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MEASUREMENT OF THE DYNAMIC RESPONSE OF DIFFERENTIAL PRESSURE TRANSMITTERS USING A RESPONSE TIME TESTER

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ABSTRACT

AECL's response time tester (RTT) for pressure and differential-pressure (DP) transmitters provide a simple, fast and accurate means of measuring pressure transmitter *step response time* and *response time characteristics* as defined in ISA Standard ISA-S67.06. The step response method of measuring response time is used by all prominent sensor suppliers and provides a result that is readily understood. The measurement of response time characteristics, which includes the transfer function, provides a complete and sensitive characterization of the dynamic response of the sensor that can be used to predict the response to ramps or any other transient.

The AECL Model 200 RTT uses standard instrument air as the source of test pressure, and is suitable for testing transmitters that operate at pressures less than 650 kPa. It can accurately measure step response times in the range of 20 to 2000 ms. It is thus capable of measuring the response times of most of the pressure instruments in the CANDU safety systems. The Model 200 RTT is completely contained in a cabinet that can be easily moved on built-in shock-absorbent wheels, to facilitate testing transmitter while on the bench or mounted on the instrument rack.

The RTT comprises pressurized components in the front end, and computerized data acquisition components and analysis software in the back end. Tests are conducted by switching the pressure applied to the transmitter between two values using a long-life, fast-acting 3-way solenoid valve. The actual pressure applied to the transmitter is measured with a high-frequency reference transducer.

Once the operator has connected the air supply and transmitter, and set the test pressures, the actual testing and analysis proceeds automatically. Four sets of tests are conducted. A number of comparisons, as required by ISA-S67.06, are made to verify that:

- the transmitter is linear with respect to direction and rate of change, and
- the results are consistent between two diverse test methods.

The broadband noise tests are used to find the transfer function (all the significant time constants) of the transmitter. Given the transfer function, the expected response to a step input can be computed and compared to the measured step response, thus verifying both measurements. The results are summarized and printed on the built-in printer. Files are saved to disk for later review.

1. INTRODUCTION

Every CANDU reactor had two independent and diverse safety shutdown systems (SDS1 and SDS2) which act to mitigate potentially dangerous situations in a safe manner by rapidly shutting down the reactor whenever operation outside the safe range is detected. SDS1 drops shutoff rods into the reactor, while SDS2 injects liquid poison into the moderator. Both SDSs are channelized and operate in a two-out-of-three logic mode. An SDS consists of a chain of elements, namely, primary sensors (transmitters), alarm detection, Boolean logic and the final mitigating device. A major safety consideration is the speed with which the SDS acts. This speed consists of the response times of all the various elements in the SDS chain.

Several of the primary sensors measure pressures, levels or flows within the reactor system. All three types of measurement are pressure-based. Flow is measured by the differential pressure (DP) across an orifice plate, while level is measured by the DP caused by the fluid gravitational head. A list of these pressure-based sensors for the Ontario Hydro CANDU stations is given in Table 1 along with their ranges.

ISA Standard S67.06 [1] describes methodologies for measuring response times of the various SDS elements. AECL has designed and built a commercial instrument which provides a simple, fast and accurate means of measuring pressure (and DP) transmitter *step response time*[1] and *response time characteristics*[2] conforming to ISA Standard ISA-S67.06. The step response method of measuring response time is used by all prominent sensor suppliers and provides a result that is readily understood. The measurement of response time characteristics, which includes the transfer function, provides a complete and sensitive characterization of the dynamic response of the sensor that can be used to predict the response to ramps or any other transient.

This paper discusses a new AECL Response Time Tester (RTT) for pressure (and DP) transmitters. Other methods of measuring response times, e.g., noise analysis, are discussed elsewhere.

