AN ACCURATE MEASUREMENT OF THE ROSEMOUNT 1152 DIFFERENTIAL PRESSURE CELL RESPONSE TIME

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ABSTRACT

The primary heat-transport (PHT) system of a CANDU®[1] reactor includes four quadrants of reactor coolant channels, each fed from its own inlet header through a large number of inlet feeders. As part of the safety shutdown system 1 (SDS1) and Reactor Regulating System (RRS) of CANDU reactors, differential-pressure (DP) cells are used to monitor the reactor coolant flows in each quadrant and to register changes with a prescribed response time. This paper describes an accurate in-situ measurement of the response time of two Rosemount 1152 DPA22PB DP cells, one from SDS1 and one from an RRS fully instrumented channel. The response time measurement was done using high-frequency pressure-measurement devices temporarily installed on the high- and low-pressure sides of the DP cells. The results suggest that the actual time constant of the Rosemount DP cell is much faster than indicated in the specification which is based on the traditional instrument-air-step-response measurement method. Furthermore, the actual time constant is much faster than that assumed in the safety analysis report. An examination of the instrument-air-step-response method indicates that it produces conservative estimates of time constants, especially for small time constants. If further work confirms this finding it suggests that the actual time constant may be increased considerably without exceeding the time constant assumed in the safety analysis.

1. INTRODUCTION

The primary heat-transport (PHT) system of a CANDU reactor consists of four quadrants of reactor coolant channels, each fed from its own inlet header through a large number of inlet feeders. Part of the SDS1 safety system of a CANDU reactor is the measurement of reactor coolant flow. The flow in three inlet feeders per quadrant is monitored using a differential-pressure (DP) measurement system comprising orifice plates, DP cells (also called transmitters) and impulse lines that connect the DP cells to the measured process. If one of these three measurements indicates low flow, then a Low Gross Flow (LGF) alarm occurs; if two out of three indicate low flow then a reactor trip occurs on LGF [1].

Pickering Nuclear Generation Station (PNGS) B recently raised its LGF trip point from 84% of nominal flow to 90% and, as a result, began experiencing a large number of LGF channel trips, up to 30 per day [1]. Similar problems have occurred at both Bruce and Darlington Nuclear Generating

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[1] CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL).

Stations [1]. An initial investigation into the cause of these LGF alarms revealed very short (70 ms) but fairly large (up to 22%) drops in DP cell output, termed "flow dips."

Analysis of the data revealed that these flow dips are not correlated to each other or to inlet header pressure or to fully instrumented channel (FINCH) flow measurements. The FINCH channel flow measurements, which are used for reactor regulating purposes, are done with a DP measuring system that uses venturis instead of orifice plates as the primary element. No flow dips occur on FINCH flow measurements. The conclusion of a preliminary analysis was that the flow dips were a local turbulence phenomena related to orifice plates, and they were not caused by low flow in the quadrant as a whole or in the individual channel.

It is fairly easy to filter out flow dips by increasing the damping (time constant) of the DP cell. The DP cell manufacturer, Rosemount, specifies a response time of 200 ms for the DP cell itself. The same value is used in the Safety Analysis Report (SAR) [2]. In response to a PNGS B request, the Atomic Energy Control Board (AECB) allowed PNGS B to increase the time constant on the one particular DP cell that was causing the most LGF alarms. This was done, and the LGF alarms associated with that particular DP cell were eliminated. However, the AECB requested that PNGS B investigate the root cause of the flow-dip phenomena [3], and a research program with that objective was established [1]. Conclusions of this research are that flow does not change significantly during a flow dip and that pressure pulses originating in the header-feeder junction are the root cause of the flow dip [1].

In the course of the flow-dip investigation, the question raised was how a very short (70 ms) but large (22%) flow dip could be output by a DP cell having a specified time constant of 200 ms. To investigate this, PNGS B performed time constant measurements on the DP cell using an instrument-air-step-response test. This measurement method indicated a response time of 200 ms, in apparent good agreement with the manufacturer's specification.

However, further investigation of the instrument-air-step-response test method suggests that the measurement method itself has a systematic error. In this test, the time taken to reach an output of 63% in response to a step change in input air pressure is defined as the response time. The input air-pressure step change is generated using a three-way solenoid valve, and the output transients are recorded using an electronic strip-chart recorder. Time zero is taken as the time at which the electrical signal to the solenoid valve is switched. Given the fact that it may take about 100 ms for the solenoid valve to fully open, the instrument-air-step-response method consistently indicates a response time that is in the order of 100 ms slower than the true response time of the DP cell alone. Thus the 200 ms time constant obtained using the instrument-air-step-response measurement technique is actually an indication that the true time constant of the DP cell is approximately 100 ms. Moreover, careful reading of the manufacturer's specification for the DP cell indicates that the 200 ms specified is intended to be a maximum value and that the actual time constant is equal or faster than this. Thus a time constant of 100 ms is not inconsistent with the manufacturer's specification and it explains how a 70 ms pulse might pass through the DP cell.

