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RECENT TECHNIQUES OF WATER TURBINE

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1 FOREWORD

About 1980, hydroelectric power generation facilities were re-examined in the light of the jump in oil prices and many large projects were constructed. Fuji Electric manufactured many record-breaking units, including four 495 MW Francis turbines for the Revelstoke Power Plant in Canada. Thereafter, total output and average unit output decreased, reflecting the age of low growth. Therefore, future plans will be centered about medium and low capacity units.

Fuji Electric forecast today's age of medium and low capacity units early and promoted standardization and simplification beginning from 1975. The completion of field tests and the placing into operation of the Yamanashi Narata No. 3 Power Plant, a medium and low capacity standardization model plant, in particular, is evaluated highly in Japan. *Table 1* lists the main turbines which have entered operation in the past five years. These recent turbines are outlined below, centered about their technological features.

2 LARGE AND MEDIUM CAPACITY TURBINES

2.1 Recent design and development

(1) Turbine research and development using laser velocimeter

The try and cut method of developing turbine by manufacturing and testing a model turbine is time consuming and expensive. In 1976, Fuji Electric began development of a turbine internal flow numerical analysis program by computer and made optimum design in a short time possible by repeated comparisons with model tests.

To improve the precision of this flow analysis program, the actual flow must be compared. A two focus laser velocimeter was introduced into the model test facility to make high precision velocity measurement. This velocimeter finds the velocity by shining two laser beams into the flow and detecting the diffused light produced when the particles in the water flow across the focal point and measuring the time required for these particles to pass through the two laser beams. Not only the velocity, but the direction of flow can be measured by rotating

Table 1 Main turbines placed in service in the past five years

Machine		Power station name	Specifications			Commercial operation
			Output (MW)	Head (m)	Speed (rpm)	
General water power	Francis turbine	Revelstoke	495	130.15	113	1984 - 5
		Pieman	119	92	167	1986 - 6
		Shin-o-i	33	44	180	1982 - 10
	Pelton turbine	Sultan River	57	340	257	1984 - 5
		Pyramid	43.3	218.2	200	1982 - 10
	Kaplan turbine	Oyodogawa No. 2	39.7	55.7	240	1985 - 3
		Saigo	19.2	26.16	212	1983 - 8
	Bulb turbine	Shingo No. 2	40.6	22.45	136	1984 - 8
		Main Canal Headworks	26.8	12.8	112.5	1986 - 7
	S type tubular turbine	Lowell	8.7	10.7	120	1985 - 10
		Tainai No. 3	2.15	14.01	300	1983 - 11
	Crossflow turbine	Kurami	0.71	77.5	730	1983 - 11
		Hikawa	0.617	30.72	270	1986 - 3
Pumping storage	Francis type pump turbine	Paithan	(T) 13.7 (P) 15.0	(T) 31.9 (P) 32.6	188	1984 - 11

