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Draft Paper
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Balanced Discharge Method of Flow Measurement

Summary

In the field of efficiency testing of hydroelectric turbines, it is generally agreed that the measurement of discharge at a close-coupled hydro station is one of the most challenging measurement techniques in the industry. Yet, at the same time, a large percentage of the stations in existence around the world have short water conveyances. This makes both conventional and modern methods of flow measurement either impractical or inaccurate.

In this paper, the "balanced discharge" method of flow measurement is presented which utilizes flow measurements performed at a more suitable location upstream or downstream of the station, winter-kennedy flow readings and reservoir water level measurements in order to determine the discharge through the station. The method is applicable to any method of flow measurement and is a rigorous type of analysis involving the solution to a system of three equations with three unknowns. The details of the method and assumptions will be presented.

Continuity Balance Equation

For any body of standing water, the outflow, inflow and storage flow can be expressed as follows:

$$Q_o = Q_i + Q_s$$

$$= Q_i + dh/dt*A$$

where Q_s is the "storage flow" caused by a change in the level, **dh**, over a period of time, **dt**, multiplied by the water surface area, **A**. In this form of the equation, the sign convention of dh is taken to be positive for drawdown (ie. lowering level). The inflow and outflow can be further separated into sub-components which are unique to the headpond (or tailpond) of a hydroelectric station.

The equation is applicable to either headponds or tailponds, however, for most cases the headpond tends to be more suitable for measurement due to its size and accessibility. For this reason and also for clarity, the continuity balance equation has been developed for the headpond of a hydro station in which the inflow to the headpond is measured using a conventional flow measurement method and the outflow through the turbine is the parameter to be determined. The equation is then written as follows:

$$Q_T + Q_L = Q_M + Q_R + dh/dt{*}A \qquad (1)$$

Figure 1 illustrates the continuity balance equation graphically and shows the sub-components of the inflow and outflow from the headpond of a hydroelectric station. Each sub-component is described in more detail as follows.

Turbine Flow, Q_T

Discharge through the turbine under test.

Leakage Flow, Q_L

All outflows other than the turbine flow. This could include groundwater leakage, dam leakage, leakage past gates and other units drawing water from the same headpond (operating at a fixed gate setting).

Measured Flow, Q_M

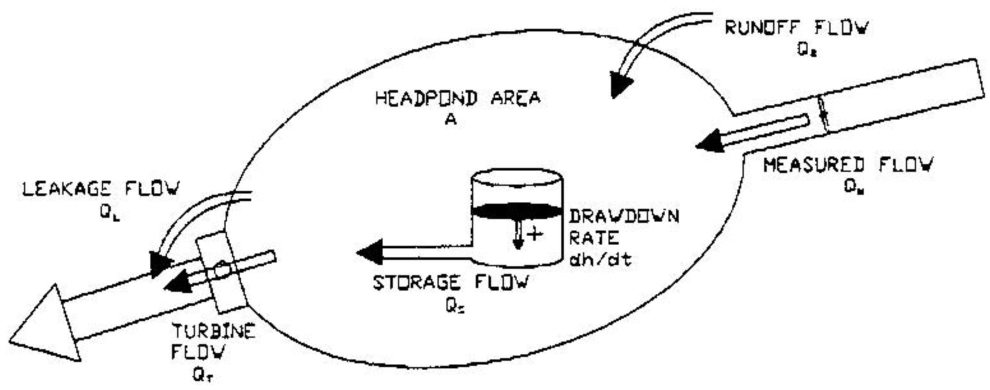
Discharge measured by an acceptable method suitable for the measurement location. The location could be a gated sluiceway, turbine, tunnel, canal or river.

Runoff Flow, Q_R

All inflows other than the measured flow. This could include natural drainage, leakage flows, etc.