As part of the flow-dip investigation, special, temporarily installed high-frequency pressure transmitters were used to measure the pressure on each side of two DP cells, one associated with SDS1, the other associated with a FINCH channel. These high-frequency pressure transmitters were installed to obtain a cleaner record of high-frequency pressure pulses that were suspected to be the cause of the flow dips. An additional benefit of these measurements is that they can be used to obtain a more accurate measure of the DP cell response time. Analyzing these high-frequency pressure measurements to provide an accurate measurement of DP cell response time is the subject of this report. The experimental setup and measurement obtained are described in Section 2. Non-parametric and parametric analyses are given in Sections 3 and 4, respectively.

2. EXPERIMENTAL SETUP AND MEASUREMENTS OBTAINED

The temporary high-frequency pressure transmitters measuring the pressure on each side of the DP cell are shown in Figure 1. The pressure transmitters were piezoelectric sensors, ICP model 101A06, from Intertechnology. These sensors can withstand high static pressure while having fairly high sensitivity to small pressure changes. They operate as a band pass filter with both a low-frequency breakpoint (50 s time constant) and a high-frequency limit (>100 kHz). They contain integral voltage amplifiers. They were installed using about 250 mm of tubing to the drain holes of the DP cells. The data used in this analysis were sampled at a frequency of 2200 Hz. Two sets of high-frequency measurements were made: one on a DP cell measuring pressure drop across an orifice plate (Rosemount 1152DP6A22PBCE), the other on a DP cell measuring pressure drops across a venturi (Rosemount 1152DP5A22PBCE).

The two DP cells from PNGS Unit 7 that were examined were RRS FINCH channel-flow transmitter F1CFT7 on fuel channel N16 (a venturi-based flow measurement) and SDS1 gross low-flow transmitter F3F (an orifice-plate-based flow measurement). The FINCH cell has an upper range limit (URL) of 0-186.0 kPa and a calibrated span of 77.1 kPa (41% of URL), whereas the SDS1 cell has a URL of 0-690.0 kPa and a calibrated span of 491.0 kPa (71% of URL). Figure 2 shows a portion of the F3F DP cell output.

A difference signal (Diff) was created by subtracting the output of the two high-frequency pressure cells, Phi and Plo:

$$\text{Diff} = \text{Phi} - \text{Plo} \qquad (1)$$

A portion of the Diff signal is shown in Figure 3. Note that the DC values of Phi, Plo, and hence, Diff are arbitrary.

It should be noted that the actual variation in DP across the cell is ±150 kPa (Figure 3), which is about 61% of the actual transmitter span (calibrated value 491.0 kPa). This indicates that large variations are considered in this analysis. However, the variation in cell output is only about ±12 kPa, which is about 5% of the full scale (Figure 2). This is due to the internal filter of the DP cell.

