UDC 621. 224. 7

EXTENSION OF TEST RIGS FOR HYDRAULIC LABORATORY

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I. INTRODUCTION

As is well known, the development of recent domestic hydraulic power stations has stressed the construction of pumped-storage power stations. Since 1955, Fuji Electric has been performing research on reversible pump-turbines, but formerly this research emphasized characteristics. In the actual design of reversible pump-turbines, research on characteristics during pump and turbine operation is naturally necessary and research on four-quadrant characteristics, start/stop operation, pressure fluctuations, stress in various parts and transient phenomena such as load rejection and pump trip are also important. In the study of these transient phenomena not only computer simulation but also confirmation by means of model tests is necessary. *Fig. 1* shows models of pump-turbine runners.

There are more items to be investigated on pump-turbines than those of conventional turbines. Since the former test rigs have become too small, the extension of the test rigs for the hydraulic laboratory has been carried out so that research and development of pump-turbines can be timely perform and necessary test including tests on transient characteristics can be efficiently performed.

For the research of pump-turbine, a medium head model test rig and a actual high head pump model test rig have been completed and explanations of the following items will be given:

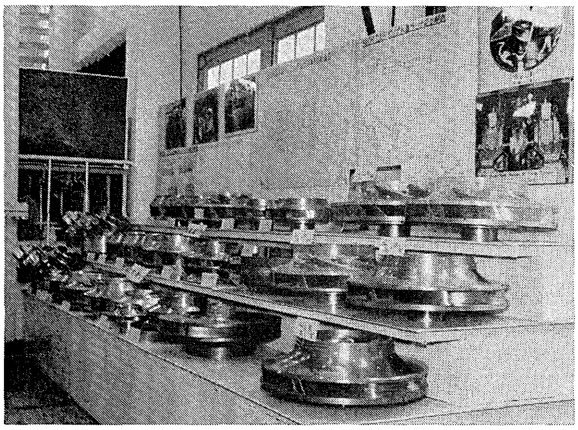


Fig. 1 Models of pump-turbine runner

1) Equipments
2) Control methods
3) Measuring methods
4) Test results

II. FOR MEDIUM HEAD MODEL TEST RIG

1. Outline and Features

This equipment is related with the existing test rig for the model hydraulic turbine,[1] and emphasis is placed on tests of the Francis type and Deriaz type pump-turbine models which are more frequently tested. It has been designed as special test rig for medium n_S pump-turbines and turbines of $n_S = 80 \sim 300$ m-kW.

For efficiency tests during pump and turbine operation, the open loop operating system is used for improvements in measuring accuracy and highly effective testing is possible during tests on cavitation, pump-turbine four-quadrant characteristics vibration and stress by the use of the closed loop operating system.

When this new test rig was planned, the following conditions were taken into consideration:

1) This test rig can simulate any operating conditions of prototype including transient characteristics such as load rejection, starting and stopping of the pump-turbine etc. with same model.
2) Large scale models are used which can be used together with the existing equipment.
3) The measuring accuracy of efficiency test is within 0.2%.
4) Various measurements such as vibration, stress and hydraulic water thrust can be carried out.
5) The test head is over 25 m which fulfills the JIS B8103 (1972) Methods for Hydraulic Turbines Using Model and JIS B8104 (1972) Methods for Model Tests of Reversible Pump-Turbines.
6) Test equipment control is automated using centralized one-man control.
7) Many measuring values necessary for calculation of the efficiency and the cavitation characteristics are measured automatically, displayed in the control room, and processed by on-line data process-

ing by a computer.

8) The equipment is of the energy saving type and tests can be made efficiently.

2. Test Rig Capacity

The test rig capacity is mainly determined by the model specific speed, dimension and the test head.

The model is limited to the $n_S=80\sim300$ range and the dimension range is an impeller-runner diameter of 400～700 mm which can be used together with the existing test rig.

It is desirable that the test head is the same as the head for the prototype but recently the heads of pump-turbines have become very high and it is impossible in respect to capacity to perform tests at the actual head. From the results of former tests it is clear that the test results at the test head of 50～60 m can reproduce the operating conditions of the prototype including transient phenomena with sufficient accuracy. Therefore, considering measuring accuracy, easiness of operating, etc. the maximum test head was selected at 60 m and the capacity of the service pump and dynamometer was determined.

The main capacities of the new test rig are as follows:

Test head:	25～60 m
Discharge:	800 l/s
Power of dynamometer:	
	400 kW as a generator
	400 kW as a motor
Rotational speed:	1,250～2,000 rpm
Suction head:	$H_S=+7.5\sim-20$ m
Model:	$n_S=80\sim300$ m-kW Francis type and Deriaz type, both pump-turbine and turbine
Impeller runner diameter:	
	400～700 mm

3. Composition of the Test Rig

Fig. 2 shows a view of the model test rig during pump-turbine test. The layout and water passages in each operating mode for the new equipment are shown in *Fig. 3*. The equipment is arranged in a straight line with the upper and lower tanks and the model located in the center. This is to prevent the occurrence of deviated flow, pressure fluctuations, etc. in the pipe line to the model.