2. DESCRIPTION OF AECL RESPONSE TIME TESTER

The AECL Model 200 RTT is a newly designed commercial instrument which uses standard instrument air as the source of test pressure, and is suitable for testing transmitters that operate at pressures less than 650 kPa. Thus it is suitable for all SDS pressure transmitters, except the last two items on Table 1 (BFLP and PHT pressure), which require pressure

[1] *Step response time* in ISA S67.06 is defined as: "Of a system or a component, the time required for an output to go through a specified percentage of the total excursion either before, or (in the absence of overshoot) as a result of a step change in the input."
[2] *Response time characteristics* is defined in ISA S67.06 as: "Those properties (e.g., transfer function, time constant, delay time, power spectral density) of the equipment from which its response time can be determined." In this report, *response time characteristics* shall refer to the transfer function and its associated time constants.

sources in the several megapascal range. Item 6 (PHT DP) is marginal; it can be tested over one third of its range using the RTT.

Table 1: Ontario Hydro Safety System Parameters Measured using Pressure Sensors

Parameter	Station	SDS1 (kPa)			SDS2 (kPa)		
		zero	high	span	zero	high	span
1. PHT flow	DNGS	0	141.5	141.5	0	141.5	141.5
	BNGS B	0	120	120	n/a	n/a	n/a
	PNGS B	0	550	550	n/a	n/a	n/a
2. pressurizer level	DNGS	-112.08	-43.68	68.4	-112.15	-44.14	68.01
	BNGS B	-105.8	-33.99	71.81	-105.8	-33.99	71.81
	PNGS B	n/a	n/a	n/a	n/a	n/a	n/a
3. boiler level	DNGS	-52.42	-14.25	38.17	-58.37	-14.2	44.17
	BNGS B	-73.1	-16.4	56.7	-73.1	-16.4	56.7
	PNGS B	-41.52	-9.45	32.07	-41.64	-9.37	32.27
4. moderator level	DNGS	-20.3	-5.63	14.67	-37.94	-18.74	19.2
	BNGS B	n/a	n/a	n/a	n/a	n/a	n/a
	PNGS B	n/a	n/a	n/a	-17.28	-20.14	2.86
5. Reactor building pressure	DNGS	n/a	n/a	n/a	n/a	n/a	n/a
	BNGS B	n/a	n/a	n/a	n/a	n/a	n/a
	PNGS B	-5.0	5.0	10.0	-5.0	5.0	10.0
6. PHT DP	DNGS	n/a	n/a	n/a	n/a	n/a	n/a
	BNGS B	n/a	n/a	n/a	0	2000	2000
	PNGS B	n/a	n/a	n/a	0	1500	1500
7. BFLP	DNGS (1-4)	15	8015	8000	15	8015	8000
	DNGS (5)	3885	7885	4000	-124	7876	8000
	BNGS B	2037	7032	4995	2037	7032	4995
	PNGS B	2500	5500	3000	2500	5500	3000
8. PHT pressure	DNGS	129	14129	14000	129	14129	14000
	BNGS B	4000	12000	8000	4000	12000	8000
	PNGS B	4080	10080	6000	3160	12160	9000

PHT = Primary Heat Transport
BFLP = Boiler Feedline Pressure

The AECL Model 200 RTT can accurately measure step response times in the range of 20 to 2000 ms. It is thus capable of measuring the response times of most of the pressure instruments in the CANDU safety systems. For example, according to the manufacturer, the Rosemount model 1152 transmitters commonly used in CANDU stations have a response time between 200 and 2000 ms depending on the setting of the adjustable damping potentiometer.

The Model 200 RTT is completely contained in a cabinet that can be easily moved on built-in shock-absorbent wheels to facilitate testing transmitters while on the bench or mounted on the instrument rack.

The RTT comprises pressurized components in the front end, and computerized data acquisition components and analysis software in the back end. Figure 1 shows a simplified schematic. Tests are conducted by switching the pressure applied to the transmitter between two values using a long-life, fast-acting 3-way solenoid valve. The actual pressure applied to the transmitter is measured with a high-frequency reference transducer. Both the solenoid valve and the reference transmitter are at the end of a 3 m "umbilical", which carries both pneumatic and electrical signals. The umbilical performs two important functions. It provides a storage reservoir for the pneumatic pressures, thus minimizing pressure disturbances which might occur when the solenoid valve switches. It also allows the solenoid and the reference transducer to be located very close to the transmitter under test (TUT) under all circumstances, including when the TUT is installed in its normal place in the transmitter rack in the instrument room. The distance from the solenoid to the TUT is less than 20 cm.