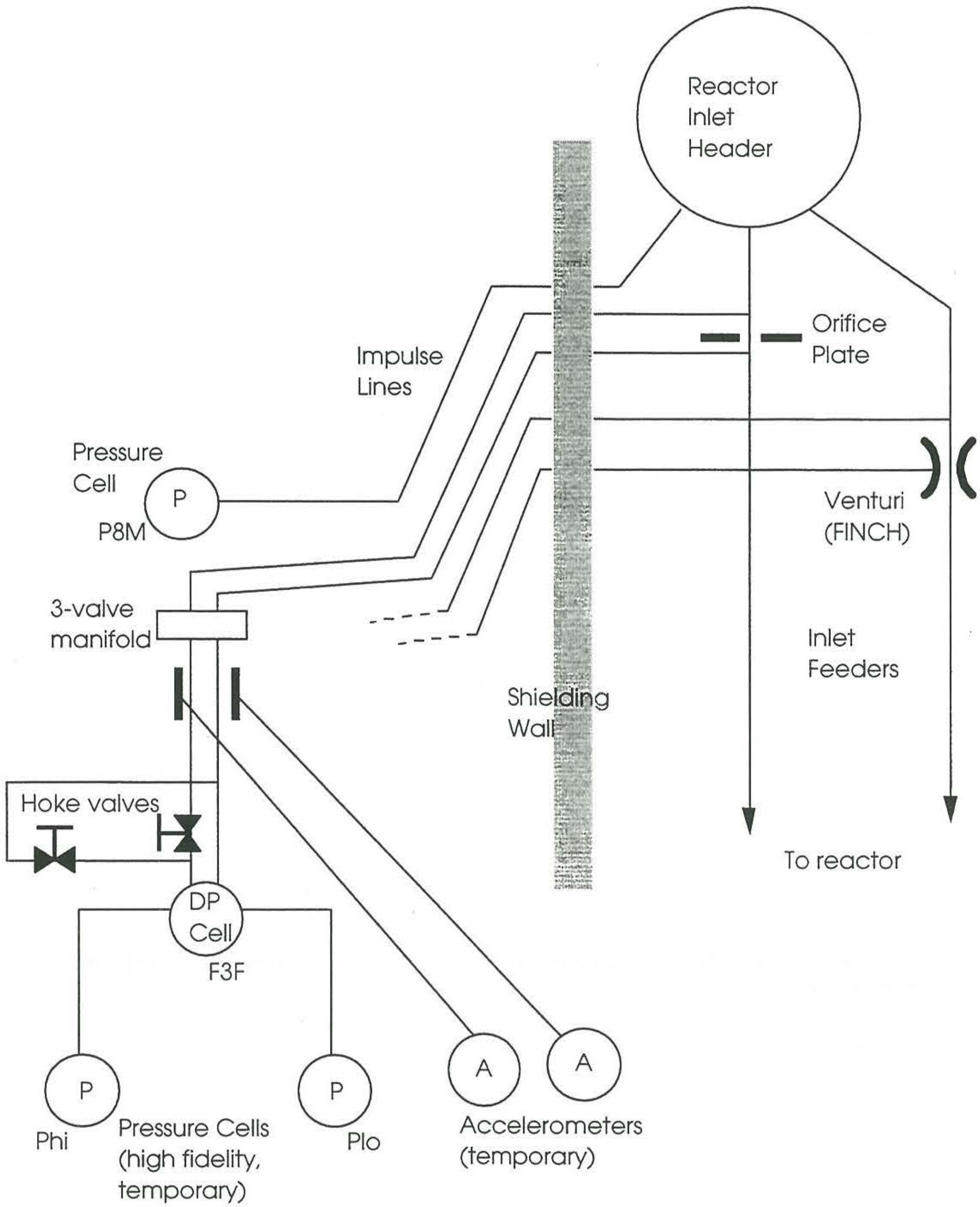

Figure 1: Experimental setup of the DP cell pressure measurements; Phi and Plo are temporarily installed high-frequency pressure cells.

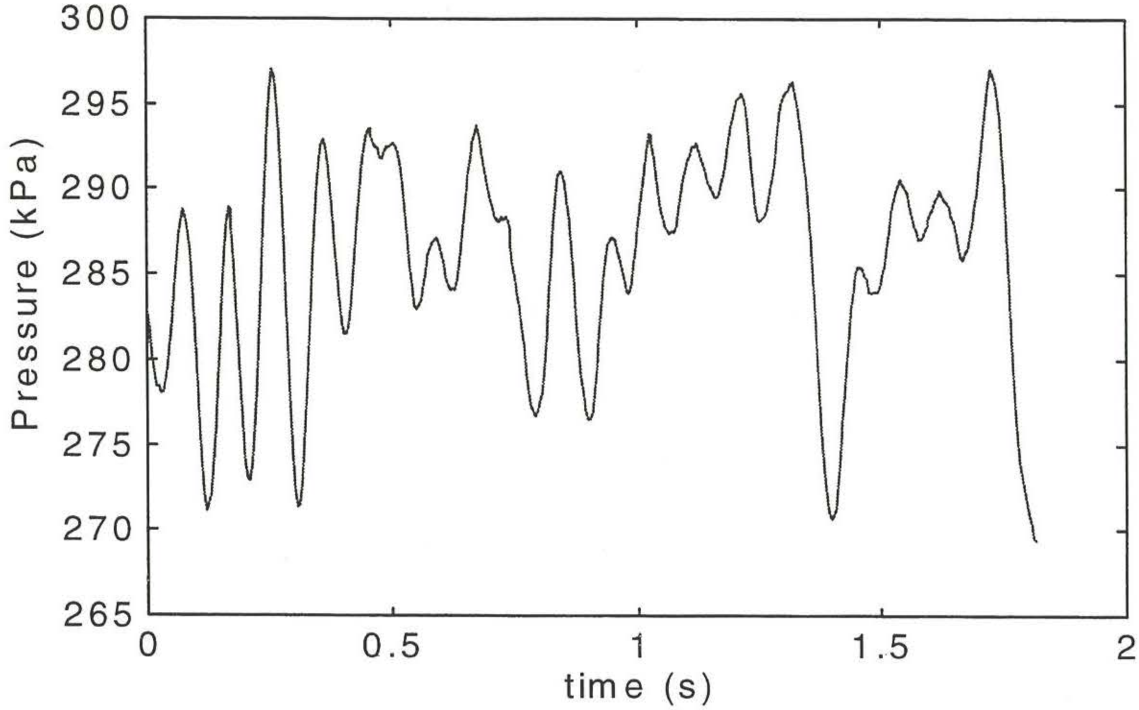

Figure 2: Portion of DP cell output F3F.