The venturi meter for both flow directions of the pump and turbine is arranged between the upper water tank and the model and it measures the discharge in and out of the model.

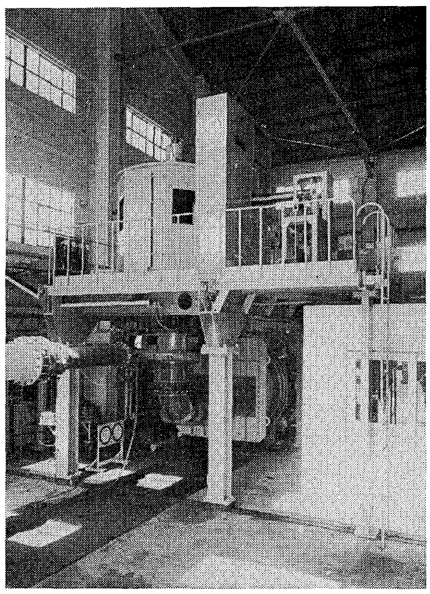
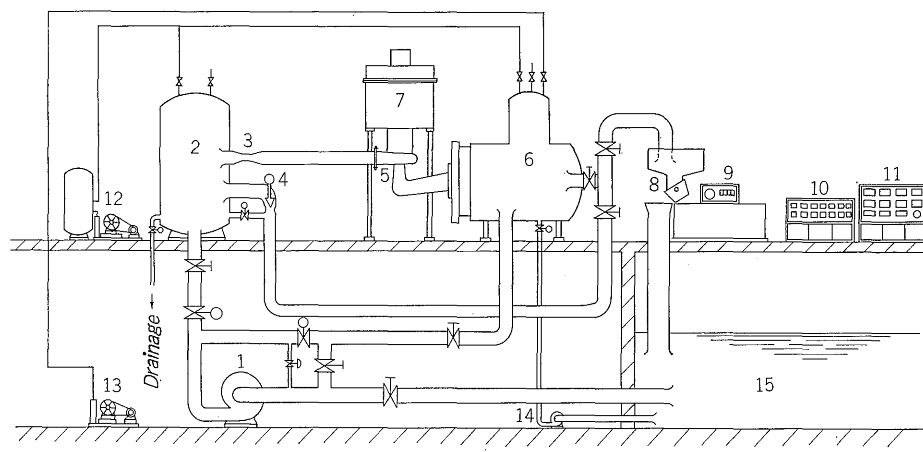
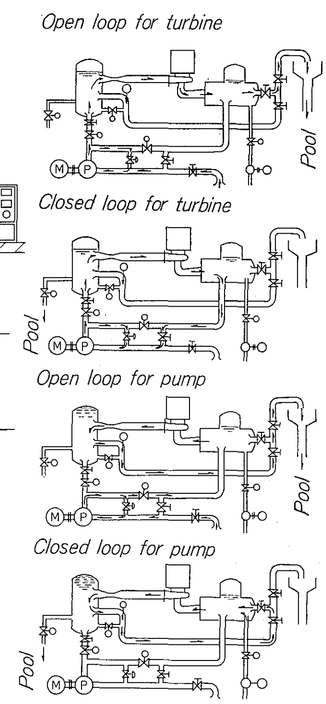


Fig. 2 Test rig for medium head pump-turbine model





1. Service pump
2. Upper water tank
3. Venturi
4. Delivery valve
5. Pump-turbine model
6. Lower water tank
7. Dynamometer
8. Change over device
9. Weighing instrument
10. Measuring panel
11. Control panel
12. Air compressor
13. Vacuum pump
14. Water feed pump
15. Pool

Fig. 3 Schematic diagram of test rig for medium head model

A service pump, a measuring equipment for absolute discharge by the gravimetric method and various changeover valves are arranged on the outside of the upper and lower water tanks so that it is possible to change quickly between the four operating modes in accordance with the test aims by controlling the valves. These modes are as follows:

1) Open loop for turbine
2) Closed loop for turbine
3) Open loop for pump
4) Closed loop for pump

In open loop operation, the water from the pool under the test room is pressurized by the service pump and after stabilization in the tank, it flows to the model and the gravimetric measuring equipment and is then returned to the pool.

In closed loop operation, the test is performed by circulating the water in the upper and lower tanks. Cooling water is injected in the lower tank from the exterior and the excess water overflows from the upper tank so that the temperature of the water circulating in the closed loop is kept constant.

4. Equipment in the Test Rig

1) Service pump

The pump unit is arranged under the test room in order to prevent noise and also in order that the service pump will not enter the cavitation limit even when a high suction head is achieved during cavitation tests.

The service pump is directly coupled to the DC motor which has its speed controlled by the thyristor static Leonard system. In this way, the rotational speed is automatically controlled in accordance with the test head.