Fig. 1 Kaplan turbine model runner inlet flow comparison

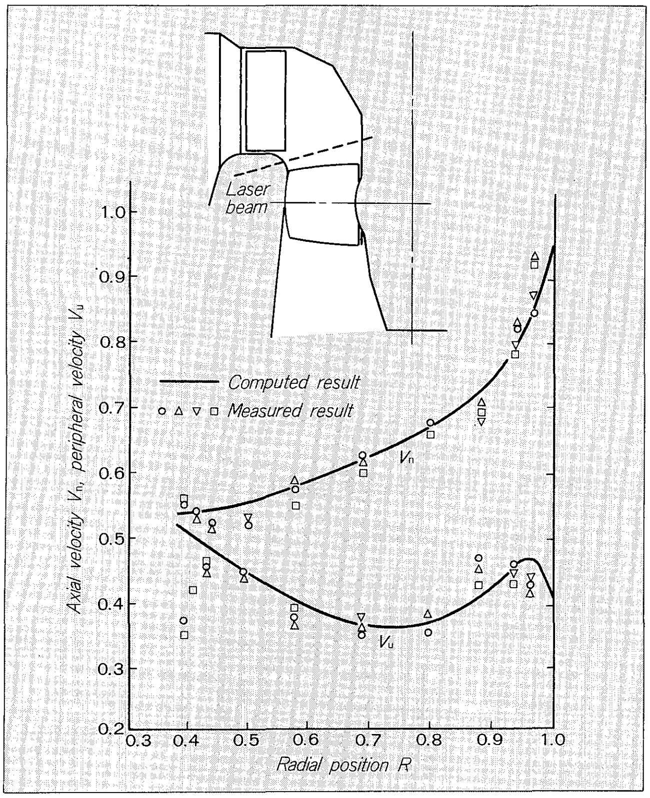
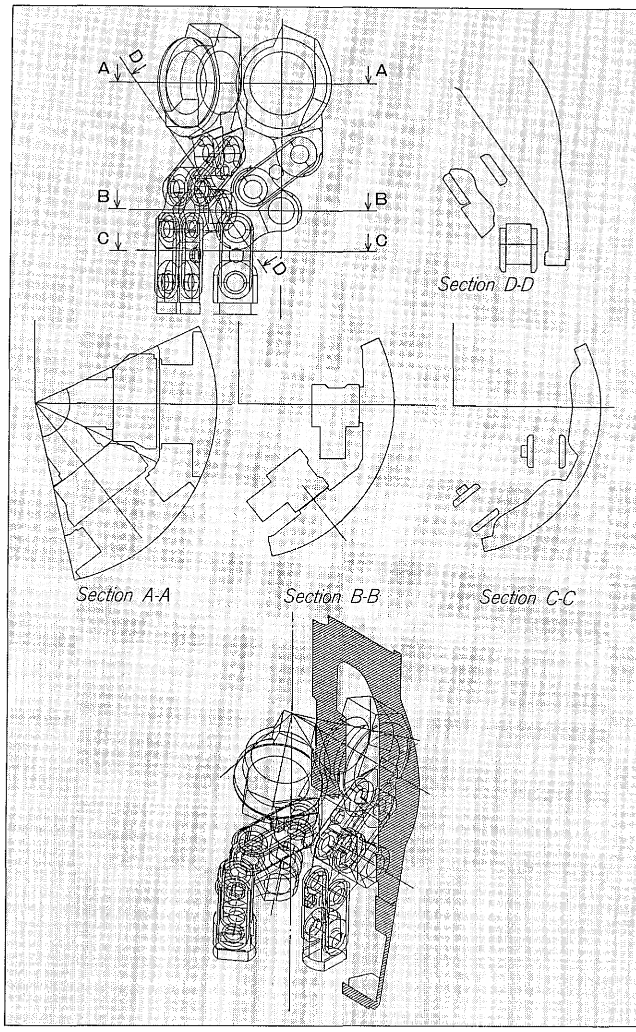


Fig. 2 Link mechanism in runner hub



one beam around the other beam. Therefore, whereas with measurement methods such as the pitot tube, insertion of the measuring device disturbs the flow and precision measurements cannot be made, the laser velocimeter does not disturb the flow and can even measure the flow through narrow passages, such as between wicket gate and runner, at high precision.

The results of the runner inlet flow of a Kaplan model turbine measured with the laser velocimeter and the results computed by flow analysis program are compared in *Fig. 1*. In the future, the precision of the flow analysis program by computer will be improved by measuring the flow around the runner by many model facilities.

(2) CAD technology in turbine design

Beginning in 1980, the turbine department began the shift to CAD/CAM and rationalized design. Today, medium and low capacity unit, whose constructural standardization is almost complete, are designed automatically by CAD. Nonstandard products can also be handled by interactive editing and design.

CAD is used not only in planning and production drawings, but also in large canned products material development, nesting, turbine blade NC machining, etc. Moreover, because a computer is used and three dimensional computation is possible, housing many parts with complex shapes in a certain part can also be confirmed. *Fig. 2* is an example of checking if adjacent link mechanism intefere from full closing to full opening of the runner blade in the runner hub of an adjustable blade turbine.

When CAD was introduced, CAD/CAM of low capacity vertical flange Francis machines was advanced.

Thereafter, schematic diagram for pressure oil and/or water system, valve diagram, and other piping related software was enhanced and design and drafting productivity was improved substantially.

2.2 Francis turbine

Between May and December 1985, all four turbines of the Revelstoke Power Plant of the British Columbia Hydroelectric Power Corporation (B.C.H.) of Canada were placed into commercial operation sequentially and are continued to operate today. The 495 MW maximum output of a single turbine of the Revelstoke Power Plant is a Fuji Electric record, and shows the consistently high level of Fuji Electric quality control technology, from design to test running.

This power plant has one of the highest single unit capacities in the world and is one of the few plants for which all the turbines and generators were made by the same manufacturer.

The runner has an outside diameter of 7 m and weighs approximately 160 t and was split into two parts due to shipping restrictions. The runner crown side was bolted

