepting the pump-turbine) in Japan. Unit 2 (max. power output 1.8MW) is a turbine installed to harness the discharge and maintain the downstream flow used for irrigation.

Because both Units 1 and 2 are double-speed units with 50/60 Hz operation, and because both units vary with

Fig. 4 Relative efficiency of model turbine



variations in the head, a runner with a highly reliable inlet cavitation performance is adopted so that inlet cavitation does not occur over the widest possible operating range.

Large capacity turbines are operating satisfactorily overseas: EGAT's Chiew Larn Power Station (max. power output 92MW) in Thailand and ICE's Ventanas-Garita Power Station (max. power output 58.2MW) in Costa Rica.

3.2 Bulb turbines

Recently, the development of low head, large discharge construction sites is increasing. Among them, ultra low head sites of less than 10m particularly stand out. Also in the case of bulb turbines, the size of the turbine with respect to its power output is larger than that of other types; hence, it is less economical. Therefore, in order to achieve economical performance, reduction of equipment size, and increase of power output by means of efficiency improvement are considered important. Size reduction is achieved by operating at a higher specific speed.

Fuji Electric has been attempting since its early days to improve turbine performance. To that effect, Fuji Electric has concentrated on the development of high specific speed, high efficiency bulb turbines with 3- and 4-runner blades. As shown in **Fig. 4**, efficiency of the high specific speed turbines has been improved every year. In addition, for bulb turbines to be installed in a by pass flow passage, the increase of net head and hence an efficiency improvement of the entire power station are achieved by utilizing the optimum curved draft tube for the curved channel, which was traditionally the open channel.

In the last five years, numerous bulb turbines have been put into operation. In India, HSEB's Western Yamuna Canal Power Station (8 units, max. power output 9.4MW), TNEB's Lower Mettur Power Station (8 units, 17.2MW), and BHPC's Eastern Gandak Canal Power Station (3 units, 5.7MW) have commenced commercial operation. Turbines for India, including the units currently being manufactured for WBSEB's Teesta Canal Falls Power Station (9 units, 8.6MW), will reach 80% in the number of units and 74% in capacity of the total number of units manufactured by Fuji Electric in the last five years. Development in this region is expected to continue in the future.

In Japan, Tohoku Electric Power Co., Inc.'s Yamazato No. 2 Power Station (max. power output 23.7MW) began commercial operation in July 1992. This power station is equipped with a long penstock; therefore, simulation analyses made beforehand of the load rejection characteristics determined the optimum (J) and closing time for guide vanes and runner blades.

The turbine for The Kansai Electric Power Co., Inc.'s Minokawai Power Station (max. power output 24.2MW, presently being designed), which will be installed in a bypass on a river bank, is one to which the previously mentioned curved draft tube will be applied. Model tests confirmed that the total efficiency of an entire power station with a curved draft tube will improve by 0.7% as compared to that of one equipped with a conventional straight draft tube and curved open channel.

Beside those already mentioned, Fuji Electric has delivered numerous other bulb turbines, as its bulb turbine technology is highly regarded both in Japan and overseas.

3.3 Vertical shaft Kaplan turbines

For both Tottori Prefecture's Shinhatasato Power Station Unit 1 (max. power output 7MW) and The Hokkaido Electric Power Co., Inc's Pirika Power Station (max. power output 4.2MW), the oilless runner was utilized to protect the environment, preventing oil from flowing into the river. Further, a recently developed runner equipped with a Kaplan turbine with positive suction head was applied to Chubu Electric Power Co., Inc's Sasado Power Station (max. power output 9.7MW).

Replacement of an existing runner made by a manufacturer other than Fuji was carried out at Wells Dam Power Station (10 units, max. power output 96.9MW) in Washington, U.S.A. The optimum runner for the water passage with different design philosophy was developed as a result of extensive numerical analyses and model tests. Superior performance of Fuji's runner was verified in a performance comparison with overseas manufacturers during model tests done by a third organization.