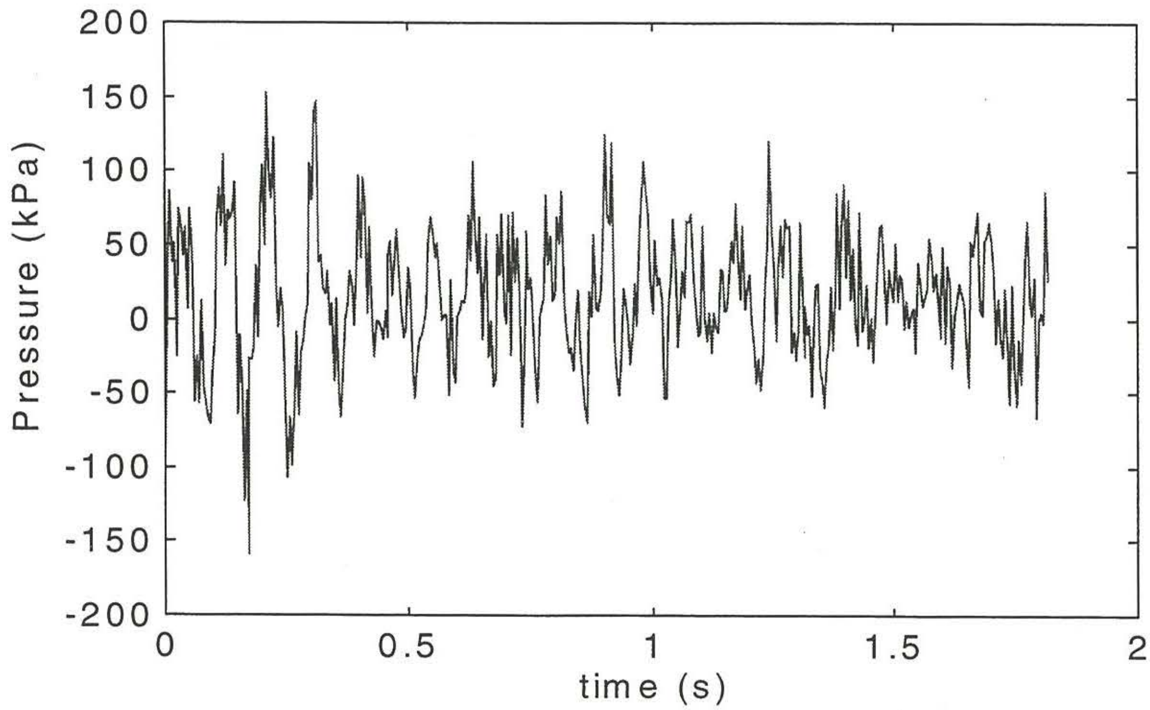

Figure 3: Portion of signal Diff = Phi -Plo (arbitrary mean value).

3. NON-PARAMETRIC RESPONSE TIME ESTIMATION

It can be assumed that the high-frequency pressure cells measure actual pressure without distortion; thus the Diff signal (Figure 3) represents the *actual* pressure difference across the DP cell. In contrast to this, the F3F signal (Figure 2) represents the pressure difference across the DP cell as *measured* by the DP cell. Therefore, the transfer function between Diff signal and F3F signal reflects the response of the DP cell itself.

The Diff-to-F3F transfer function was derived by dividing F3F by Diff in the frequency domain and is shown in Figure 4 with a frequency resolution of 0.9746 rad/s.