Storage Flow, Q_S

As described previously, flow caused by a change in level within a certain period of time. This flow can be positive or negative depending on the direction of headpond level change. The effective area of the headpond, A, could vary if large changes in level occur. With the exception of very small reservoirs, a level change of +/- 50 mm will result in an area change which is well within the accuracy of the flow measurement.



$$Q_T + Q_L = Q_M + Q_R + dh/dt*A$$

CONTINUITY BALANCE EQUATION

FIGURE 1

Unknowns

The application of the continuity balance equation to the problem of measuring turbine discharge requires a discussion of the knowns and unknown terms of the equation. Once this has been established, the method of solution can be determined.

Considering the five terms of the continuity balance equation shown on Figure 1, and considering the typical layout of a hydro station, there is only one term, Q_M, which will be known (within a certain level of accuracy). There is, however, one other parameter, the drawdown rate (**dh/dt**), which can be measured and which forms part of the last term, the storage flow. All other terms including the turbine flow, leakage flow, runoff flow and the headpond area are unknowns. The turbine flow is the term which is ultimately required, however, the question is, "How can we solve for the turbine flow with so many other unknown terms?" This question is addressed in the following section.

Method of Solution

Of the unknown terms described in the preceeding section, three of the terms, the leakage flow, runoff flow and headpond area can be considered to be relatively constant over a period of 12 hours or less if the headpond level does not change sifnificantly. (There are exceptions to this statement which are discussed in a later section entitled "Limitations".) Furthermore, these three terms are independent of the turbine flow meaning that, if the turbine discharge is varied and the headpond level is maintained relatively constant, the leakage flow, runoff flow and headpond area will remain constant.

The continuity balance equation can now be further simplified by combining two of the unknown constant terms, the leakage flow and the runoff flow. After rearranging, the equation takes the form shown below. The three unknown terms are on the left-hand-side and the one known term is on the right-hand-side.

$$Q_T + Q_{L/R} - dh/dt * A = Q_M \qquad (2)$$

where

$$Q_{L/R} = Q_L - Q_R$$

In order to determine the solution to Equation 2, a set of three independent equations, each containing the three unknowns, will be required.

The three independent equations can be obtained by the performance of three tests at three different turbine discharges. There is one complication, however, since each of the turbine discharges will be unknown resulting in a situation with more unknowns than equations. The answer to this latest complication is to use relative flow measurements at the turbine in order to relate the three turbine discharges. The use of Winter-Kennedy pressure measurements or other similar methods of relative flow measurement reduces the number of unknowns on the turbine discharge to one. All unknowns can therefore be determined using this method of solution and three different balanced discharge tests.

Methods of Measurement

The key to the success and accuracy of the balanced discharge method of flow measurement is the measurement of the various parameters required for the continuity balance equation. This includes the measurement of flow at the remote measurement location, the monitoring of headpond level, the relative flow measurements at the turbine under test and the various other parameters required to determine the efficiency of a hydro station. It is not the intention to discuss in this paper the standard methods of flow, level, power, head, etc measurement as they are adequately covered in the IEC 41 and ASME PT 18 standards. There are, however, certain measurements which are especially pertinent to the balanced discharge method and will therefore be described in the following sections.

Headpond Level

The precise measurement of the headpond level and its variation with time, **dh/dt**, is important since this quantity is the coefficient to the headpond area. In order to ensure accuracy, a transducer with automated data acquisition should be used. A large number of data points can be obtained with such instruments and the ability to visualize trending on the data is essential if wind setup or sloshing oscillations on the headpond are present. If possible, more than one measurement station should be used, preferrably one at either end of the reservoir.

The ratio of the headpond area to the turbine flow determines the sensitivity of the headpond to flow imbalances and has a strong influence on the duration of the test. Reservoirs with area/flow ratios of 20,000 sec/m or less have a high sensitivity and require relatively short periods of time to determine the value of the drawdown rate. Reservoirs with area/flow ratios of 100,000 sec/m or more have less sensitivity and require long periods of time to determine the value of the drawdown rate.