3.4 Pelton turbines

The application of 6 nozzles will enable a higher specific speed and the compactization of the Pelton turbine. On the other hand, in 6-nozzle Pelton turbines, it is evident that efficiency drops considerably in some areas due to jet interference. Fuji Electric has developed a runner with improved jet interference which has been adopted by many power stations.

Bradley Lake Power Station (max. power output 63.1MW) in Alaska, U.S.A., was put into operation in September 1991. Here the tailrace is lead into the sea; thus, the tailwater level varies with sea level. To keep the distance between the tailwater surface and runner even during the rise in sea level, the turbine is designed to carry out water depression operation with the use of compressed air. Also, a trough is placed on the housing's inside wall to receive water flowing out of the runner which will be used as cooling water. The effects of water depression, configuration of water intake, etc. are therefore checked by the

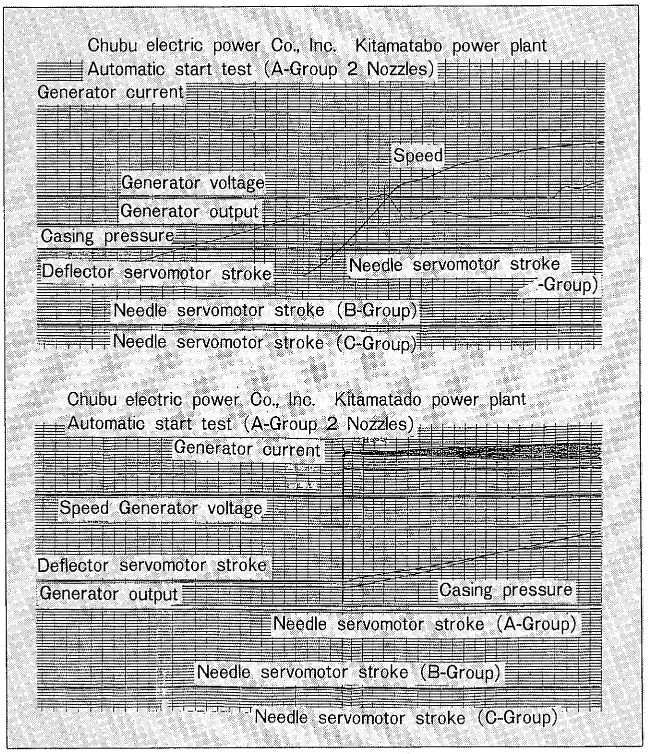


Fig. 5 Characteristics in automatic start of Kitamatado Power Station

model tests.

At Chubu Electric Power Co., Inc.'s Kitamatado Power Station (max. power output 24.9MW), which began commercial operation in November 1991, the spillway was eliminated and deflector operation was carried out, as described in Section 4. In addition, the application of the 6-nozzle Pelton turbine with improved jet interference made possible the approx. 20% reduction in powerhouse area when compared to the 4-nozzle Pelton turbine.

4. Latest Technology of Medium/Small Hydropower

Development of medium/small hydropower tends to result in higher total construction costs, whether measured in cost per kWh or cost per unit. This increase in cost is due to a smaller power generating capacity. Therefore, the application of various new technologies to improve economy becomes inevitable.

For many years, Fuji Electric has been developing and applying new technology to a large number of prototypes. Examples of such applications are described below.

4.1 Runaway machine—Nikko No. 1 Power Station

Conventionally, the speed variation during load rejection was limited to approx. 60%. Thus, for medium/small units, it was necessary to provide a flywheel and/or make generator body larger than the standard design in order to give suitable (*J*) (moment of inertia) of generator against speed variation.

However, setting the speed variation equivalent to the runaway speed will eliminate the flywheel (horizontal machine), reduce the number of bearings, and enable the utilization of natural moment of inertia (*Jn*), resulting in improvements in economy and maintenance.