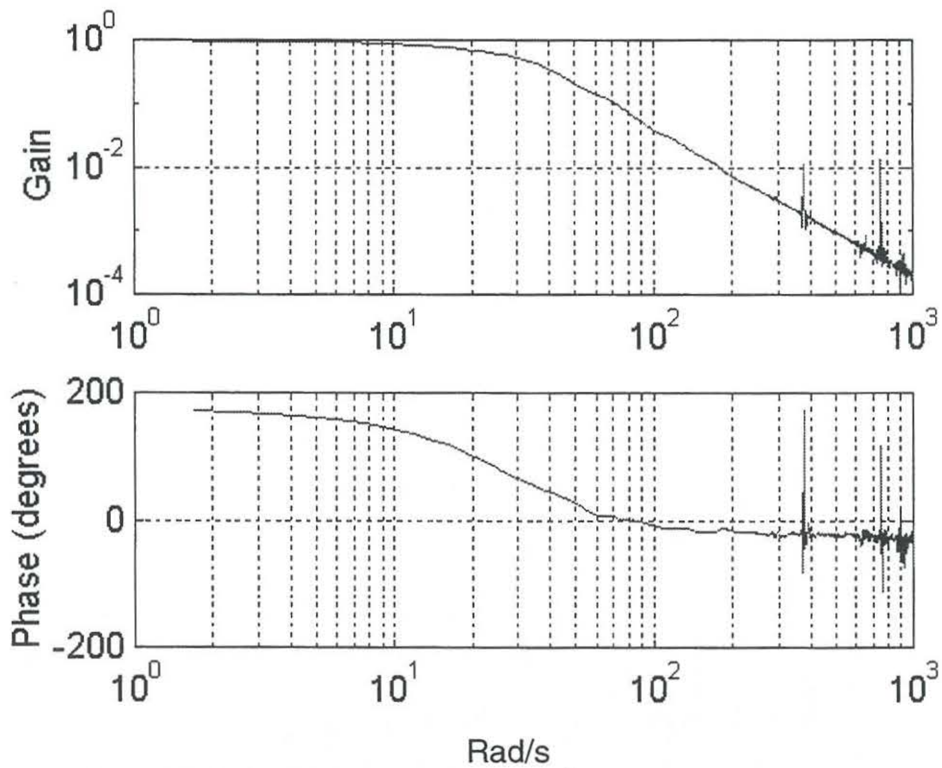

Figure 4: Diff-to-F3F transfer function[2] derived from measurements.

This transfer function is approximately unity gain at low frequencies and falls off at a rate slightly greater than 40 dB/decade above the cutoff angular frequency, ω_c, which occurs at about 25 rad/s (4 Hz). The phase similarly drops from near 180 degrees at low frequencies to slightly below 0 degrees at high frequencies. The shape and rate of fall indicate a transfer function G(s) given approximately by:

$$G(s) = \frac{1}{(1+s\tau)^2} \qquad (2)$$

[2] Transfer function includes a minus sign, equivalent to adding +/- 180 degrees to the phase, to make them appear more normal on the plot.

where s = Laplace variable
τ = dual time constant

The dual time constant τ ($=1/\omega_c$) is equal to 40 ms. Based on the above transfer function, the corresponding response to a step input $U(s) = 1/s$ is given by

$$Y(s) = G(s)\,U(s) = \frac{1}{(1+s\tau)^2 s} \quad . \qquad (3)$$

The response of $y(t)$ is calculated through the inverse Laplace transform:

$$y(t) = \mathcal{L}^{-1}\,[Y(s)] = 1 - e^{-t/\tau} - t/\tau\, e^{-t/\tau} \; . \qquad (4)$$

The response of $y(t)$ to a step input is shown in Figure 5. The response time of the DP cell described by the transfer function in equation (1) is obtained by calculating the time at which $y(t)$ equals 63.2% of the steady-state value, which occurs at $t = 86$ ms. Thus the response time of the DP cell, based on a non-parametric analysis is 86 ms.

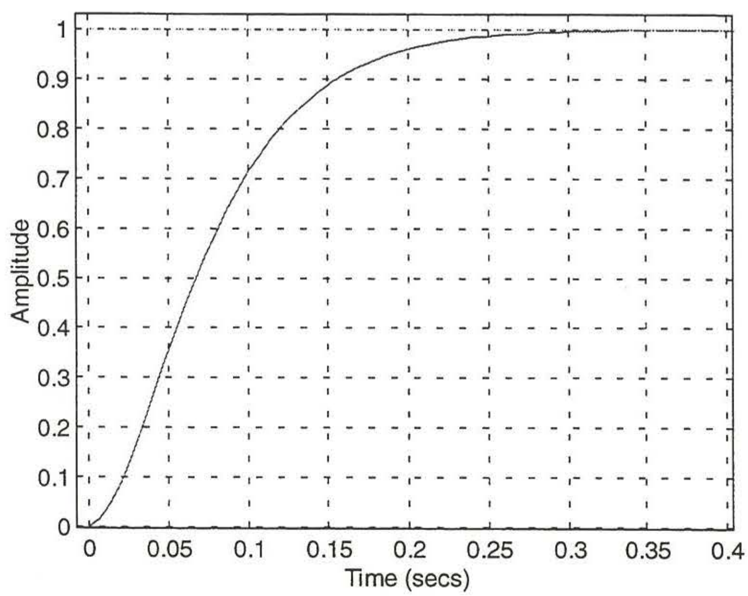

Figure 5: The step response of the transfer function described by Equation (1).