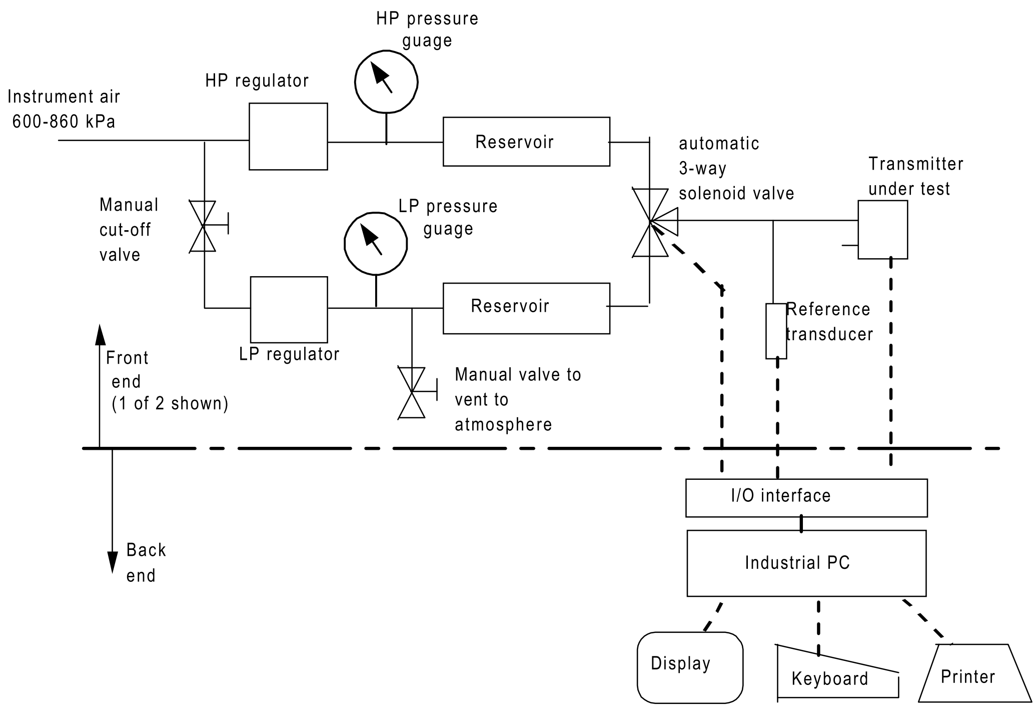

Figure 1: Simplified schematic of Response Time Tester

The two test pressures are set manually by a pair of regulators (unless one of them is zero, i.e., atmospheric, in which case a valve is used to vent to atmosphere), each of which is associated with a pressure gauge. The regulators are adjusted so that both test pressures fall within the calibrated range of the TUT. For the transmitters with a range from one positive or zero pressure to another positive pressure, e.g., primary heat transport (PHT) flow, the test pressure is applied to the high side of the DP cell, leaving the low side open to atmosphere (Figure 2a). For the level transmitters in a CANDU, the calibrated range is from one negative pressure difference to another negative pressure difference. Pressures within these ranges are achieved by feeding the RTT pressure into the low side of the TUT while leaving the high side open to atmosphere (Figure 2b). Thus the RTT is able to test the response times of the transmitters without requiring any change to their normal calibrations. Also, testing of response times should not affect calibration as all tests are conducted with pressures within the normal transmitter range.