This runaway machine was adopted at The Tokyo Electric Power Co., Inc.'s Nikko No. 1 Power Station (horizontal Francis turbine). It is a compact unit, with a reduction in powerhouse area and maintenance. The continual runaway speed test, conducted on site, confirmed that mechanical characteristics such as bearing characteristics and vibration characteristics were all performing within specifications.

4.2 Elimination of spillway—Kitamatado Power Station

In the case of Pelton turbines, control by means of deflector operation eliminates the spillway. During deflector operation of turbine shut-down such as load rejection, the needle controls head water level by maintaining a certain water level and the deflector deflects the direction of the jet from the runner, and thus the deflector discharge is continuously carried out. Also, when starting the turbine, start and speed are regulated by the deflector's flow control, regardless of the needle opening.

At Chubu Electric Power Co., Inc's Kitamatado Power Station, deflector operation control was adopted and the elimination of the spillway was achieved.

Figure 5 shows the automatic start of a turbine, an example of deflector operation. Smooth control is evident from start to synchronization without pressure variation in the penstock.

4.3 Utilization of drinking water supply system—Ken-oh No. 1 Power Station

Ken-oh No. 1 Power Station was constructed utilizing the existing head and water supply pipeline. The head is approx. 100m between the head and sump tanks of the water supply pipeline. The water supply pipe is approx. 3,600m long.

Therefore, the water utilized is fully treated drinking water. Several branch fittings and a piping network for each user are provided on the penstock (existing water supply pipe) that connects the head and sump tanks.

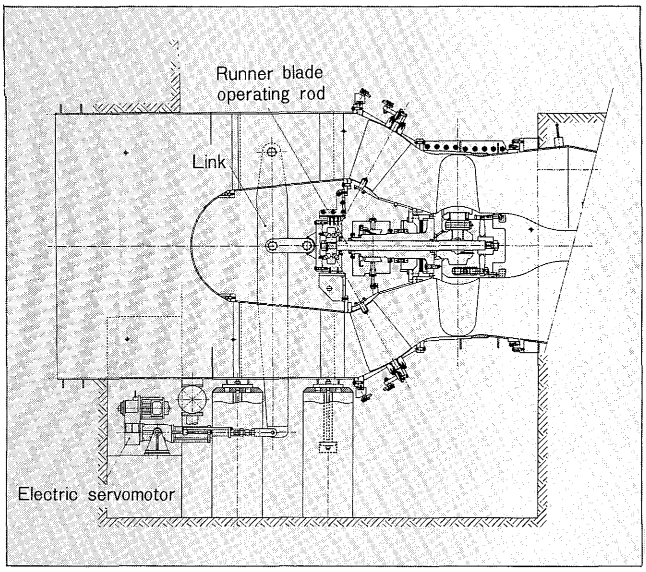
As previously described, the penstock of this power station is extremely long and has numerous branch fittings. Thus, the pressure variation at each location during load rejection was analyzed by the characteristics curve program to ensure that pressure variation had no effect on the strength of the penstock or each end user.

Furthermore, in the case of this power station, vibration and noise are controlled by fins attached to the draft tube, avoiding any change in the density of any chemical's content, such as Sodiumhypochlorite (NaOC) of the drinking water.

4.4 Electric runner blade servomotor—Ebisugawa Power Station

The turbine installed at The Kansai Electric Power Co., Inc's Ebisugawa Power Station is an S-type tubular turbine with adjustable runner blades.

Fig. 6 Electric operating mechanism for runner blade



Conventionally, the runner blades were opened and closed by the hydraulic servomotor. Installation of the hydraulic servomotor was complex, requiring many auxiliary facilities such as pressure oil equipment, a compressed air system and oil head, as well as their installation space and maintenance and inspection.

Generally, for turbines with adjustable runner blades, the application of an electric servomotor is rather difficult, since the operating mechanism of the runner blades is in the rotation system. For the Ebisugawa Power Station, however, the electric servomotor was installed outside the turbine, resulting in a simpler equipment construction and improved economy.