Fig. 3 Revelstoke power plant runner

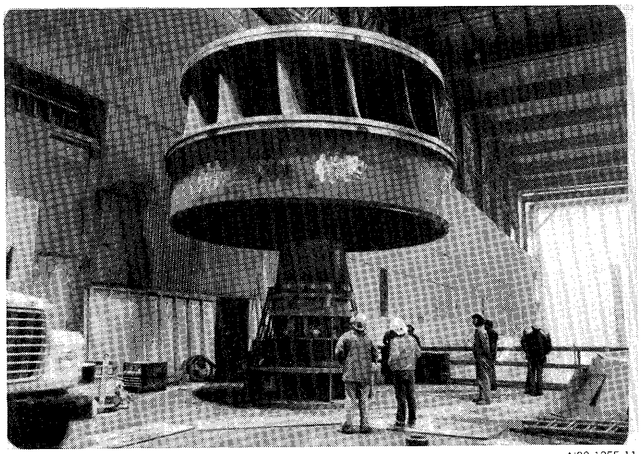


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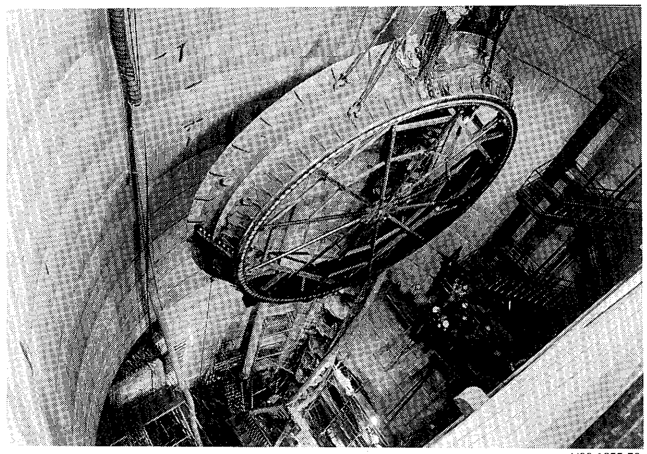
Fig. 4 Bulb turbine (40.6 MW) being installed for Shingo No. 2 Power Plant



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and the runner band side was welded at the site. Therefore, after the outer edge of the runner assembled in the field was machined by a special cutting machine, a dynamic balance test was performed.

The runner dynamic balance test performed in the field is shown in *Fig. 3*. The turbine efficiency test was performed by the multi-path acoustical method and results which satisfied the guarantee efficiency were obtained.

On the other hand, in June 1986, the No. 1 unit (maximum output 119 MW, two Francis turbines) of the Pieman Power Plant of the Tasmania Hydro Electric Commission (H.E.C.) of Australia entered commercial operation. Fuji Electric has delivered more than 10 plants to H.E.C. The capacity of this plant is second only to that of the Gordan Power Plant (maximum output 157 MW, three Francis turbines) already operating.

The Tasmania Hydro Electric Commission has many power plants which are obliged to perform synchronous condenser operation. There are also examples of synchronous condenser operation being performed for more than 3000 hours per year. This was given special consideration in the design stage.

Long-term synchronous condenser operation was made possible by using a unique Fuji Electric jet pump that uses iron pipe water pressure at water depression.

2.3 Bulb turbine

Fuji Electric developed a bulb turbine for very low head power plants from an early period. This technology was expanded to higher capacity and larger size by the success of the Akao Power Plant placed in commercial operation in 1978.

The Tohoku Power Company No. 2 Shingo Power Plant placed into commercial operation in 1984 has a turbine output of 40.6 MW and is the largest bulb turbine operating in Japan today. Since it has a high head, maximum head 22.45 m, for a bulb turbine whether or not the various loads which act on the turbine and generator are transmitted rationally to the civil engineering foundation was amply studied in advance. Since the turbine inlet and spillway cross section was made circular from the standpoint of civil engineering work method economy, its affect was studied during the hydraulic model test and reflected in the design. Because it is called a bulb turbine, the GD^2 of the rotating part is small. On the other hand, since the spillway is comparatively long, the draft tube side water pressure fluctuation at turbine load rejection was forecast to be severe. Therefore, the load rejection characteristics for general cases was simulated by computer and the optimum wicket gate closing mode was selected in advance and, therefore, results which amply satisfied the guarantee values without any problems were obtained at the field test.

The point with high capacity bulb turbines is the size of the bend and vibration of the entire bulb. The structure is made rational by using stress analysis by the finite elements method and the experimental mode analysis method in the design stage.

The Main Canal Headworks Power Station in the state of Washington, U.S.A., which started operation in 1986, uses a single 26.8 MW output, 12.8 m net head bulb turbine. As a result of three cases, double S-type tubular turbine, single vertical Kaplan turbine, and single bulb turbine, the single bulb turbine, which is the cheapest to build, was selected at the beginning of planning.

A comparison of the turbine rejection characteristics at design and the result of the field test is shown in *Fig. 5*.

Fig. 6 shows the bulb turbine runner diameter transition for the world and for Fuji Electric. For both, the trend toward larger size from the 1970s is noticeable. Since the New Martinsville Power Station (20 MW, two bulb turbines) currently being built in the state of Ohio, U.S.A. often operates at net head of about 5 m, it has three runner blades. It runner diameter of 7.3 m makes it one of the largest units in the world.

