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Modelling Penstock Pressure Pulsations in Hydro-Electric Power Stations

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Abstract

‘Penstock pressure pulsations’ (PPP, also known as ‘penstock resonance’) are a phenomenon in hydro power stations which, if uncontrolled, can be dangerous and potentially destructive. PPP are known to have been self-excited by small seal leakage on turbine main inlet valves. A controlled PPP event was induced at Hydro Tasmania’s Gordon Power Station in 2002 for testing purposes. This study uses two computer modelling methods to explore the event at Gordon: a model developed using the commercial software package ‘Hytran Solutions’ which uses the method-of-characteristics; and a frequency-domain model called the ‘impedance method’. Both models employ forced frequency response modelling, and the capabilities and limitations of each modelling method are highlighted. The process of ‘matching’ models to describe the same hydraulic system is described. The impedance modelling results are useful to locate the natural frequencies of the pipe network, which can reduce Hytran modelling time significantly. The way in which the models might be extended to include the self-excitation effect at the leaking valve seal is described. To produce realistic results from an extended model, a detailed study of the characteristics and dynamics of the leaking valve seal is also required.

Introduction

‘Penstock pressure pulsations’ are the phenomenon of the oscillation of a water column in the penstock pipe network of a hydro-electric power station. It is an extension of ‘waterhammer’, where pressure waves are generated by an ‘exciter’ and combine in such a manner to produce growing resonant pressure oscillations. PPP can be excited in many ways, however this paper focuses on cases which have been ‘self-excited’ by a leaking seal on a turbine main inlet valve (TIV). This particular method of ‘self-excitation’ has been the cause of many documented events in the international hydro-electric industry [2,4,5,6]. If uncontrolled, PPP can become a violent and dangerous phenomenon. Penstocks may theoretically be exposed to pressures between cavitation and twice the usual static pressure [6], with induced vibrations, stresses and/or fatigue potentially having catastrophic consequences.

Hydro Tasmania has determined to take a proactive approach to PPP. Due to the complex nature of PPP it is difficult to eliminate with absolute certainty any chance of future events occurring. Thus PPP protection systems have been installed in stations at risk. These systems detect PPP through pressure monitoring, and trigger a response accordingly (responses vary between installations). At Gordon Power Station in South-West Tasmania, the effectiveness of the PPP protection system was tested and proven through the deliberate and controlled instigation of a PPP event in 2002 [1].

The hydraulic layout of Gordon Power Station is shown in Figure 1. The intake is a vertical tower beneath which is a vertical penstock approximately 150 m long. This is followed by a 90-degree bend, another penstock section approximately 150 m long, and the distributor. There is space for 5 machines, though only 3 are installed, the other distributor off-takes are dead-ends.

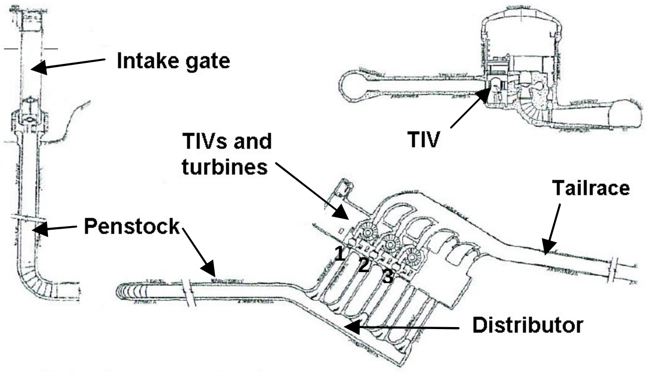

Figure 1. Hydraulic layout of Gordon Power Station, from [1].

Due to the dangerous nature of PPP, it is not usually ideal to induce an event to test the effectiveness of a protection system. In future, computer models could be used to help test the effectiveness of both preventative and control actions for known and suspected modes of PPP. Models might also be used to investigate PPP events which are known to have occurred, not only their mechanics but also unseen consequences such as fatigue implications. This paper demonstrates the application of two computer modelling methods, and scopes the potential for extending and improving the developed models.