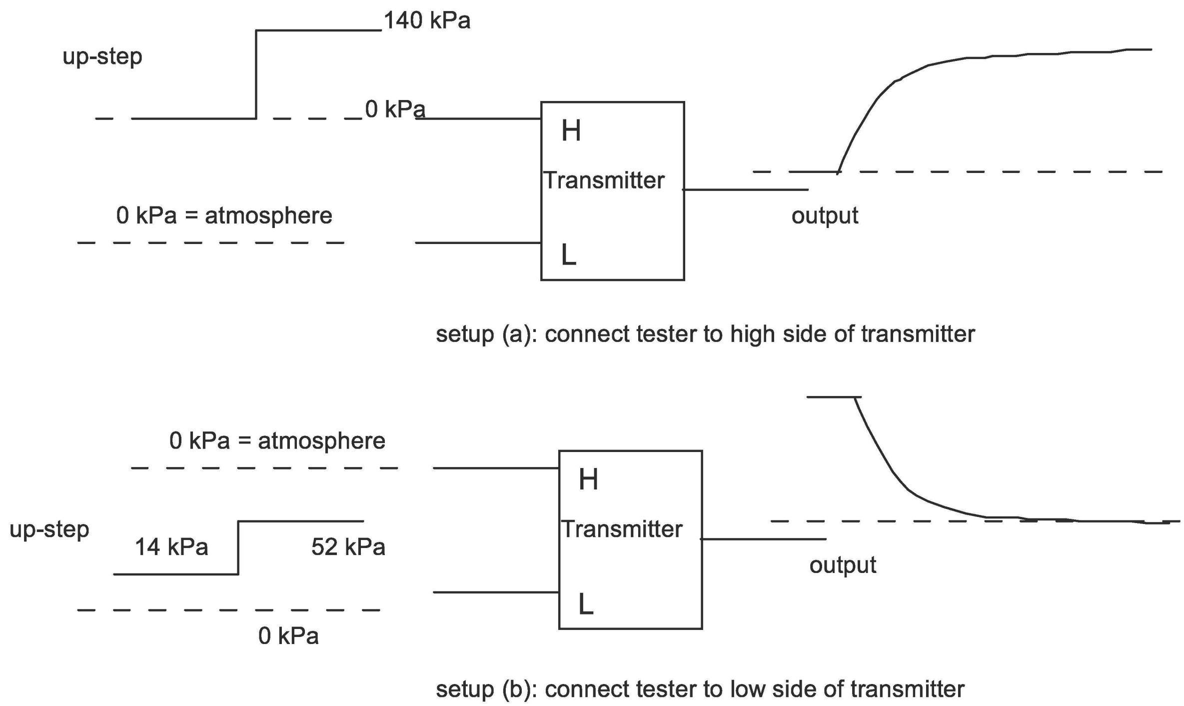

Figure 2: Connections to transmitter under test to achieve required test pressures
(a) DP cell with "zero" at 0 kPa and positive full scale (e.g., PHT flow),
(b) DP with a negative "zero" and a negative full scale (e.g., boiler level).

In fact, the RTT contains two similar front ends, only one of which is used at a time. One front end is for pressures below 100 kPa (low range) while the other is for pressures up to 650 kPa (mid-range). Both are contained within the single cabinet. Cabinet space is allocated for a third front end for high pressure applications, e.g., up to 10 MPa, and thus cover all the pressure transmitters in a CANDU SDS.

3. THEORY

3.1 General

In general, the response of any linear system can be obtained using Laplace transform theory. The linear system can be characterized by a transfer function, which has time constants as parameters:

$$F(s) = \frac{K(1+s\tau_a)(1+s\tau_b)\cdots}{(1+s\tau_1)(1+s\tau_2)\cdots} \qquad (1)$$

where $F(s)$ is the transfer function,
s is the Laplace variable (s^{-1}),

τ_a, τ_b ... are the numerator time constants (s),
τ_1, τ_2 ... are the denominator time constants (s), and
K is the gain.

Because this RTT instrument is dealing only response times and not calibration, the gain, K, of the transfer function is normalized to unity for simplicity.

The time constants are most often real numbers, but may also occur in complex conjugate pairs. In this latter case, we have an underdamped second-order (sub)system, which is characterized by a damped sinusoidal (oscillatory) response.

The Laplace variable s can also be thought of as a complex frequency:

$$s = j\omega = j2\pi f \qquad (2)$$

where ω is the angular velocity (rad/s),
f is the frequency (Hz), and
$j = \sqrt{-1}$.

The output of a system is related to its input by:

$$Y(s) = F(s)X(s) \qquad (3)$$

where $X(s)$ is the Laplace transform of the input $x(t)$, and
$Y(s)$ is the Laplace transform of the output $y(t)$.