2.4 Vertical Kaplan turbine

During the past five years, the Kyushu Power Company Oyodogawa No. 2 Power Plant (maximum output 39.7 MW,

Fig. 5 Load rejection characteristics of Main Canal Head Works

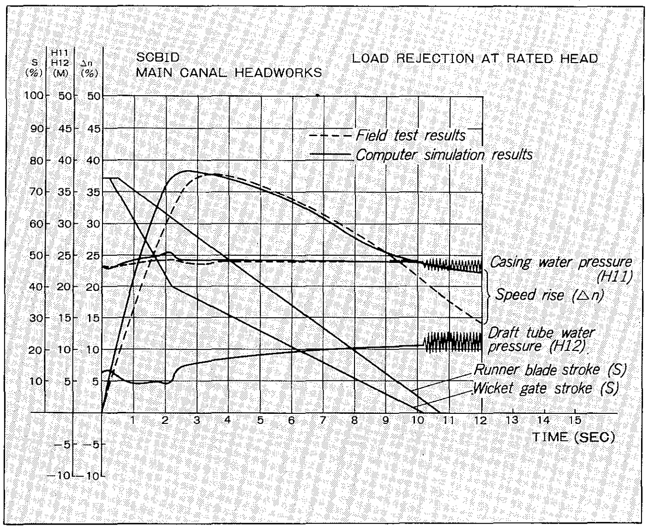
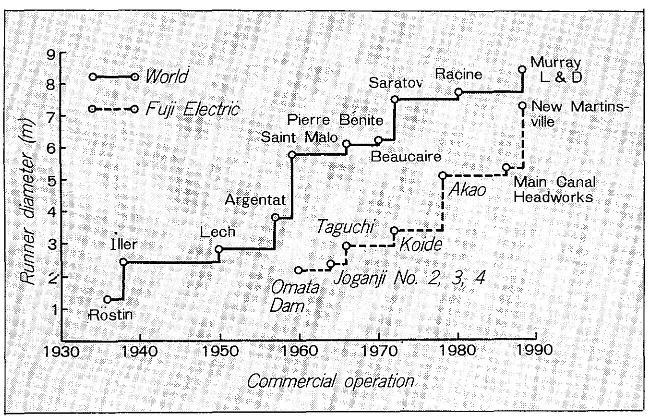


Fig. 6 Bulb turbine runner diameter transition



head 55.7 m) and Saigo Power Plant (maximum output 19.2 MW, head 26.16 m) have begun operation. The Oyodogawa No. 2 Power Plant has a high head for a Kaplan turbine and its capacity also ranks sixth in the country.

The Kaplan turbines for the Lucky Peak Power Plant in the state of Ohio, U.S.A. (maximum output 46 MW x 2, maximum output 11.5 MW x 1) are currently being installed. Their 72.2 m net head is the highest limit for a Kaplan turbine. Since the turbines are installed to the existing penstock and penstock design water pressure is low (approximately 7% as water pressure rise value), to reduce the water pressure rise, the wicket gate closing time was made 90 seconds. Therefore, the speed rise value remains near the runaway speed for one minute or longer. The runaway speed of a Kaplan turbine changes with the relationship between the runner blade opening angle and wicket gate opening. Thus, for this power plant, the wicket gate and runner blade closing mode was simulated by computer and the speed rise was made 84%. In the design stage, natural frequency analysis was performed not only for the main shaft, but also for around the turbine body so that mechanical vibration does not become large during this long high speed rise and measures were taken so that the resonance phenomena deos not occur up to the small rib.

2.5 Pelton turbine

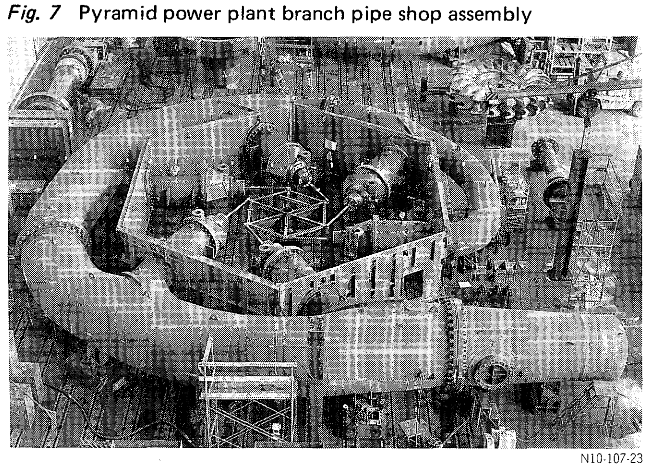
The Pelton turbine has many features not seen in other kinds, such as efficient operation at partial loads by changing the number of nozzles, low water pressure rise by needle slow closing, responsible discharge to downstream areas by deflector, etc. Fuji Electric has continuously manufactured and developed the Pelton turbine. Currently, we are developing a high specific speed six nozzle Pelton runner with improved jet interference which is gaining much attention both domestically and overseas.