Therefore, the delivery valve is normally completely open and the water flow through the by-pass valve is about 5% of the total water flow. The temperature rise of the circulating water during closed loop operation are therefore so small that they can be disregarded.

The specifications of the pump unit are as follows:

(1) Service pump

Type 600×400 harizontal shaft double suction volute pump
Head 65 m (shut-off head: 78 m)
Discharge 700 l/s (max. discharge: 1,000 l/s)
Rotational speed 980 rpm

(2) Driving motor

Type horizontal shaft direct current motor
Output 700 kW
Rotational speed 200～1,000 rpm
Power supply equipment
thyristor static Leonard equipment
DC 440 V 1,710 A

2) Dynamometer

The dynamometer is one of the important equipments which has a large effect on the accuracy of measurement of the model test. This dynamometer has the following specifications which allow good stability in the wide speed and load ranges operated as generator and motor in both the forward/reverse rotating direction.

Fig. 2 shows an outer view of the dynamometer.

Type vertical shaft direct current electrical dynamometer
Output 400 kW
Rotational speed 1,250～2,000 rpm
Max. speed at no-load 2,880 rpm
Power supply equipment
thyristor static Leonard equipment
440 V 1,000 A

In order to improve the accuracy of the torque measurement by the dynamometer, the friction torque due to the very small rotation of the swinging part and the unconfirmed torque in the dynamometer must be minimized very small. Therefore, the bearings are of the double bearing type. Ball bearings are used as internal rotating bearings and as the external swinging bearings, newly developed hydrostatic bearings especially for this dynamometer are used. Therefore, since all of the swinging parts are completely floated in oil, the friction torque can be almost zero so that the measuring accuracy and the reproducibility of the measuring results are good.

The use of hydrostatic bearing makes possible by measuring the oil pressure at the guide bearing pad on the turbine side the measurement of the direction and magnitude of the radial water thrust in the model impeller-runner which was difficult to measure previously.

In order to match the model output or input with the torque measured by the torque meter, the housing of the bearing of the rotating parts is connected to the swinging part so that the mechanical torque occuring in the bearing part is transferred completely to the stator. Therefore, it is not necessary to compensate for the mechanical losses in respect to the measuring value of the torque meter and the model torque itself is measured.

The cooling air of the dynamometer is supplied and exhausted in the radial direction by the guide vanes located in the inlet/outlet parts. The influence of the torque generated by the cooling air and the air torque by the rotation is small.

The supply and drain pipes for lubricating oil is located between the swinging and stationary parts and oil is discharged into air in the axial direction. The electrical leads to the swinging part are all flexible and long enough so that no unnecessary torque is generated.

Devices for operation control such as a tachodynamo for control of rotational speed, a detector for the bearing temperature, a tachometer, a pickup for the stroboscope, a load cell for axial thrust, a slip-ring for measuring runner stress and a ro-