The following example illustrates the relationship between the area/flow ratio and the test duration. A headpond with a surface area of 1 km^2 (1,000,000 m^2) supplies water to a turbine at 100 m^3/s. The inflow to the headpond is 90 m^3/s.

The headpond area/flow ratio in this example is 10,000 sec/m. The drawdown rate, based on the flow imbalance of 10 m^3/s, is

$$(10/1{,}000{,}000) * 3600 \text{ (sec/hr)} * 1000 \text{ (mm/m)} = 36 \text{ mm/hr.}$$

This drawdown rate could be measured with excellent accuracy over a period of 1 hour using a good quality transducer and a large number of readings (100 or more). Note that high absolute accuracy of the level measuring instrument is not required. High precision (relative accuracy) is more important.

If, in the above example, the headpond area were 10 km^2 and the flow imbalance were the same 10 m^3/s, then the drawdown rate during the test would be reduced considerably to 3.6 mm/hr. Under such conditions, a test duration of 3 hrs and two measurement instruments (one located at each end of the headpond) would likely be required to achieve a reasonable degree of accuracy on the drawdown rate.

Flow at Remote Location

The measurement of flow at the remote location is entirely dependent on the arrangement and structures present. Frequently, the remote location may actually be another hydro station either upstream or downstream from the station of interest. In this case, the test engineer must choose the most suitable of the conventional measurement methods such as current meter, pressure time, tracers, thermodynamic, acoustic, etc. If the remote measurement location is a river or stream, the tracer method is often the only suitable method of flow measurement.

It is the opinion of the author that the measurement of flow at a remote location is not necessary if all flows other than the turbine flow are maintained constant for all three tests. This theory is still under investigation and has not been verified with actual field measurements. The method of solution would be somewhat different from that which is described here.

Limitations

There are certain limitations to the application of the method which must be examined prior to undertaking the balanced discharge method of measurement. If not considered, the factors discussed below could impact on the accuracy and the entire success of the test.

Precipitation

One of the underlying assumptions to the method is that the runoff flow into the headpond will remain constant over the duration of all three tests. Heavy precipitaion, snow melt and any other factors resulting in varying runoff flow will influence the accuracy of this assumption. Therefore, balanced discharge tests should be carried out within the following general guidelines:

- test should be performed during dry periods when the rate of change of runoff flow is at a minimum

- test should not be carried out within 48 hours after a moderate to heavy rainfall

- all three measurements which make-up a test should be performed within a 12-hour period.

Level Variations

Similar to the runoff flow, the leakage flow and headpond area must also remain relatively constant over the duration of the test. Since these two parameters are dependent on the headpond level, it is important that the headpond level be maintained relatively constant for all test points.

The leakage flow past gates, stoplogs, dams and shutdown turbines will vary if the level changes significantly. Leakage at or near the surface of the headpond is particularly important. Overflow spillage should be eliminated, if possible, prior to the start of a test.

The variation in headpond area with level is a function of the perimeter and the average bank slope at the perimeter. Steep bank slopes (ie. hilly terrain) will result in considerably less variation in the headpond area than shallow slopes for a given change in level.

The following table illustrates the variation in the headpond area to a level change of 100 mm for several different areas and bank slopes. The perimeter of the headpond has, for all cases, been taken as 3 times the perimeter of a circular headpond with the same area.

Headpond Area Variance (% of Area)

Bank Slope	Area (km^2) / Perimeter (km	0.25 / 5.32	0.5 / 7.52	1 / 10.63	2 / 15.04	5 / 23.78	10 / 33.63
1:1		0.21	0.15	0.11	0.08	0.05	0.03
1:2		0.43	0.30	0.21	0.15	0.10	0.07
1:5		1.06	0.75	0.53	0.38	0.24	0.17
1:10		2.13	1.50	1.06	0.75	0.48	0.34

Headpond Size

As discussed in the previous section, the size of the headpond will determine the duration of each test point.

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