The Sultan River Power Plant (maximum output 57 MW x 2) in the state of Washington, U.S.A. began operation in May 1984. This power plant was the first to be designed by Fuji Electric to perform the water depression operation. Even if the tail water level rises during flooding, power generation can be performed and the annual power production can be increased by depressing the water level in the pit by supplying compressed air into the turbine housing. For this reason, a curtain baffle to eliminate air leakage and recover the air mixed in the discharge water is provided at the tailwater and the housing, etc. are made air tight.

The amount of air supplied inside the housing varies considerably with the position of this curtain baffle. For the Sultan Power Plant, the optimum position of the curtain baffle was decided and the air supply compressor capacity was made small by model tests. This water depression operation is also performed at the Terror Lake Power Plant (maximum output 13.7 MW, operation started in December 1984) in the state of Alaska, U.S.A.

The Pyramid Power Plant (maximum output 43.3 MW x 2) and San Francisquito Power Plant (output 25.18 MW x 2) in the U.S.A. use the water of the water supply pipe to Los Angeles for power generation. Therefore, they are obligated to discharge water even when the turbine is stopped. At this time, needle full open and deflector full close, deflector discharge operation is performed. Especially, the San Francisquito Power Plant has performed the discharge operation for 1500 hours since it began

Fig. 7 Pyramid power plant branch pipe shop assembly



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operation in 1983.

The flow pattern inside the housing of the jet deflected by the deflector during discharge operation was observed by model tests. Stainless steel overlay and reinforcement are provided where the high energy jet strikes to prevent damage by the jet and guarantee that even long discharge operation has no adverse affects.

3 LOW CAPACITY TURBINE AND MAINTENANCE-FREE OPERATION

3.1 Narata No. 3 Power Plant

The Yamanashi Prefecture Narata No. 3 Power Plant, which started operation in 1985, is a so-called medium and low capacity hydraulic standardized model plant. For half the year, this plant is a run-of-river plant which often operates at partial load at a flow of 50% or less. Therefore, partial load was improved by using a new light load Francis runner developed as a new technique for medium and high head turbines.

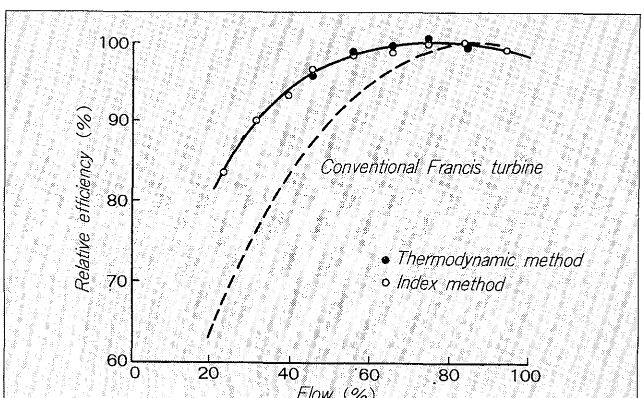
The field efficiency test results are shown by relative efficiency in *Fig. 8*. The light load runner not only improved the partial load efficiency, but also has a water pressure fluctuation reduction effect. Vibration is also small and the expected purposed was achieved.

Power plant oil and compressed air were eliminated at the Narata No. 3 Power Plant by using a motor operated servomotor instead of the conventional oil pressure to operate the wicket gate. To reduce the motor capacity of the motor operated servomotor, the opening and closing time was made 20 seconds and the maximum speed rise at turbine load rejection was made the runaway speed. This was accompanied by a 10 minutes continuous runaway speed operation test in the field. The vibration of each bearing was a very small value.

3.2 Water lubricated bearing and water lubricated hub turbine

Oil lubricated bearings have been used as turbine bearing for some time. The development of the oil-free water lubricated bearing was begun in 1980 to make the turbine maintenance-free. Up to now, the water lubricated bearing has been used in the actual machines of about 10 plants.

Fig. 8 Narata No. 3 Power Plant field efficiency test results



The water lubricated bearing uses water as the lubricant. The bearing is constructed by wrapping fiber glass reinforced phenol resin in layers around cotton reinforced phenol resin. Since a dynamic pressure system is used as the bearing lubrication system and a wedge-shaped water film is produced by the relative slippage between the shaft and bearing and the viscosity of water, and the bearing load is supported by the pressure of the water film generated at the load face, pressurized water such as the static bearing system is unnecessary and a self-contained system is possible. The assembly drawing of a water lubricated bearing for a vertical Kaplan turbine is shown in *Fig. 9*.