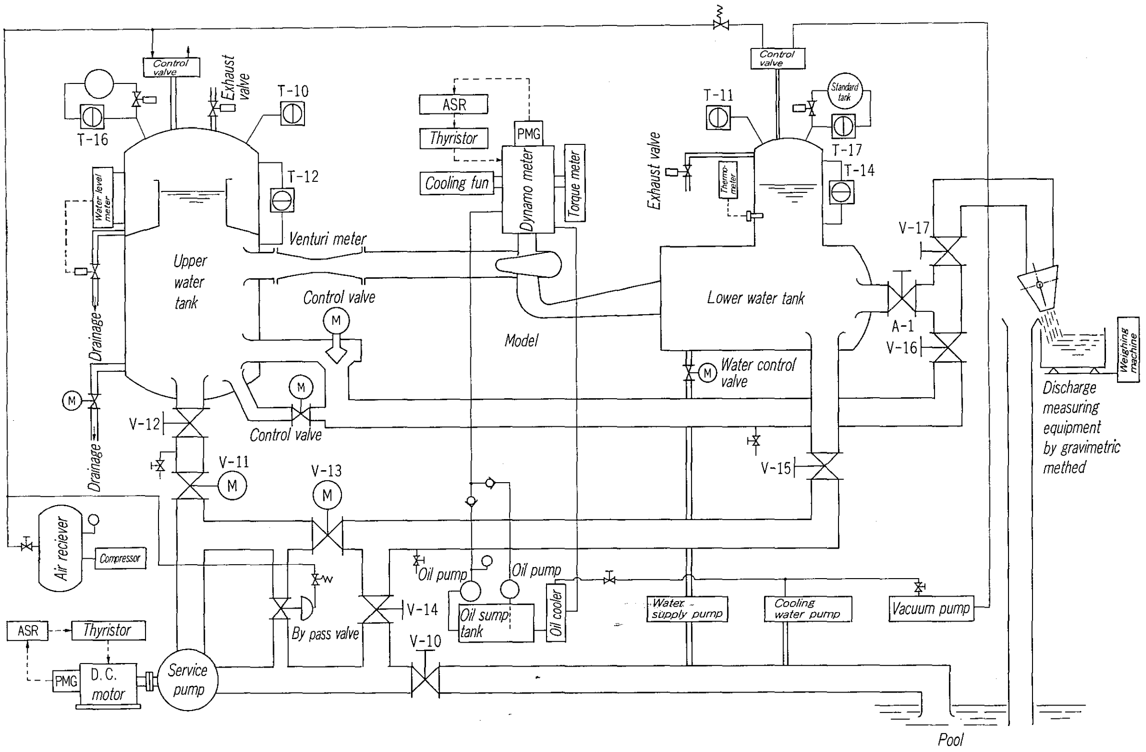


Fig. 4 Control diagram of test rig for medium head model

tating flange to change GD² are attached to the dynamometer.

5. Control System for Operation

Fig. 4 is a schematic control diagram. As was described previously, this equipment has four operating modes in accordance with the model test aim. The operating sequence and control methods of the main parts of the test rig such as the pipe circuit, auxiliary machines, service pump and dynamometer differ in accordance with the various operating modes. Therefore, the automatic operating system by effective matching of the operating sequence and automatic control devices decreases the burden on the operator during the tests and permits to devote himself to the research on hydraulic problems for the test aims. When considering operation control from the standpoint of measuring accuracy, the equipment stability becomes a major problem.

Since the measuring accuracy of the efficiency is within 0.2%, it is necessary that the stability of the head, rotational speed etc. be equal to or better than the measuring accuracy.

For this reason, the Teleperm IS system, the most recent Fuji automatic control device is used and ASR control by means of the thyristor static Leonard equipment mentioned previously is employed for service pump control so that the control system has a very high degree of stability.

1) Operating system

Completely automatic operation of the test rig from starting to stopping is possible in accordance with the operating sequence showh in *Fig. 5.*

When it is confirmed sequentially that the water passage is correct in accordance with the operation mode, the subsequent operating control system of the main and auxiliary machinery is determined.

Therefore, if the sequence steps proceed when it is confirmed that the previous operation step has been completed by the display lamps, safety operation can be achieved.

2) Turbine operating system

There are two automatic control systems used,

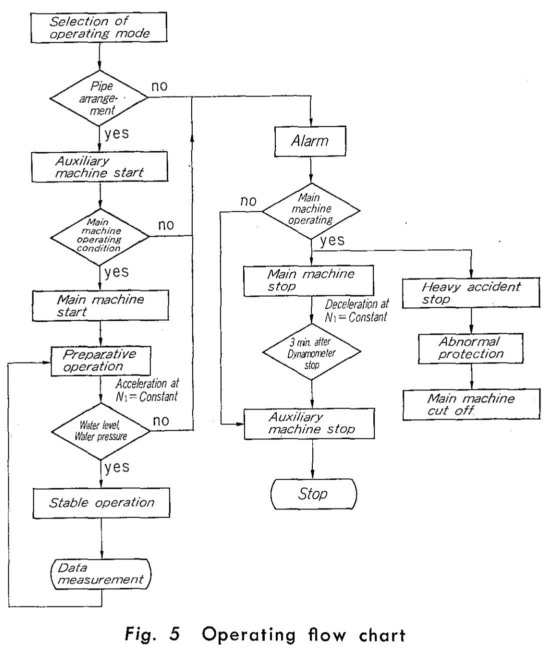


Fig. 5 Operating flow chart

one of which is the preparative operation system which has a wide control range for the times when there are large fluctuations in water level and pressure such as during service pump or model starting and stopping, and the other is the stable operation system which has high stability and a narrow control range.

The preparative operation system provides increases in pressure and speed automatically from starting until the set values of H_0 and N_0 are reached by setting controllers the desired values of test head (H_0) and rotational speed (N_0). This control detects the differential pressure (h) between the upper and lower tanks and controls the amount of air in the upper tank so that a constant water level is maintained and the value of the head becomes equal to the set value H_0 by means of speed change of the service pump. The model rotational speed is controlled to the standard value $n=N_0\times\sqrt{h/H_0}$ corresponding to the changeable pressure difference (h) of the upper and lower tanks. This control results in operation under the condition that the rotational speed N_1 ($N_1=N_0/\sqrt{H_0}=n/\sqrt{h}$) per unit head is constant, and safety operation is possible by setting N_1 in hydraulically stable range during starting, stopping, etc.

It is desirable to perform tests by changing the cavitation coefficient (σ) at constant head. Because this preparative operation control keeps constant the pressure difference between the upper and lower tanks which is almost equal to the head, it is possible to change σ at a constant head by changing only the pressure of the lower tank.

The stable operation system is the control system at the time of data measurement and there is a switch over to automatic control as in *Table 1* by pushing the "Stable" pushbutton after setting the standard values by the preparative operation system. This stable control system lay emphasis on the stability of the head which is related with the model turbine input.