3.2 Step response

The response of a simple first-order system to a step input at time, $t = 0$, is shown in Figure 3. In this case, the transfer function is simply:

$$F(s) = \frac{1}{(1 + s\tau)} \qquad (4)$$

The response to a unit step input is given by:

$$y(t) = 1 - e^{-t/\tau} \qquad (5)$$

The output $y(t)$ reaches 63.2% of its final value in time τ, 90% of its final value in time 2.30τ, 95% of its final value in time 3.00τ, and 99% of its final value in time 4.61τ (Table 2).

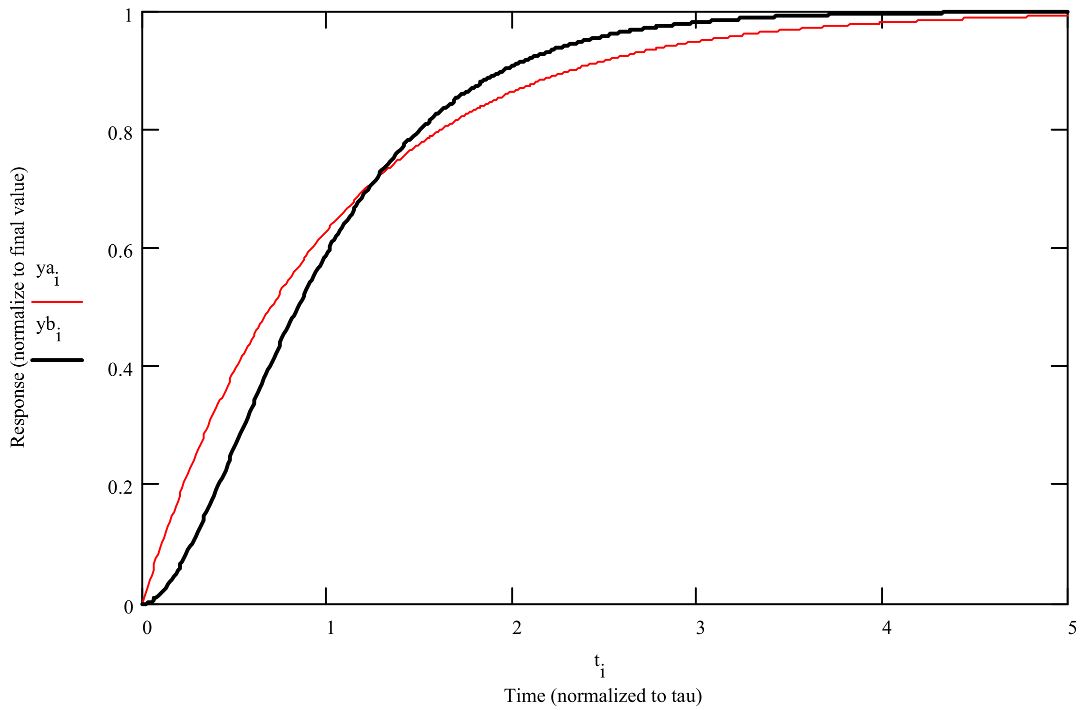

Figure 3: Comparison of first- and second-order step responses;
first-order system (light line) has time constant τ, and
second-order system (heavy line) has two equal time constants of 0.5τ.

However, for more complex systems (and no pressure transmitter measured to date is simple first-order) having more than one time constant, the relationship is not so simple. For example, for a system having two equal time constants ($\tau_1 = \tau_2 = 0.5\tau$):

$$F(s) = \frac{1}{\left(1+s\frac{\tau}{2}\right)^2} \tag{6}$$

The response is given by (Figure 3):

$$y(t) = \left(1+\frac{2t}{\tau}\right)\left(1-e^{-2t/\tau}\right) \tag{7}$$

The output *y(t)* reaches 63.2% of its final value in time 1.07τ, 90% of its final value in time 1.95τ, 95% of its final value in time 2.37τ, and 99% of its final value in time 3.32τ (Table 2). Note that the 63.2% value is slightly greater (7%) than the sum of the two time constants, while the 99% value is considerably (28%) less than 4.61 times the sum of the time constants. Step response times of non-first-order systems should not be converted from one measurement basis (e.g., 63.2%) to another measurement basis (e.g., 99%); significant errors may result.