General Theory & Scope

Instances of PPP relevant to this paper have been self-excited by the seal on a turbine inlet valve of the ‘rotary’ (‘spherical’/‘ball’) valve type shown in Figure 2, with two stages of closing. The door of the valve rotates closed, and then a metal sliding seal is applied on the downstream side of the valve, held in place by control water tapped from the penstock. This arrangement has a potentially unstable, negative pressure/flow characteristic curve, where flow rate through the seal increases when pressure at the valve decreases [1,6]. If there is a disturbance such as a leaking seal or a drop in control water pressure, the seal may flutter, creating further flow disturbances and pressure waves upstream of the valve. If the penstock pipe system responds to the frequency at which the seal flutters, the pressure waves will combine in such a way that resonant oscillations will grow until a failure/change occurs, or until steady state resonant oscillatory conditions are reached.

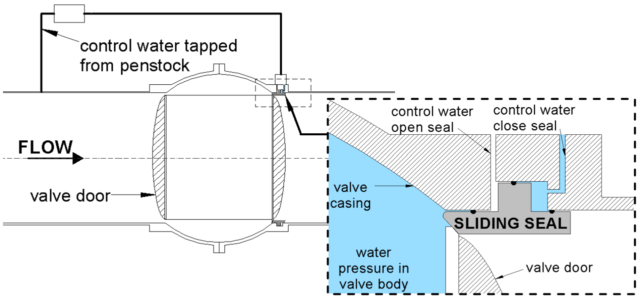

Figure 2. Sliding seal on a rotary TIV, diagram adapted from [4].

Resonant pressure fluctuations may also be induced in a system in a forced manner [6]. For example, a valve which is repeatedly opened and closed may act as an exciter, and if oscillated at a frequency near the natural frequency of a pipe system will induce pressure pulsations. Whilst this is not a common scenario in practice, it is useful for modelling purposes.

Hydro Tasmania has extensively used a program called 'Hytran' to undertake hydraulic transient modelling. Hytran is a waterhammer/hydraulic transient analysis program which uses the 'method of characteristics'. It is used by Hydro Tasmania to model pressure transients in power stations (and other hydraulic networks) under various normal and emergency operating scenarios. It has also been used to investigate PPP. This study extends PPP modelling in Hytran by using the 'impedance method' developed by Wylie [6]. It explores matching Hytran and impedance models for a system resembling Gordon Power Station. It is of significance that all PPP modelling undertaken at Hydro Tasmania to date, including this study, simulates 'forced' oscillations. 'Forced' oscillations are simulated in both Hytran and impedance models by opening and closing a downstream discharge valve in a sinusoidal manner. The magnitude and nature of the response of the penstock pipe system to different forcing frequencies is able to be investigated using this approach. However, the method of 'forced' oscillation neglects the self-excitation effect. To accurately model the real pressure pulsations that occurred at Gordon Power Station the models would require extra features. In addition, a detailed investigation into the characteristics of the leaking valve seal would be required.

Modelling Theory

The method of characteristics (MOC) is a time-domain modelling approach used commonly for fluid transient analysis. It models the system over time, and one-dimensionally in space (x = distance along pipe). It is a numerical method used to solve the quasilinear hyperbolic partial differential equations of momentum and continuity. The equations describe the relationship between fluid velocity, fluid head, distance along the pipe, and time [6]. Hytran [3], a waterhammer analysis program developed by Dr N. Lawgun in New Zealand, makes use of MOC to solve these equations for a modelled pipe network. The program divides the network into short pipe lengths and the equations are solved for these pipe lengths in a time-marching numerical manner. Hytran also employs other mathematical and approximation techniques to iterate towards a solution.