For the runner of an adjustable blade turbine, lubricating oil was usually sealed inside the hub to lubricate the runner bearing inside the hub, the operating mechanism bearing, and each sliding part. The disadvantages of this system were that a construction for preventing the entry of water and oil leakage from the runner blade seal was complex and maintenance and inspection were difficult. Therefore, the bearings inside the hub were made oiless and an oiless adjustable blade turbine that uses water as the lubricant (water filled turbine) was researched, developed, and practicalized. This system has a construction developed to eliminate maintenance and is matched to current market needs.

3.3 Motor operated servomotor

The wicket gate that adjusts the turbine flow was

Fig. 9 Water lubricated bearing assembly drawing

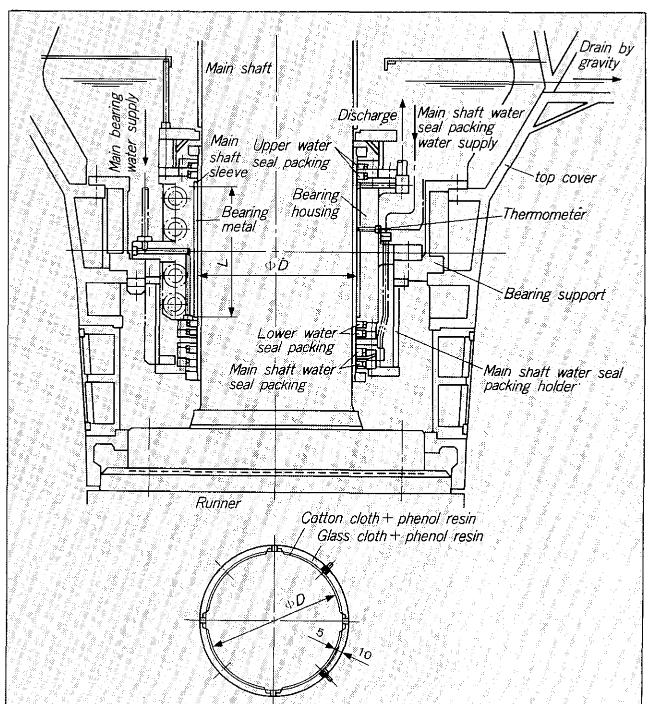


Fig. 10 Horizontal Francis turbine motor operated servomotor

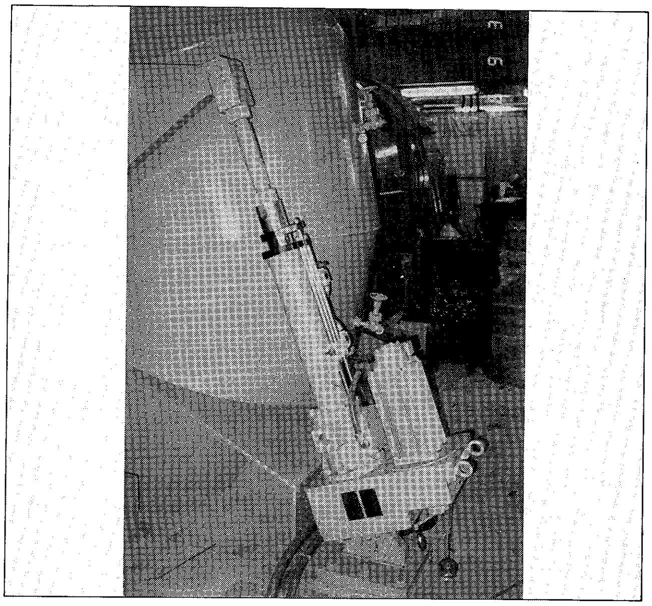
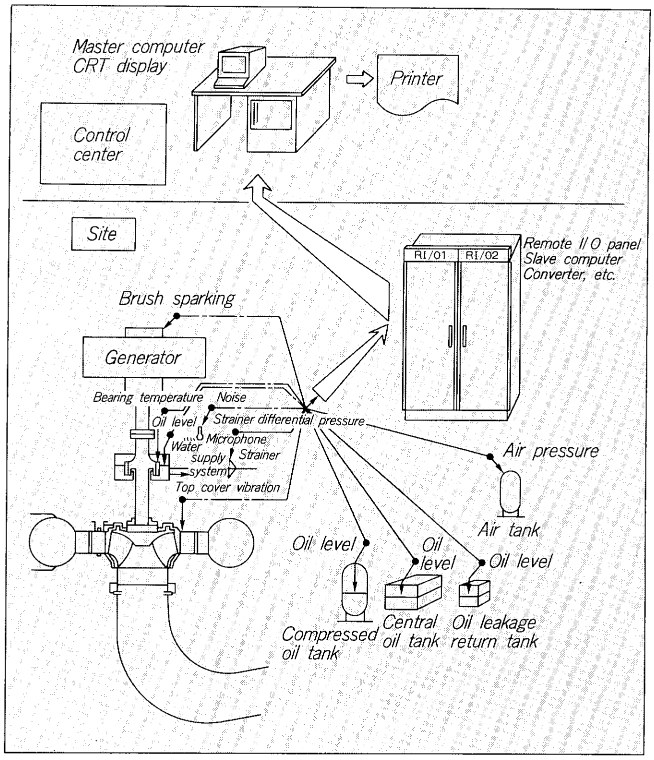


Fig. 11 Automatic inspection system



operated by oil pressure from olden times. Because the oil pressure system requires oil pressure and air pressure systems made up of many parts and uses oil as the working fluid, maintenance and inspection are complex. In 1978, Fuji Electric began development of a motor operated servomotor that simplifies these auxiliary devices and makes them maintenance-free. Currently, this servomotor has been delivered to more than 20 plants.