Table 2: Comparison of first- and second-order step responses; first-order system has time constant τ, and second-order system has two equal time constants of 0.5τ.

Response % of final value	First-order system τ	Second-order system τ	Difference %
63.2	1.00	1.07	+7
90	2.30	1.95	-15
95	3.00	2.37	-21
99	4.61	3.32	-28

In spite of these complications, it is still useful to consider step response times to various percentages of the final result. The AECL RTT outputs step response results for these three values (63.2%, 90%, 95%) which are common in the industry.

3.3 Ramp response

The response of a simple first-order system to an unterminated ramp input starting at $t = 0$, is shown in Figure 4. The response to a unit ramp input is given by:

$$y(t) = t - \tau\left(1 - e^{-t/\tau}\right) \tag{8}$$

For long times, where $t >> \tau$ (practically $t > 5\tau$), then the response approaches:

$$y(t) = t - \tau \tag{9}$$

which is a ramp parallel to the input ramp but delayed by τ. The delay between when the input passes a particular setpoint and the output passes that same setpoint is simply τ. Symbolically, we write this as:

$$\Delta T_{ramp} = \tau \tag{10}$$

where ΔT_{ramp} = (long time) ramp response time

This analysis can be generalized for any order of transfer function giving the ramp response time as:

$$\Delta T_{ramp} = \sum_{\substack{denominator\\terms}} \tau_i - \sum_{\substack{numerator\\terms}} \tau_j \tag{11}$$

The (long time) ramp response is the sum of all the time constants with the numerator terms treated as negative.

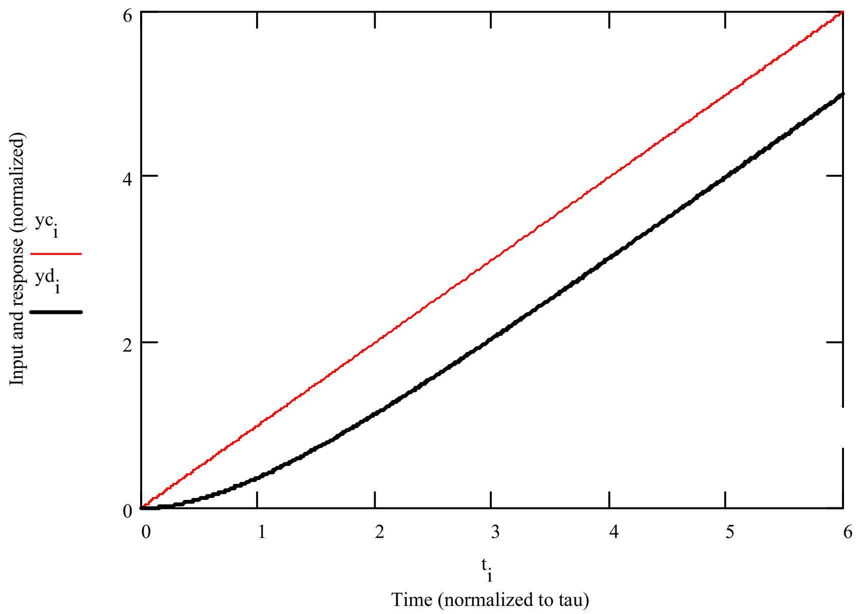

Figure 4: Response of a first-order system to a unit ramp input; light line is the input ramp; heavy line is the response. Note that input and response are parallel after *t* = 5.

If all time constants are real, then this ramp response time is the maximum ramp delay which occurs between input and output. If there are underdamped second-order terms (complex conjugate pairs of time constants), then the ramp response time, may not be the maximum delay between input and output ramps.

The AECL model 200 RTT calculates the ramp response time given by equation 11 from the results of the broadband noise tests (see next section).

3.4 Frequency response

If a system is stimulated by broadband noise, the frequency response can be obtained using Fourier transformation, and complex division.

$$F(j\omega) = \frac{Y(j\omega)}{X(j\omega)} \tag{12}$$

where $Y(j\omega)$ is obtained by Fourier transformation of the output signal $y(t)$, and
$X(j\omega)$ is obtained by Fourier transformation of the input signal $x(t)$.