Hytran has a user interface through which pipe networks can be drawn, and pipe properties assigned. Boundary conditions, such as valves, reservoirs, dead ends, pumps and turbines, can be assigned to complete the characterisation of the model. After specifying suitable initial conditions the model can be run to simulate the pressure and flow in the system over time. The boundary conditions can also be dynamic during a model run, for example a valve may open, close, or oscillate over time. To model forced oscillations in Hytran, a valve is used. The valve discharges to atmosphere, and can be forced to oscillate such that the area of opening varies in a sinusoidal fashion. The mean position and magnitude of the oscillation are specified as a percentage of the valve opening. The valve effective area ($C_D A_G$) must be sized according to the specified initial flow (Q), such that the head loss over the valve (H_{drop}) is matched to the hydraulic grade line in the pipe according to the orifice equation:

$$Q = C_D A_G \sqrt{2gH_{drop}} \qquad (1)$$

The impedance method [6] is a frequency domain modelling approach, which focuses on steady-state oscillatory conditions in the frequency domain, therefore skipping the transient development of the pressure oscillations. It is based on the same equations used in the MOC method. The equations are linearised and mathematically manipulated, making use of methods from linear vibration theory and electrical transmission line theory, to define the complex parameter 'impedance':

$$Z(x) = \frac{H(x)}{Q(x)} \qquad (2)$$

The 'impedance' can be defined as a ratio of two complex parameters, the real components of which are the physical head and flow oscillations about mean values at a particular position 'x' along the pipeline. The impedance analysis undertaken for this study is a frequency response analysis, and uses Matlab. The analysis illustrates the response of the modelled system to potential exciters, based on forced vibrations. In this approach, a pipe network is represented using real and imaginary numbers which are expressed as functions of the forcing frequency.

Pipes are characterised by defining the 'linearised resistance' R, 'capacitance' C, 'inertance' L, the 'propagation constant' γ, and the 'characteristic impedance' Z_C, as defined in [6]. These parameters are functions of pipe characteristics such as diameter, mean flow, Darcy friction factor and wavespeed. The mean flow through the pipes is used to calculate the corresponding head at key locations in the system by considering the friction losses.

Boundary conditions are defined by impedance Z. At a reservoir where there are no fluctuations in head, $H = 0 \rightarrow Z = 0$. At a dead end there is no flow, $Q = 0$, $\rightarrow Z \rightarrow$ infinite. Impedance transfer functions (functions of complex numbers), as derived in [6], are then used to relate the impedance at a boundary to the impedance at the other end of the pipe. In this way the impedance can be traced through a pipe system from known boundary conditions to any point of interest. The resulting impedance at this point of interest describes the relationship between head and flow oscillations for any particular forcing frequency.

For the purposes of this study the point of interest was the 'exciter', an oscillating valve which discharges to atmosphere. The valve oscillation is characterised by specifying both the mean and oscillatory components of dimensionless valve opening area, ($\bar{\tau}$ and Tv respectively). The head drop over the valve ($\bar{H}_{drop}$) is calculated for the mean flow condition ($\bar{Q}$) as equal to the upstream head since the valve discharges to atmosphere. The flow and head oscillations at the valve (Q_V, H_V) can now be determined using the impedance at the valve Z_D.

$$Q_V = \frac{T_V \left(2\bar{H}_{drop} / \bar{\tau} \right)}{\left(2\bar{H}_{drop} / \bar{Q} \right) - Z_D} \qquad (3)$$

$$H_V = Z_D Q_V \qquad (4)$$

Developing and Matching Models

This study demonstrates how the same scenario can be modelled with both MOC and impedance modelling methods to produce agreeable results, albeit within limitations.