The feature of the stable operation is that the standard values of the service pump and dynamometer are cut off from the secondary pressure system, constant speed control is performed independently and disturbances due to supply power fluctuations, etc. are compensated for.

In the pressure control the constant pressures of the upper and lower tanks before switching over to stable operation are sealed in the standard tank and the air pressures are controlled in accordance with the very small pressure differences between these pressures and the pressures of the upper and lower tanks.

The main feature of the stable operation control system is the water level control of the upper water tank which has a special double construction to guarantee a sufficient air volume and minimize the pressure change due to water level change so that the water level detection sensitivity is increased. The by-pass valve for water level control is controlled by a pneumatic type diaphragm valve with excellent sensitivity.

3) Pump operating system

The upper tank is completely filled with water during pump operation for rapid stability of the model pump delivery pressure and discharge. The test is performed changing the head by opening and closing the upper water tank delivery valve at constant rotational speed of the model. As the control valve, a large aperture valve for rough adjustments and a small aperture valve for fine adjustments by by-passing are equipped. In this way, the discharge can be adjusted accurately over a wide range.

The operating system is the same as turbine operation and automatic operation can be carried out by setting the controller the model rotational speed (N_0). Control of the lower water tank water level is necessary but because the lower tank pressure

***Table 1* Automatic control system for turbine operation**

Operating system		Upper water tank: Pressure of water		Upper water tank: Level of water	Lower water tank: Pressure of water	Lower water tank: Level of water	Dynamometer
Preparative operation	Detection terminal	Differential pressure between upper and lower water tank (T-10)—(T-11)		Tank level (T-12)	Tank pressure (T-11)	Tank level (T-14)	Differential pressure between upper and lower water tank ↓ Calculation ($n=N_0\sqrt{h/H_0}$)
	Control target	Setting value of H_0		Setting level	Setting value of H_s	Setting level	Setting value of N_0
	Operating terminal	Rotational speed of service pump		Air control valve	Air control valve	Water control valve	Dynamometer
Stable operation	Detection terminal	Small differential pressure of upper tank (T-16)	Rotational speed of service pump (PMG)	Tank level (T-12)	Small diffesential pressurd of lower tank (T-17)	Tank level (T-14)	Speed of dynamometer (PMG)
	Control target	Differential pressure zero	Setting speed	Setting level	Diffesential pressure zero	Setting level	Setting value of N_0
	Operating terminal	Air control valve	Service pump (P 11)	By-pass valve	Air control valve	Water control valve	Dynamometer

is low, there is little influence of the air compressibility by change in the water level and excellent control is possible.

4) Other operating systems

In addition to the four operating modes described previously, there is an operation mode by manual operation and the various automatic systems for simulation of the transient conditions such as pump-turbine starting and load rejection. As the control system for transient phenomena, an oil drive system with high response is used to drive the discharge valve during pump operation. This valve control by program relating to the opening of the model guide vane and control by the servo-valve from the upper tank water level are both used. Therefore the wide discharge variations during the transient operation is compensated for and the head is stabilized. This system is now being designed.

6. Measuring Equipment

The measuring accuracy of the equipment as a whole is improved by the afore-mentioned stabilization of the model input by means of automatic control and the use of high precision measuring instrument.

Because of the on-line data processing using FACOM 270–20 computer, the digital automatic measuring system is used for all measuring instruments and the accuracy of each instrument is specified as within 0.1% including the deviations caused by the model input fluctuations. By this way the efficiency measuring accuracy is maintained within 0.2%.

The measuring instrument have been planned as a unit including the calibration devices so that calibrations before and after tests according to the IEC and JIS model test standards are simplified and high accuracy can be maintained.

Fig. 6 shows a schematic diagram of the measuring system.

1) Torque meter

An arm protrudes from the dynamometer stator and the usual method to measure the force at the tip of this arm by an automatically balanced weighing machine is used. The specifications are as follows:

Max. weighing capacity:	250 kg
Minimum scale:	0.05 kg
	accuracy: 0.02%
Arm length:	1,217.4 mm

Considerations were given to simplifying calibration of the torque meter. During calibration, a standard torque is applied to the dynamometer from the calibrating equipment by means of standard weights and comparison is performed with the value measured by the weighing machine at that time.

However, in this calibration method it is generally difficult to measure the arm length L from the center of the dynamometer and the arm length is measured by the following indirect method.

As shown in *Fig. 7*, the standard weights W_1 and W_0 are placed on the weighing machine and calibrating equipment respectively so as to equalize both readings. From the equilibrium condition $L_1 W_1 = L W_0 = (L_1 + L_0) W_0$. Therefore $L_1 = L_0 \cdot W_0 / (W_1 - W_0)$.