The frequency response is a series of complex values at a corresponding set of frequencies. The frequency response is commonly plotted as a Bode plot, which consists of two curves: gain and phase. The gain curve is usually plotted as a log-log plot. The phase curve is usually plotted as a semi-log plot. Alternatively, the gain may be expressed logarithmically in decibels (dB), in which case the gain plot is also semi-log. The plots obtained from the RTT use this latter approach.

$$G(\omega) = 20\log\left(\left|F(j\omega)\right|\right) \tag{13a}$$

$$\theta(\omega) = \frac{180}{\pi}\arctan\left[\frac{\mathrm{Im}\left(F(j\omega)\right)}{\mathrm{Re}\left(F(j\omega)\right)}\right] \tag{13b}$$

where G is the gain (dB),
θ is the phase (degrees),
Re is the real part, and
Im is the imaginary part

3.5 Curve fitting

This frequency response can then be fitted to a transfer function of the form given in equation 1. The fitting is done to a series of orders (number of time constant terms), with 1 to 4 terms in the denominator, and 0 or 1 terms in the numerator. The fitting is done following an algorithm similar to that used in MATLAB [2].

The desired transfer function can be written as the ratio of two polynomials in s characterized by coefficients a_n and b_m respectively:

$$F(s) = \frac{K(1+s\tau_a)(1+s\tau_b)\cdots}{(1+s\tau_1)(1+s\tau_2)\cdots} = \frac{B(s)}{A(s)} = \frac{\sum_{m=0}^{M} b_m s^M}{1+\sum_{n=1}^{N} a_n s^N} \tag{14}$$

Note that $a_0 = 1$ by definition.

4. OPERATION OF THE RTT

To get ready for a test, the operator must first:
- isolate the TUT, and dry it out (if wet);
- connect the end of the umbilical to the appropriate port of the TUT (Figure 2);
- connect the two wires at the end of the umbilcal to the TUT terminals;
- connect the air supply to the TUT; and
- plug in the RTT and switch it on.

The computer program starts up automatically. It allows the operator the enter important data such as equipment code, make, model and serial number of the TUT, and its zero and full scale pressures. A database of station-specific information based on equipment code is available as a default set of parameters. The program then presents a checklist for the TUT-umbilcal connection, and instructs the operator how to set the valves and regulators on the RTT. The actual testing and analysis proceeds automatically. Four sets of tests, with pauses between them for manual observation of results and pressure adjustments, are conducted. The four tests are:

- a full-pressure[3] step test,
- a full-pressure broadband noise test,
- a half-pressure[4] step test, and
- a half-pressure broadband noise test.

The step tests consist of 8 steps each consisting of 4 up-steps and 4 down-steps. The step response time is taken as the difference in time between the 50% point of the reference transducer response and the 63.2% point in the TUT response. The 90% and 95% step response times are also computed. The results of the 8 steps are averaged (after identifying any outliers) to give an overall step response time. All information is present on a display which may also be printed on the built-in printer.

The broadband noise tests use pseudo-random binary sequences (PRBS) and fast Fourier transformation (FFT) to find the frequency response of the TUT [3]. Fitting this frequency response to a variable-order transfer function yields all the significant time constants of the transmitter. Given the transfer function, the expected response to a step input can be easily computed and compared to the measured step response, thus verifying both measurements. Given the transfer function, the expected response to a ramp input can also be computed using equation 11. Again, all information is present on a display which may also be printed.

A number of comparisons, as required by ISA-S67.06, are made to verify that:

- the transmitter is linear with respect to direction (by comparing up-steps with down-steps),
- the transmitter is linear with respect to rate of change (by comparing full pressure tests with half pressure tests), and
- the results are consistent between two diverse test methods (steps and broadband noise).

Failure to be sufficiently consistent in these tests results in a diagnostic message. Also, diagnostic messages appear under various other abnormal circumstances, such as a transmitter exceeding its 4-20 mA range, indicating that the regulators were set incorrectly. The operator can readjust a regulator and redo a test as desired.

When all four tests are complete, the results are summarized on a single sheet and printed as illustrated in Figure 5. The final response time ("value for use") is conservatively chosen as the greatest of:

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[3] Full pressure is really between 50 and 90% of full scale.
[4] Half pressure is really between 20 and 50% of full scale.