A similar non-parametric analysis applied to the measurements of the FINCH DP gives a dual time constant of 53 ms (a cut-off frequency of 19 rad/s) and a response time of 115 ms.

4. PARAMETRIC RESPONSE TIME ESTIMATION

To verify the above results of response time estimation for the SDS1 DP cell and to obtain a more accurate estimate, a frequency-domain parametric analysis was employed. Given the transfer function shown in Figure 4, as a single-input, single-output system, the following form of transfer function is expected to fit this non-parametric derived transfer function to a high degree of accuracy:

$$G(s) = \frac{b_1 s^{nb} + b_2 s^{nb-1} + \dots + b_{nb+1}}{a_1 s^{na} + a_2 s^{na-1} + \dots + a_{na+1}} \qquad (5)$$

where nb and na are the orders for the numerator and denominator respectively, and b and a are two coefficient vectors. To identify the two vectors, the least-squares error criterion is used. Denoting the complex frequency response in Figure 4, as tf(k), the corresponding frequencies as freq(k), k = 1, ..., 1024 are the number of frequency points (the length of tf(k) and freq(k)), the squared error between the actual frequency response points and the desired response is minimized through the following criterion, with equal weighting at all frequency points selected:

$$\min_{b,a} \sum_{k=1}^{n} \left| tf(k) - \frac{B(freq(k))}{A(freq(k))} \right|^2 \qquad (6)$$

where B(freq(k)) and A(freq(k)) are the numerator and denominator of equation (5) evaluated at frequencies freq(k) using the coefficients b and a respectively.

Selecting third-order models, for both the numerator and denominator, i.e., na = nb = 3 for Equation (5), the coefficient vectors were identified by using the MATLAB package. The transfer function obtained through the parametric analysis is

$$G(s) = \frac{245s + 34197}{s^3 + 81s^2 + 2824s + 36242} \qquad (7)$$

The frequency response of the transfer function described by Equation (7) is shown in Figure 6. It matches very well with the transfer function shown in Figure 4.