In this case, $L_1 = L_0$ is 1,217.4 mm and L_0 can be measured simply by slide caliper, etc. and the arm lengths L_1 and L can be calculated. The accuracy is determined by the sensitivity of the weighing machine included with the dynamometer but

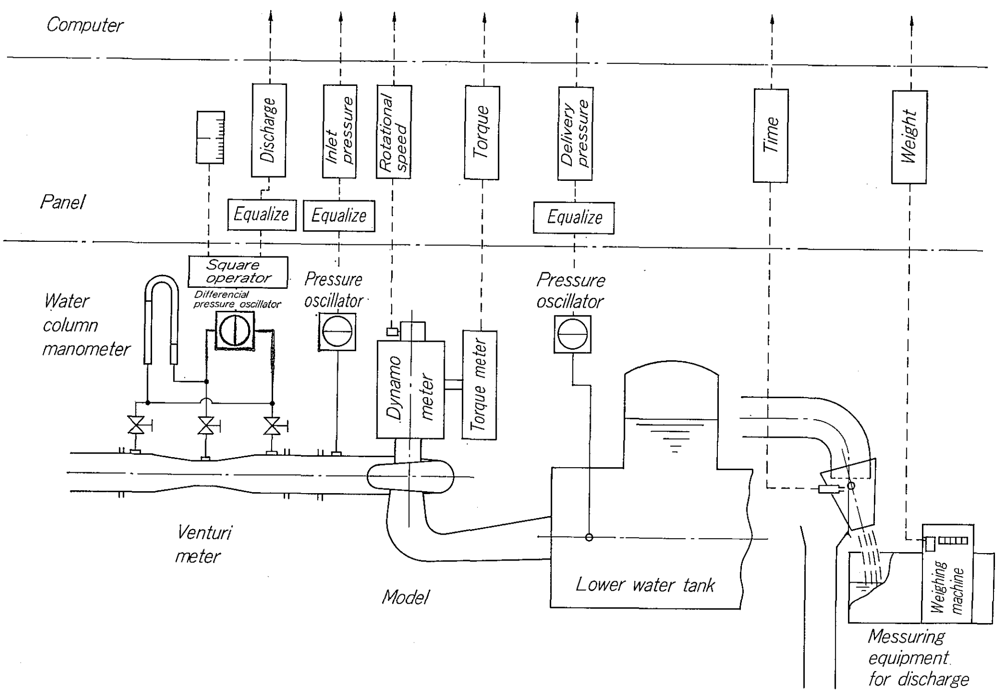


Fig. 6 Schematic diagram of measuring system

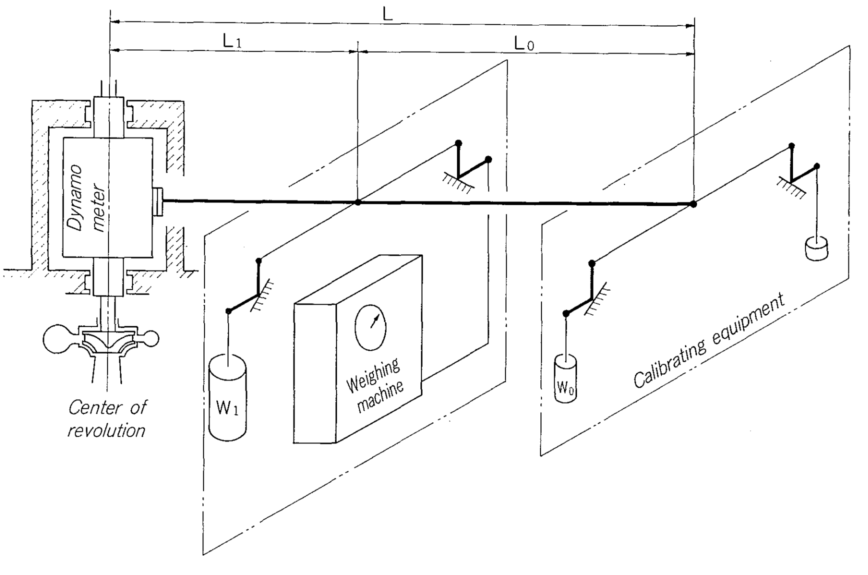


Fig. 7 Calibration method of torque measuring device

because of the use of the oil bearing in the swinging part of the dynamometer and due to the sensitivity of the weighing machine analog meter, the adjustment can be made up to 0.02 kg. The arm length can be calibrated at an accuracy of 0.01%.

2) Discharge

During the open loop operation, absolute discharge measuring equipment by the gravimetric method is used. The specifications are as follows:

Weighing machine: max. capacity 10,000 kg (effective capacity = 8,000 kg) min. scale 1 kg

Changeover equipment: changeover time less than 0.1 sec.

Time measurement: by universal counter

Discharge accuracy: 0.07% at 600 l/s of discharge

Discharge measurement during closed loop operation is now performed by a venturi meter. The measuring value is displayed on a flowmeter by digital display using the output of a water column manometer and a differential pressure oscillator as the square operator. This venturi meter can be calibrated simply by the gravimetric method during open loop operation.