- measured 63.2% step response time,
- ramp response time calculated from the measured transfer function, or
- 63.2% step response time calculated from the measured transfer function.

Data files are saved to disk for later possible review, and to assist in diagnosing the cause of any anomalies.

Pressure Transmitter Test Results

Work Package No: 1-94-9727-0	CMP: 63742.1	
Equipment Function: PHT Pressure Transmitter	System: SDS1	
Equipment Code: 6-63742-LT-1D	Stock Code: 601W6361	
Manufacturer: Rosemount	Model Number: C1152DP5E22PBCE	Serial Number: L8790
Location: PL 1975	Elevation: 615	Room: 210
Test Equipment: AECL DPRTT Model 200 S/N 1002	Mtce. Info & Dwgs: 63742-7002-004	
Zero Calibration Info: 4 mA = -112.0800 kPa	Span Calibration Info: 20 mA = -43.6800 kPa	
Time of Test: 20:00 Date of Test: 1999/03/03	File Name: Damping Test 1	
Comments: Damping Pot set to Maximum	Diagnostics All Tests Consistent	

Response Times (ms):

	Full Pressure Test:	Half PressureTest:
down pressure (kPa)	50	55
up pressure (kPa)	100	80
step 63%	122	120
time constants: numerator	0	0
denominator 1	81	79
denominator 2	43	45
denominator 3	3	0
denominator 4	0	0
calculated ramp	127	124
calcualted step	133	130
conservative value for use:	**133**	

Operator Name: G. I.Joe	Signature:	Op'r Badge No: 615
Supervisor: G. I.Joe	Signature:	Sup'r Badge No: 615

Figure 5: Summary Form as produced by the RTT

5. CONCLUSIONS

Knowing the response times of the various elements in CANDU safety system, and being able to demonstrate in the field that they are within the bounds used in the safety analysis, are important aspects of CANDU safety. The AECL model 200 Response Time Tester is an excellent instrument for measuring accurately the dynamic characteristics of a pressure (or DP) transmitter. The RTT measures directly step response times to 63, 90 and 95% of final value. It also measures directly, using broadband noise, the frequency response, which is then fitted to a transfer function. From the fit, all significant (i.e., greater than 1 ms) time constants can be obtained. From this fitted transfer function, the response to any input signal including steps and ramps can be easily calculated. The final result is a response time which is the largest (most conservative) of the ramp response time and the 63% step response time, both calculated from the fitted transfer function and the directly measured 63% step response time. The AECL model 200 RTT performs these measurements in conformance with ISA standard S67.06, including performing a number of linearity and validation checks.

Typical safety analysis in Canada currently associates a single time constant to a pressure trip obtained by summing the time constants of the individual components, e.g., impulse lines, transmitter and alarm unit. The time constant of the transmitter is typically taken as either the ramp response time or the 63% step response time. If the transmitter were first-order, these would be identical. However, no transmitter tested to date has been found to be first order, and hence the two values are not identical. The difference for real transmitters has been found to be as large as 25%. By choosing the largest (most conservative) of a number of possible results as its final summary result, the RTT is judged suitable to measure response times directly comparable to the safety analysis values.

The AECL RTT is highly automated. It provides on-line instruction to the operator on connecting the RTT to the TUT and in setting the valves and regulators. Diagnostics attract the user's attention when the setup is incorrect, or the results of the various tests are inconsistent. It provides a printed record and test summary giving the response time (directly comparable to the safety analysis values), as well as all major results (including 63% step response time, ramp response time and the set of time constants found), and any diagnostics.

6. REFERENCES

[1] Instrument Society of America, "Response time Testing of Nuclear Safety-Related Instrument Channels in Nuclear Power Plants", ANSI/ISA-S67.06-1984.

[2] T. P. Krauss, L. Shure, and J. N. Little, "Signal Processing Toolbox for use with MATLAB", The MathWorks, Inc., 1994 February.

[3] C. B. Lawrence and A. Pearson, "Measurement Techniques using a Pseudo-Random Binary Sequence and Fourier Transformation for Determining a System's Transfer Function", AECL-3601, 1970 April.