Models resembling Gordon Power Station were developed and could be considered ‘matched’ when the boundary conditions, initial conditions, geometry and all other specified parameters were identical. The models are compared to test results from controlled PPP testing undertaken at the station in 2002. Whilst the models are representative of the penstock at Gordon Power Station (Figure 1), they are not fully calibrated or proven to represent real conditions. Calibration of Hytran transient models is usually achieved by fine tuning model characteristics for the pipeline (e.g. friction factors and wavespeed) to match real test data to modelling results for a scenario such as a machine load rejection. To calibrate a model for PPP would require considering the characteristics of the leaking valve in addition to the pipeline.

The basic pipe characteristics which are important in both Hytran and impedance models are the lengths, diameters, and (Darcy-Wiesbach) friction factors. All these pipe characteristics are straightforward to specify in both models. The Gordon model contains a significant number of pipes, and Hytran pipe characteristics were imported into a spreadsheet, which was then used in the Matlab impedance analysis.

Wavespeed is an important pipe-parameter for both models. It depends upon the nature of the pipe and the fluid and can vary between roughly 1000 – 1400 m/s for water [6]. Details of pipe wall thickness, elastic modulus of pipe wall material, and the way in which the pipe is restrained are required to determine wavespeed. A previous Hytran ‘Gordon’ model used a wavespeed of 1250 m/s and was considered acceptable to use again for this study. This wavespeed was specified directly in Hytran, however, when the model is run the wavespeed is modified slightly in each pipe for numerical solving purposes. The modified wavespeeds were extracted from Hytran output files, and used in the ‘matched’ impedance analysis. Only pipe dimensions and layout need to be correct in Hytran to determine these modified wavespeeds, flow parameters can be entered later.

The Gordon models contain three types of boundary conditions: a reservoir at the intake; dead ends at TIVs #1 and #3 and other distributor pipes; and the oscillating valve at TIV #2. The oscillatory valve characteristics (size, mean position and magnitude of oscillation) are directly linked to the flow rates in the models, since the main head loss in the system is through the valve according to the orifice equation. The size of the valve must be specified in Hytran, but is not directly input in the impedance model (it can be calculated from the valve head loss).

The flow rate should be matched as closely as possible in the models. An initial flow rate is specified in Hytran. This is not necessarily the same as the mean flow rate in the impedance model, since Hytran uses a cosine wave for the valve oscillation, such that the valve begins to oscillate from the maximum position. In order to achieve reasonable mean flow agreement a flow rate calculation can be performed using the orifice equation and the information in Hytran to specify a mean flow for the impedance analysis. Having specified the valve characteristics it is necessary to find the flow rate which would produce the same initial head drop across the valve if the valve were at the mean (instead of the maximum) position. This achieves reasonably close mean flow agreement. If closer agreement is required an iterative approach can be used, by extracting flow results from Hytran after it has been run and calculating the mean flow.

The valve oscillatory characteristics and flow rate were unknown during the controlled PPP testing at Gordon. For the purposes of this study in matching and exploring the limitations of the two models, a rough estimate of 40-90 L/s (estimated from the dimensions of the seal and the orifice equation) was sufficient. In order to develop a realistic model in future, further investigation would be required into the valve characteristics and flow rate.

Frequency Modelling Results

The impedance model can be used to produce a plot of the impedance magnitude at the location of the oscillating valve. The impedance peaks are representative of the natural frequencies of the hydraulic system. This output is particularly useful for Hytran modelling. Hytran models can be large and time consuming to run until steady state oscillatory conditions are reached, however an impedance model can be used to identify the natural frequencies to test in Hytran. This study showed the frequencies identified by the impedance analysis produced a growing response in Hytran.

Figure 3 shows the natural frequencies of the Gordon model as predicted by the impedance analysis (blue lines). The observed frequencies during actual PPP testing at Gordon are also shown (pink lines). These are not necessarily expected to match even if the model were properly calibrated, due to the difference between forced and self-excited oscillations. From an impedance perspective, the development of self-excited oscillations is only likely if there is a matched condition between the penstock and the valve-exciter. This study only considers the natural frequencies of the pipe system, and neglects the other half of the problem – the characteristics of the valve seal.