According to the calibration results, the linearity of the digital display part is within 0.4% and the reproducibility is within 0.2%. By correcting the measuring value using the calibration results, it has been found possible to use sufficiently during cavitation tests, etc.

There is possibility of changes in the coefficient of the venturi meter in accordance with the operating conditions during the pump test but because of the effect of the rectifier, the deviation of flow is very slight and it has been confirmed that changes in the coefficient of the venturi meter are very small at the wide discharge ranges both in the pump and turbine flow directions.

3) Measuring instrument for head

This measuring instrument is the precision pressure gauge indicating the output voltage with digital voltmeter.

The measuring error of this pressure gauge is great due to measurements of instantaneous pressure when there are considerable pressure changes. Therefore, the measurement is repeated 10 times, the values are totalled and the average value is read.

The calibration is carried out by the pneumatic standard device (accuracy: 0.03%) and the reliability of the test results is improved since simple calibration is possible during testing.

4) Rotational speed

For one turn of the shaft, 60 pulses are generated, these are counted by a universal counter and the rotational speed is measured. The measuring error is ± 0.1 rpm.

5) Other measuring instrument

In model tests on pump-turbines, the measurement of various hydraulic problems related to safety operation of pump-turbine such as pressure fluctuations is very important as well as efficiency and cavitation characteristics. For such purposes the following measuring instruments are provided.

(1) Strain gauge type axial thrust meter
(2) Oil pressure type radial thrust measuring instrument
(3) Measuring equipment for hydraulic pressure and stress of rotating parts
(4) Hot wire type velocity meter for water velocity fluctuations

Analysis equipment such as amplifiers like strain meters, recorders such as data recorders and frequency analyzer is provided so that average level and amplitude of fluctuation can be measured. Data processing is performed with these equipments. *Fig. 8* shows the measuring equipments during a test. *Fig. 9* shows some of the test results.

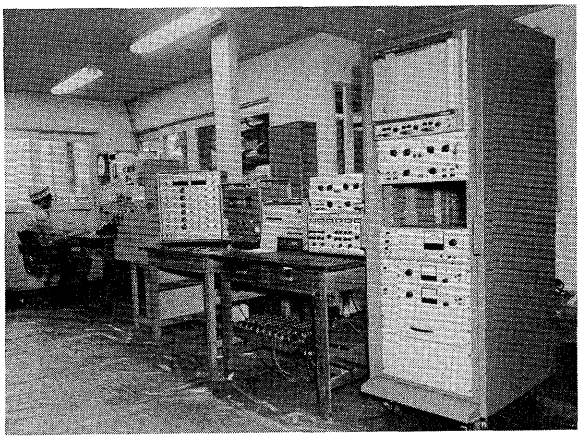


Fig. 8 Control desk and measuring devices

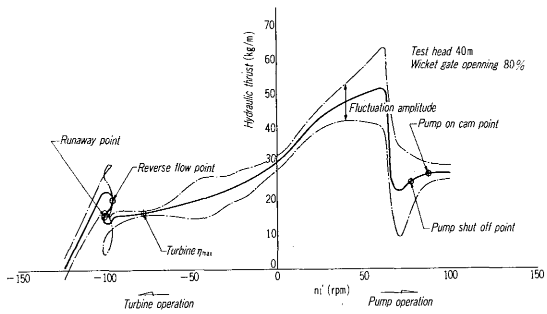


Fig. 9 Four quadrant characteristics of hydraulic thrust

III. ACTUAL HIGH HEAD PUMP MODEL TEST RIG

Pumped-storage power stations are in practical use for peak loads and load adjustments and there has been a tendency recently for heads to increase gradually. Recently in particular, there have been several cases of plans for heads exceeding 500 m.

In 1967, Fuji Electric constructed actual head test rig for heads up to 250 m and started research on high head pump-turbines. However, the impeller-runner peripheral velocity of pump-turbines of 500 m class reaches 100 m/s and the relative velocity in the impeller-runner is also fast so that the hydraulic characteristics and material strength requirements exceed those previously encountered.

In order to investigate the problems related to high heads, test rig has been extended with which actual head pump model tests with heads up to 600 m are possible.

1. Test Rig

Fig. 10 shows the model during test and *Fig. 11* shows the arrangement of the actual high head test rig. The water in pool is fed into the tank by the service pump and supplied to the model after pressure adjustment.

The model pump-turbine has a rotational speed of 7,200 rpm by means of speed-up gear directly coupled to a 1,500 kW motor and actual head operation is performed. Water with pressure increased by the model has its pressure decreased by the discharge valve and energy killer and is returned to the pool in an open loop system via a measuring weir for discharge.