In addition, the closing time of the guide vane and runner blade was extended to achieve a compact servomotor and a simplified control system. Consequently, the speed variation (Δn) became 90%; however, the site test confirmed that the mechanical characteristics were all in good order.

Figure 6 shows the construction of the equipment. The electric servomotor and the end of the runner blade's operating rod are link-connected, and the use of a roller bearing makes linear movement of the rotation system possible.

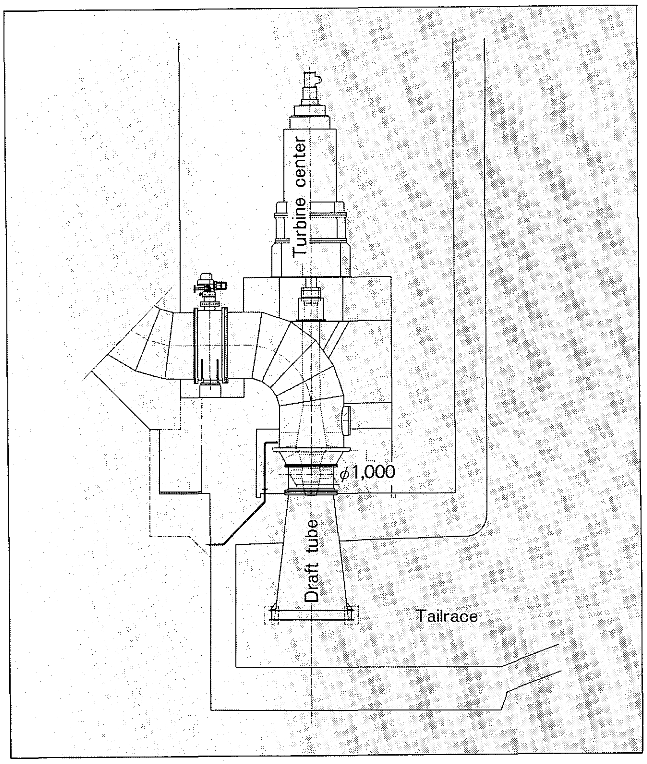
4.5 Turbine-generator with a Common Bed—Sakaigawa Dam Power Station

In recent years, water turbines with a power output of a few hundred kW and a runner diameter of about 500mm have often been designed and manufactured.

The turbine for Toyama Prefectur's Sakaigawa Dam Power Station is a compact, horizontal shaft Francis turbine with a max. power output of 320kW, a runner diameter of 525mm, a turbine/generator total length of approx. 3,000mm, and a width of approx. 2,100mm.

Minimization of the site erection schedule time and significant reduction of site cost are realized by providing a common bed for both the turbine and generator during transportation and installation.

Fig. 7 Vertical tubular turbine



4.6 Vertical tubular turbine—Yasaka Dam Power Station

A vertical tubular turbine was utilized, as shown in **Fig. 7**, at the Chugoku Regional Construction Bureau's (the Ministry of Construction) Yasaka Dam Power Station with a max. power output of 496kW and effective head of 14.5m. The reason for its adoption was that there was not enough space for installation in flow direction at the construction site, as it is located directly below the dam.

In the future, vertical tubular turbines are expected to be applied to turbines for maintaining the downstream flow as they require less construction area compared to S-type tubular turbines or bulb turbines.

5. Conclusion

An outline of Fuji Electric's hydropower technology in the last five years was described.

The first half of this five-year period involved large capacity units, but the last half was devoted mainly to the development of medium/small capacity hydropower units. Fuji was able to respond to the need for various new technologies because of its attempts early on in development.

It is very likely that the focal point of hydropower development in Japan will shift to medium/small capacity units, with a goal to reduce costs. Further development of new technology and overall lower costs including software will therefore be essential in the future.

Lastly, the authors extend heartfelt appreciation to those customers who have provided supervision and cooperation in the design and development of turbine technology.