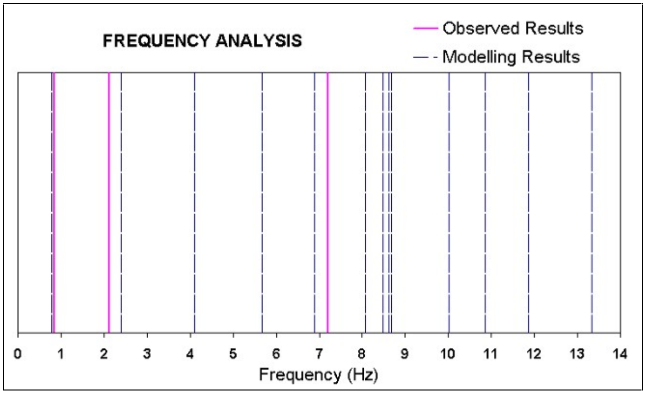

Figure 3: Frequency modelling results.

Hytran is sensitive to the valve forcing frequency. For example, one model run shows that if the forcing frequency is changed by 0.0005 Hz, the size of the pressure oscillations at steady state oscillatory conditions change from approximately 100 m to 150 m peak-peak. This highlights one of the sensitivities/limitations of forced oscillation models. Even frequencies predicted by a ‘matched’ impedance model require some fine tuning in Hytran to locate the maximum response.

Pressure Modelling Results

In most of the matched model runs for this study, the impedance and Hytran results for pressure oscillation at the valve differed significantly, with the impedance method predicting oscillations up to 400% larger than Hytran. Particularly disagreeable were the fine-tuned scenarios which produced the maximum response at the valve in Hytran (these are the ‘worst case’ scenarios the study also aimed to find). However, some matched models with small valve oscillation and a large mean flow rate produced pressure results which agreed within 10%. These varied results are significant in demonstrating the limitations of the impedance analysis. It is unrealistic for pressure oscillations to be larger in mean-peak amplitude than the pressure at the valve under static conditions; cavitation limits oscillations growing further [6].

As such, the theoretical maximum pressure the valve may experience is twice the static pressure ($\approx 2 \times 180$ m at Gordon). The linearised impedance model has no way of modelling the cavitation limitation and therefore at times predicts unrealistic results. However, even the maximum response Hytran models did not predict maximum head oscillations particularly close to the cavitation limit (e.g. Figure 4). This is likely due to the effects of non-linear friction, which Hytran is better equipped to deal with compared to the impedance model. The most disagreeable matched models were shown in Hytran to have very large flow oscillations (up to 200 times the mean flow). The impedance analysis uses a linearised friction term which assumes flow fluctuations are smaller than mean flow, and is not accurate for these large oscillatory flow scenarios.

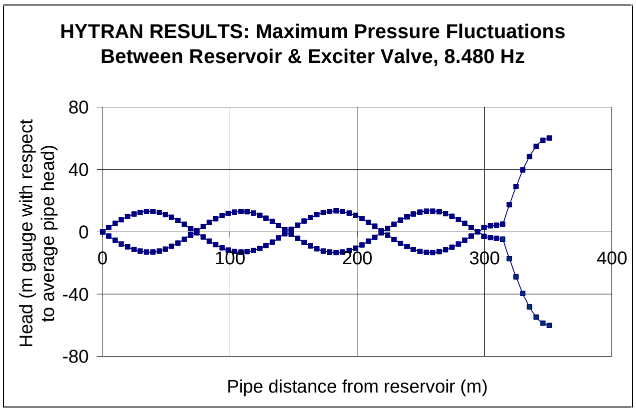

Figure 4: Maximum head oscillations, a large oscillatory flow scenario.