To motor operated servomotor open and closes the wicket gate by converting the rotary motion of a motor to linear motion through a reduction gear and ball screw and connecting it to a regulating ring. At first, an AC motor was used and a DC motor was provided for emergencies.

Now however, a system with a device that operates the wicket gate with a DC brushless motor and allows closing of the gate mechanically in an emergency when there is no inlet valve is standard.

Fig. 10 is an example of a horizontal Francis turbine with motor operated servomotor. Since the pressure oil pump and air compressor of the conventional oil pressure system can be eliminated by using the motor operated servomotor, it is economical, the equipment layout is simple, and the powerhouse area can be reduced.

3.4 Protection and safety

Turbine facilities were protected in the form of post-protection, in which repair is performed after trouble occurs, and time standard protection, in which pàrts are replaced routinely. However, regarding recent turbine power plants, improvement of reliability and advances in automation technology have been accompanied by an increase in the complexity of control systems. On the other hand, patrol inspection by experienced maintenance personnel is becoming more difficult as rationalization and automation of facilities advances.

This condition has led to the introduction of the protection and safety approach, which monitors the quantative state of the facility mechanically instead of conventional human patrol inspection, into recent turbine power plants.

The turbine system status monitoring items are bearing temperature, water pressure, vibration, liquid level, leaking and drain water, water supply, noise, differential pressure, etc. At a number of current plants, a protection and safety algorithm is established at various states.

Fig. 11 is an example of the configuration of a vertical Francis turbine automatic inspection system used by Fuji Electric.

4 ELIMINATION OF SPILLWAY AND OTHER CIVIL CONSTRUCTION RATIONALIZATION

New construction was developed about the turbine described in section 3 for medium and small hydraulic technical development and economy. Thereafter, rationalization of the entire plant, including civil construction, was studied to purpose still greater economy. One of these is a plan for eliminating the spillway installed in a run-of-river power plant.

4.1 Elimination of spillway by civil construction only (use of free space in tunnel)

Where the flow used is comparatively small and the river is comparatively wide, or the level rise of the river is less than 30 to 50 cm per 30 minutes even when the spill at load rejection is discharged from the intake facility, the spillway can be eliminated by using the raising the top of the head tank and the tunnel free space.

The Yamanashi Prefecture Yushima Power Plant (output 2.1 MW horizontal Pelton turbine), Tochigi Prefecture Miyama Power Plant (output 2.46 MW horizontal Pelton turbine), and Chugoku Power Company Azoh Power Plant (output 3.4 MW vertical Francis turbine) delivered by Fuji Electric use this method.

4.2 Elimination of spillway by civil construction and discharge valve

When the flow used by a Francis turbine is comparatively large and at the river water levelrise exceeds the standard value load rejection by civil construction only, or when the tunnel internal water pressure exceeds the allowable value noticeably and reinforcing the civil construction is costly, it can be eliminated spillway by installing the discharge valve. Energy absorption and other civil construction is necessary at the valve downstream side.

Since this discharge valve resembles the pressure relief valve, many of which have been used in Japan in the past, its reliability, including control, is considered to be high. However, there is no record of any being installed to eliminate a spillway until now.

4.3 Spillway elimination by civil construction and deflector discharge

Since the Pelton turbine has a deflector which cuts off the jet, as well as a needle which adjusts the flow, the main unit can be stopped by the deflector without opening and closing the needle. That is, the spillway can be eliminated by using intake gate slow closing at load rejection and deflector discharge.

Overseas, since industrial water, drinking water, or irrigation to downstream areas, there are examples in which deflector discharge is performed with the turbine stopped. However, abnormal sound and vibration are not generated during discharge and damage does not occur even when inspected after discharge.

On the other hand, trouble outside the power plant often recovers within five minutes. In this case, after load rejection, the needle performs the water level adjustment operation and the deflector performs unloaded operation (runner is kept at the rated speed by part of the jet cut off by the deflector). After recovery, synchronous parallel operation by deflector control only and load increase control are performed. The results of special tests on existing units confirm that the required time, precision, affect on the system, etc. are the same as synchronizing and parallel in by conventional needle control.