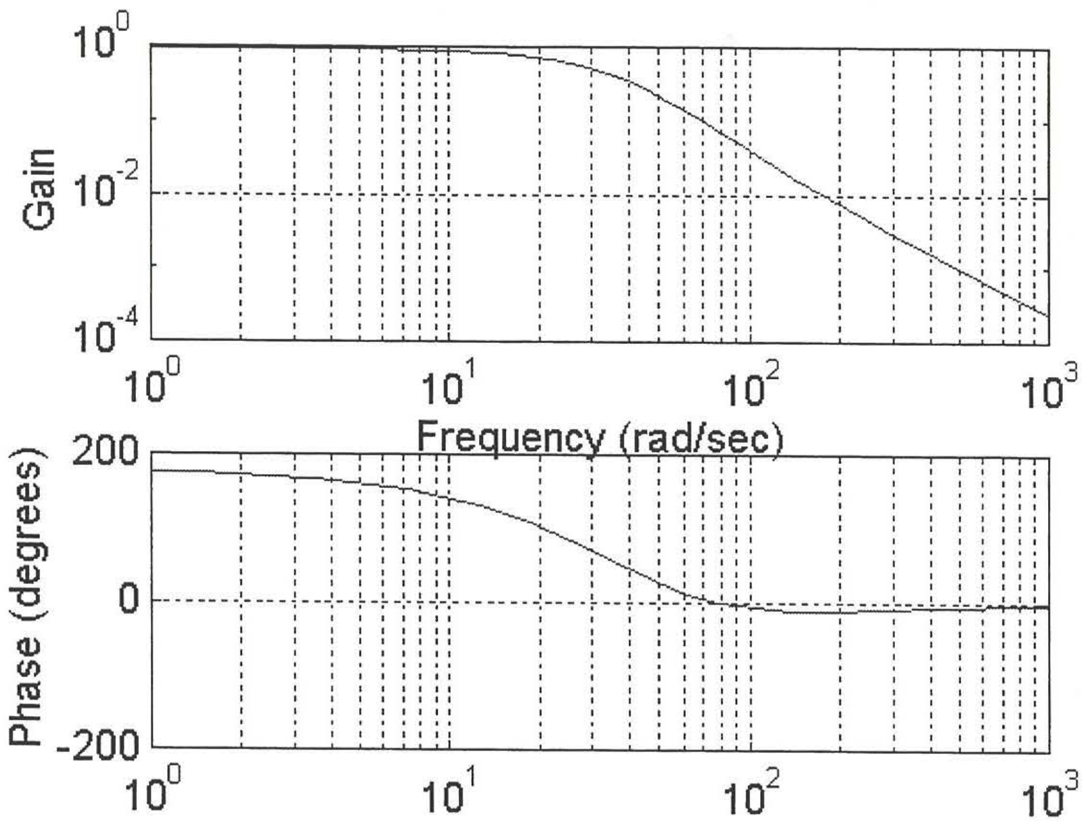

Figure 6: Diff-to-F3F transfer function derived from a parametric model.

To calculate the time constants from Equation (7), the above equation is rewritten below by factoring:

$$G(s) = 245\frac{(s+139.5796)}{(s+(27.4985+j25.5842))(s+(27.4985-j25.5842))(s+25.6908)} \quad (8)$$

The numerator consists of a first-order term, and the denominator consists of a first-order and a second-order terms, which can be described in the form of

$$G(s) = K\frac{(s+\sigma_0)}{(s+(\sigma_2+j\omega_{d2}))(s+(\sigma_2-j\omega_{d2}))(s+\sigma_3)} \quad (9)$$

or

$$G(s) = K\frac{(s+\sigma_0)}{(s^2+2\zeta\omega_n s+\omega_n{}^2)(s+\sigma_3)} \quad (10)$$

with ζ being the damping ratio and ω_n being the natural frequency of a second-order system, and $\zeta = 0.732$, $\omega_n = 37.5663$ rad/s.

The three time constants described by Equation (8) (or (9)) are

$$\tau_1 = 1/\sigma_0 = 1 / 139.5796 = 7.16 \text{ ms}$$
$$\tau_2 = 1/\sigma_2 = 1 / 27.4985 = 36.4 \text{ ms}$$
$$\tau_3 = 1/\sigma_3 = 1/ 25.6908 = 38.9 \text{ ms.}$$

The total response time of the pressure transmitter can be obtained by analyzing the time response of the transfer function (Equation (7)) to a step input.

Given the step input: $U(s) = \frac{1}{s}$, the corresponding output is

$$Y(s) = G(s)\,U(s) = \frac{245s + 34197}{(s^3 + 81s^2 + 2824s + 36242)s} \qquad (11)$$

Taking the partial fraction expansion of equation (11), Y(s) is written as

$$\begin{aligned} Y(s) &= \frac{-\sigma_1 - j\omega_{d1}}{s(s+(\sigma_2 - j\omega_{d2}))} + \frac{-\sigma_1 + j\omega_{d1}}{s(s+(\sigma_2 + j\omega_{d2}))} + \frac{k_0}{s(s+\sigma_3)} \\ &= \frac{k_2}{s^2 + 2\sigma_2 s + \omega_{n2}{}^2} + \frac{k_1}{s(s^2 + 2\sigma_2 s + \omega_{n2}{}^2)} + \frac{k_0}{s(s+\sigma_3)} \end{aligned} \qquad (12)$$

where

$\sigma_1 = 21.2086,\quad \omega_{d1} = 3.2896,$
$\sigma_2 = 27.4985,\quad \omega_{d2} = 25.5842,$
$\sigma_3 = 25.6908,$
$k_2 = -2\,\sigma_1,$
$k_1 = -2\,(\sigma_1\,\sigma_2 - \omega_{d1}\,\omega_{d2}),$
$k_0 = 42.4172,$
$\omega_{n2}{}^2 = \sigma_2{}^2 + \omega_{d2}{}^2,$

The time response of y(t) is the inverse Laplace transform of Y(s) described by Equation (13):

$$\begin{aligned} y(t) &= \mathcal{L}^{-1}\,[Y(s)] \\ &= \frac{k_2}{\omega_{d2}} e^{-\sigma_2 t} \sin(\omega_{d2} t) + k_1\left(\frac{1}{\omega_{n2}{}^2} - \frac{1}{\omega_{n2}\omega_{d2}} e^{-\sigma_2 t} \sin(\omega_{d2} t + \varphi)\right) + \frac{k_0}{\sigma_3}(1 - e^{-\sigma_3 t}) \end{aligned} \qquad (13)$$

where $\varphi = \arccos(\zeta_2)$, and $\zeta_2 = \sigma_2 / \omega_{n2}$.