The pressures at the oscillating valve predicted by the Hytran Gordon models were not representative of those observed during the PPP testing at Gordon. This is largely because the flow rate and valve oscillation characteristics have not been accurately defined. If the frequency and pressure at steady state oscillatory conditions were known from actual test results, it may be possible to use the Hytran model to estimate the flow rate and valve oscillation through trial and error. This would allow a reasonably realistic model of the PPP event at the steady state oscillatory condition to be produced. Steady oscillatory conditions were not reached during the testing at Gordon since it was too dangerous to allow the PPP to continue growing. However, there is data available for the rate of growth of the pressure oscillations. In order to realistically model the rate of growth of PPP, a forced oscillation model is not sufficient, the model must account for the self-excitation effect.

Conclusions & Recommendations

An impedance model matched to a Hytran model has been shown to be a useful tool to narrow the search for maximum response frequencies in a Hytran forced response model. Such an approach significantly reduces the amount of modelling time required. However the impedance method was not able to accurately predict pressure oscillations in the Gordon Hytran model for the maximum response conditions. This is due to the linearised nature of the impedance model, and the large flow oscillations which are present for the maximum response scenario. It is likely that Hytran could realistically model steady state oscillatory conditions if suitable test data were available for calibration.

In order to evaluate the risks of PPP as well as control strategies, it would be useful to model the development of the PPP rather than only the steady state oscillatory conditions. However both existing models do not account for the self-excitation effect and therefore cannot accurately model PPP development as caused by the leaking valve seal. To do so would involve a detailed study of the valve seal characteristics, namely the effect of pressure/flow on the physical oscillation of the valve seal. It would also require modifications to the structure of the existing models. The forced oscillation models require the physical valve oscillation to be defined and remain constant. An MOC self-excitation model would require a boundary condition which is able to take the pressure/flow data at the valve, determine the dynamic response of the seal, and thus specify the change in seal position for the subsequent modelling time step. In such a model the physical oscillation of the valve will change as the PPP develops, rather than staying constant as in the forced response model.

The impedance method could also be used to investigate self-excited PPP. The existing model only considers the pipe network. To analyse self-excited PPP, an impedance analysis of the valve must also be undertaken. A matched impedance condition at the valve, i.e. a frequency where the impedance with regard to the pipe network is approximately the same as the impedance with regard to the valve (amplitude and phase), represents a possible frequency at which a PPP could develop for the system. If the flow oscillations are not significantly larger than the mean flow, then the impedance analysis may also yield indicative pressure oscillation predictions for steady state oscillatory conditions. As for the MOC, development of an accurate impedance model would require a detailed investigation into the physical oscillation and flow characteristics of the valve.

To prove the effectiveness of the proposed modelling strategies, it is considered that the development of a test rig would be highly beneficial, allowing the valve characteristics to be explored in depth in an easily accessible and controlled environment. A motorised valve could be used to induce forced pressure oscillations and to refine the forced response models. The design of a spring loaded valve which induces unstable waterhammer in a pipe is already underway at the University of Tasmania. Such studies could be of benefit in determining the most practical way to characterise real scenarios such as a leaking valve seal at Gordon Power Station.

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References

[1] Caney, K. & Zulovic, E., Self-Excited Penstock Pressure Oscillations at Gordon Power Station in Tasmania and Other Similar Events, *Waterpower XIV*, 2005.

[2] Ehrhart, R.W., Auto oscillation in the Hyatt plant's penstock system, *Water Power and Dam Construction*, 1979, 38-41.

[3] Hytran Solutions, *Waterhammer Software from Hytran Solutions*, www.hytran.net, 2010.

[4] Nishihara, T., Akimoto, T. & Yamamoto, K., Self-induced pressure pulsation in penstock caused by movable-seat seal using tapped water from penstock, *Waterpower XIII*, 2003.

[5] Wylie E.B. & Streeter V.L., Resonance in Bersimis No. 2 Piping System,*Journal of Basic Engineering*, 1965, 925-931.

[6] Wylie, E.B., Streeter, V.L. & Suo, L., *Fluid transients in systems*, Prentice Hall, 1993.