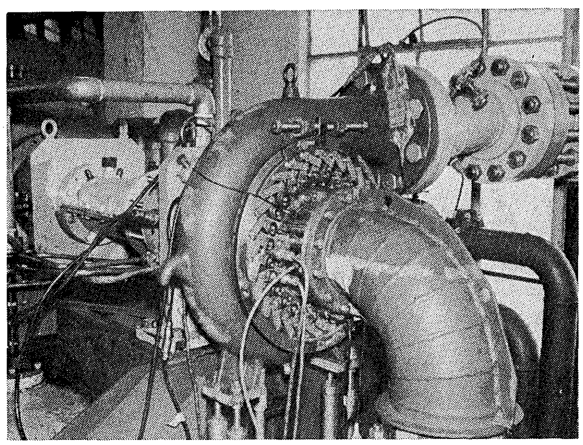


Fig. 10 Actual high head pump-turbine model

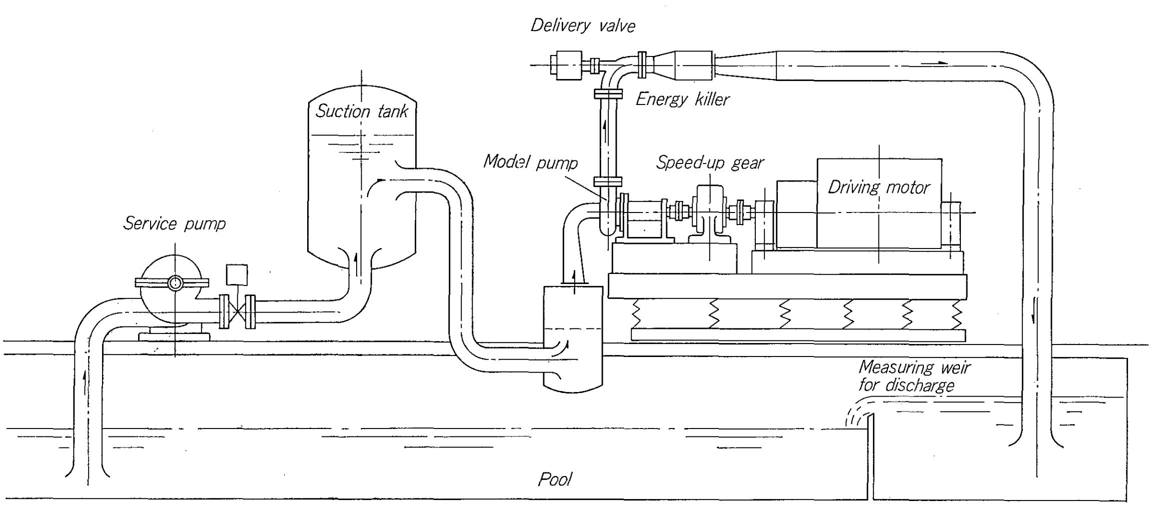


Fig. 11 Test rig of actual high head pump model

In the open loop test rig, the test model is only one for the generation source such as water pressure fluctuations and so it is easy to analyze the problem.

The model is hydraulically similar to prototype in respect to the impeller-runner with a runner diameter of 260 mm, the guide vane, spiral case and draft tube. The discharge ring part is made of transparent acryl resin and during actual head operation, the cavitation phenomena on runner can be observed.

2. Test Results

The noise during test was about 93 phons at the point one meter apart from the model and the total vibration amplitude on the discharge ring was 13μ. Operation is therefore quieter than originally expected.

In the actual head tests by similar model, the same pressure and stress equal to prototype are acted on the impeller-runner and wicket gate.

The number of repetitions of the stress per unit time is inversely proportional to the model scale ratio and the stress repetitions reach 10^7 times at short time operation. For example, when the stress fluctuation is once per one rotation, it takes about 23 hours to reach 10^7 times.

After 100 hours of operation including reverse flow range, a liquid penetrative inspection on the model impeller-runner made of SUS27 stainless cast steel was performed but no defects were found.

Cavitation limit occuring in the inlet part of the impeller-runner vane is the same as the cavitation limit in the test with the medium head test rig at the head of 50 m, but the cavitation bubbles at plant sigma (σ) are less than the latter.

In addition, pump *H-Q* characteristics have been confirmed and measurements have been made of water pressure fluctuations in several parts, the hydraulic torque of the wicket gate, etc. The results showed no particular abnormal phenomena and the frequency component of pressure fluctuations contained three times and the remarkable component of the multiple of the rotational speed and the number of impeller-runner vanes. The pressure fluctuation amplitude in all parts of the model was about the same ratio as that during the characteristics test at the medium head.

IV. CONCLUSION

This article has given an outline of two test rigs which were extended to the hydraulic laboratory for research into pump-turbines.

In near future, this new test rigs will be used for improvement of characteristics and clarification of transient phenomena and research into the manufacture of highly reliable pump-turbines will progress. For this, we request the guidance of customers and also thank all those persons both inside and outside Fuji Electric who cooperated in the construction of these new test rigs.

References:

(1) Hasegawa: Test rigs for new hydraulic laboratory, Fuji Journal, 35, No. 8 (1962)