The steady-state value can be determined by solving Equation (13) with $y(\infty)$. The time period for the system to reach 63.2% of this final value is the response time of the system, described as

$$\frac{y(\tau)}{y(\infty)} = 63.2\% . \tag{14}$$

With steady-state $y(\infty) = 0.9436$, and 63.2% of this steady-state value 0.5964, the total response time is $\tau = 78.63$ ms. This value is fairly close to the non-parametric-determined response time estimate of 86 ms. Time-domain step response y(t) is shown in Figure 7. Similar agreement was obtained between the parametric and non-parametric analyses for the FINCH channel DP cell.

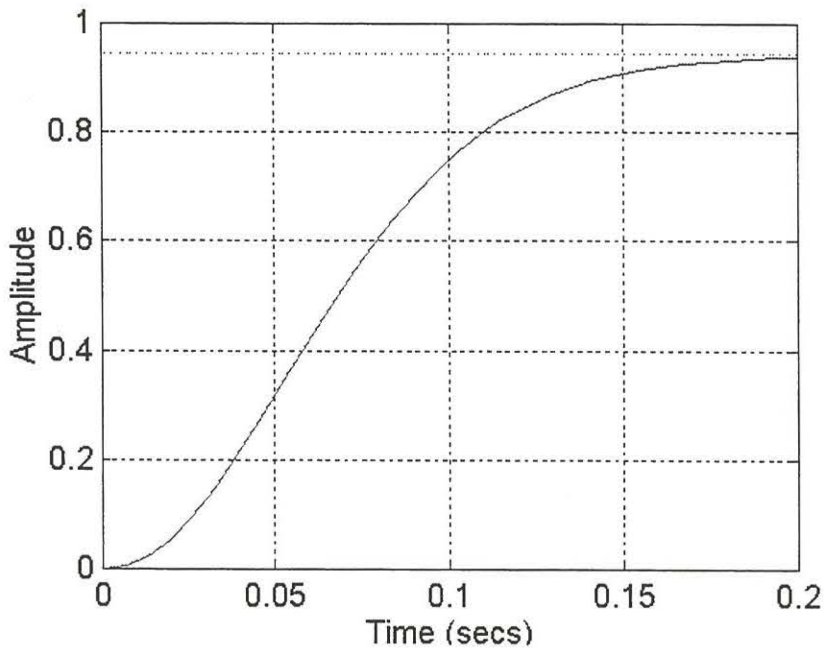

Figure 7: The step response of the pressure transmitter transfer function derived through modelling.

5. CONCLUSIONS

The response times of two Rosemount DP cells (models 1152 DP6A22PBCE and 1152 DP5A22PBCE) have been accurately estimated by analyzing high-frequency pressure measurements on the high and low side of the cells. For both cells, the frequency response follows approximately a $1/(1+ s\tau)^2$ form. Using a non-parametric approach, the response time is estimated to be 86 ms for the SDS1 DP cell and 115 ms for the FINCH DP cell. A parametric estimate for the SDS1 DP cell gave a response time of 78.6 ms, in close agreement with the non-parametric estimate. Some of the difference in response times between the SDS1 and FINCH DP cell can be accounted for the fact that, while both cells are Rosemount DP model 1152 DPA22PB, the SDS1 cell has a URL of 0 - 690.0 kPa whereas the FINCH cell has a much smaller URL of 0 - 186.0 kPa. The electronic gains within the cells are also quite different as the spans are 71% and 41% of their URLs respectively. Differences in the response times may also be due to other factors such as manufacturing tolerances.

It is noted that the pressure variations across the cell that make it possible to estimate the response time were large, suggesting that this response time estimate is correct for large changes in pressure. This is an important point since it is large changes in pressure that are considered in safety analysis. These results suggest that the 200 ms response time specified by Rosemount for this DP cell and measured using the instrument-air step-response method is conservative.

The response times mentioned in this report only apply to the DP cells themselves, without accounting for the responses of other portions of the system. In particular, the time for the hydraulic pressures to travel the length of the impulse line must also be included in any safety or transient analysis. For a typical 40 m impulse line at 25°C, filled with heavy water at 9 MPa, this additional delay time is about 25 ms.

For future safety analysis (and for control analysis where applicable), it is suggested that the response time of each pressure transmitter be verified individually, since the scales and internal gains of the pressure transmitters used will make the actual response time of the DP measurements system change. For the SDS1Rosemount Model 1152 DP cell analyzed above, it is reasonable and highly conservative to use either a single response time of 105 ms (giving 20% allowance for uncertainty to the above calculated value) or dual time constants of 50 ms as suitable approximations to flow measurements. For the FINCH channel flow measurement analyzed, a single response time of 140 ms or dual time constants of 65 ms may be used.

6. ACKNOWLEDGEMENTS

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Working Party No. 16 WPIR No. 1636

7. REFERENCES

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