There is no record of deflector discharge and deflector control being used with Pelton turbine spillway elimination. However, it does not pose any technical problems.

5 REFORM AND REHABILITATION OF EXISTING UNIT

5.1 Turbine rehabilitation (scrap and build)

Many rehabilitation plans use the newest technical construction to rehabilitate an entire aged turbine and improve performance by the same specifications as the existing unit.

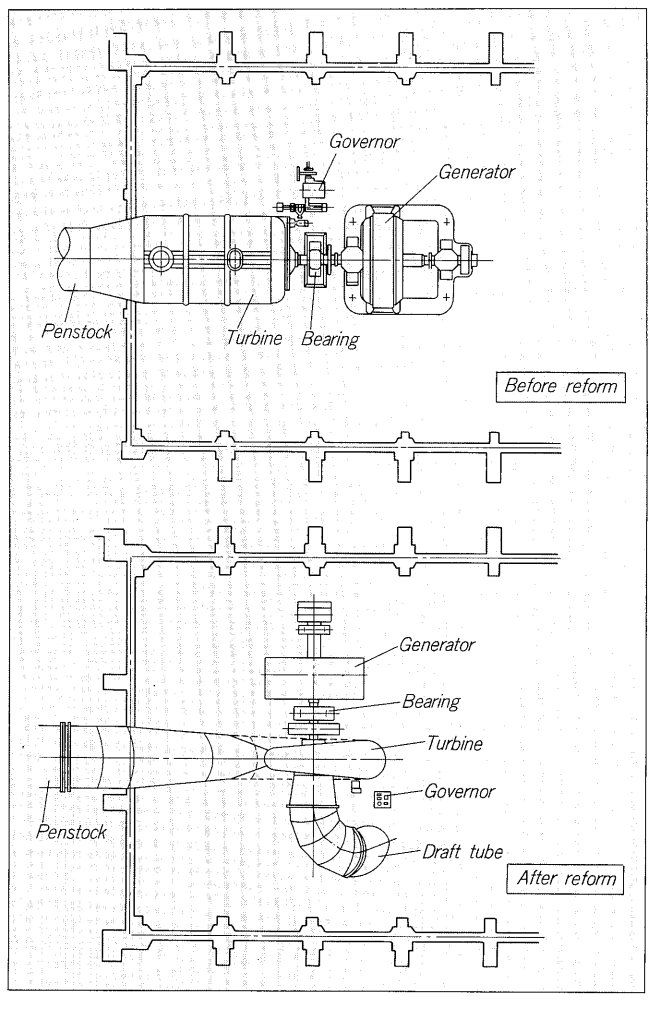
Fig.12 is an example of the Hokkaido Power Company Teshibetsu Power Plant. The existing unit was a horizontal two runner frontal twin type Francis turbine that was run for more than 60 years. Only the noticeably aged turbine and generator were rehabilitated and made a horizontal single runner type Francis turbine (output 2.39 MW).

When making a rehabilitation plan, the optimum turbine must be selected. When making this selection, a program which uses a statistical technique based on the annual water level and flow data to decide the type of turbine having the highest annual power production from the head variation and discharge variation was developed so that the most economical turbine could be selected.

5.2 Runner characteristic improvement

Recently, there have been many examples of plans for not only runner replacement due to aging, but also of runner rehabilitation by modifying the specifications and operating method of an existing turbine from those

Fig. 12 Horizontal Francis turbine rehabilitation example



when the plant was constructed. Since rehabilitation of the runner only is the casing and wicket gate and the draft tube of the existing unit is used, the water power characteristics must be improved with the runner only.

In this case, backed by performance forecasting technology by flow analysis program, Fuji Electric does not manufacture a model turbine runner, but develops a new runner with improved performances.

The Wells Dam Power Plant (maximum output 89 MW) in the state of Washington, U.S.A. now being designed has ten vertical Kaplan turbines with a runner diameter exceeding 7.4 m. This power plant could not operate at the high efficiency featured by the Kaplan turbine because of aging and rehabilitation of the runner only was planned. The manufacturer's decision was entrusted to competition of performances at model tests by a third party. As a result, the superior technology of Fuji Electric was highly evaluated and Fuji Electric received the order and is now manufacturing the plant.

6 CONCLUSION

Fuji Electric turbine technology was outlined above. Since special technology has been developed for diverse turbines, from large capacity to small capacity machines, in the past five years, quality control and manufacturing technology could not be discussed here because of space limitations.

As mentioned at the beginning, in the future water power will be centered about medium and low capacity machines, and there is a trend toward raising of the prime cost of electric power generation as the output of hydroelectric power plants becomes smaller. Therefore, new technology which raises the economical effect of the entire plant must be developed.

Finally, current Fuji Electric turbine technology owes much to the guidance of domestic users. We thank them sincerely.