A MODEL FOR TURBINE HALL PRESSURE RELIEF PANEL

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ABSTRACT

In 1994, NB Power installed engineered pressure relief panels in the Turbine Hall of the Point Lepreau Station. An individual panel must open within a given set period of time to be considered available. In order to judge the effectiveness of the new panels and to define the operating criteria based on in-situ tests, a detailed behavioral mathematical model for the turbine hall pressure relief panel is developed. The mathematical model is converted to various program designs and algorithms. Based on the test performed using these algorithms a program design is selected for modelling these panels.

1 INTRODUCTION

In 1994, NB Power installed engineered pressure relief panels in the Turbine Hall of the Point Lepreau Generating Station. The specification of the number of panels versus location of panels and performance requirements of the panels were based on previous analyses. The pressure relief panels are designed to protect the critical walls of the Turbine Hall for any steam line break. In order to judge the margins of safety and to assess the effectiveness of the new panels against steam balance header breaks, a detailed behavioral model for the turbine hall pressure relief panel is developed.

The engineered pressure relief capability in the form of panels was designed to open at a pressure differential between interior and exterior of 1.0 ± 0.1 kPa. The design criterion for these panels is to achieve a full-open position within 0.25 s of application of static pressure differential of 1.0 kPa.

A totals of 66 pressure relief panels are installed in the turbine hall. There are 43 panels above the floor on which turbine are supported and 23 panels below. Each panel is 1.2 m wide, 2.4 m high, 0.05 m (2") thick, see Figure 1. Panels are hinged at the bottom outer corner (0.007 m inward and 0.007 m higher from the outer bottom edge). The weight of the panel is 32.245 kg (71.1 lb). There are 9 panels facing north at column location L-N11 and bottom edge elevation at 125' (mass centre at 39.41 m). There are 29 panels facing west at column location 11A-17 and bottom edge elevation at 125' (mass centre at 39.41 m) and 5 panels at bottom edge elevation 133' (mass centre at 41.85 m). The 11 panels between column location R17-N and 11 panels between column location N-L face south and have their bottom edge at elevation -5' (mass centre at -0.21 m).

The mass centre of these panels is 1.303 m above the hinge location (1.310 m above the bottom edge). The mass centre is also slightly higher than area centre because of additional weight of the closure and restraining devices at the top edge. Due to the thickness of the panel, the mass centre is -0.82° ($-\sin^{-1} 0.0186/1.303$) from the vertical when in fully closed position. Therefore, the panel must be pushed by 0.82° either by pressure or a mechanical device to open by gravity force. For testing these panels and for non differential pressure assisted opening, two springs of 87 lb/in (15236.04 kg/s^2) each are provided at the top edge, which are compressed to 0.0127 m, i.e., -0.3° ($-\sin^{-1} 0.0127/2.4384$) when the panels are closed. The panel release mechanism is an electromagnet with release force equivalent to 1.0 ± 0.1 kPa. Panels are equipped with a restraining cable that limits travel to 60 degree from vertical in fully open position.

2 MATHEMATICAL MODEL FOR OPENING AREA

When panels are opening, the relief area is between panel edges and the panel frame. If the panel is open by Θ^{o} then the size of rectangular top opening is 1.2 x (2 x 2.4 x sin(Θ/2)) and the size of each triangular side opening is (2.4 x sin(Θ/2)) x (2.4 x cos(Θ/2)). Thus the total open area created between panel and its frame is:

5.76 x sin(Θ/2) x (1 + 2 x cos(Θ/2)). (Equation 1)

However, the maximum relief area cannot exceed the size of the panel frame opening, i.e., 2.88 m^2 (1.2x2.4). Therefore, the open area is given by the above equation for 0 to 16 degrees and is 2.88 from 16 to 60 degrees.

The panels frame inside face is equipped with a coarse grid thin wire bird screen. The grid size is 15 mm by 15 mm and the wire thickness is 1.1 to 1.2 mm. The ratio of the free area to the total area is $(14.425/15)^2$ i.e. 0.925. The critical time for pressure relief is when the panels are opening i.e. 0 to 16 degrees. The area reduction due to the bird screen will not have any effect on the available relief area for the opening angle 0 to 16 degrees. The area reduction due to the coarse thin wire screen (7.5%) for 0 to 16 degrees is small enough that this reduction can be assumed negligible in the calculation of open area.

3 MATHEMATICAL MODEL FOR OPENING TIME

The behaviourial model for the turbine hall pressure relief panel is developed from the Newton's second law of motion, which state;

Force = mass x acceleration

let
m = mass, kg
a = acceleration = du/dt, $m.s^{-2}$
t = time, s
u = velocity = ds/dt, $m.s^{-1}$
s = distance travelled = $L_{cg}\ \Theta$
L_{cg} = distance from hinge to mass centre, m
Θ = angle of opening for panel from vertical
F = force = $F_e - F_b - F_D$, $kg.m.s^{-2}$, N
F_e = external force
F_b = buoyancy force
F_D = drag force

Then the Newton's second law of motion can be written at the mass centre of the panel as:

$$m\ d^2(s)/dt^2 = F_e - F_b - F_D$$

The buoyancy force is due to the air mass replaced by panel volume. The mass of the air (1.24 $kg.m^{-3}$) replaced by the panel is (2.4384 x 1.2192 x 0.0508 x 1.24) 0.187 kg. The mass of the panel is 32.245 kg. Thus, the gravity force will be 172 times larger than the buoyancy force. We assumed:

F_b = buoyancy force = 0.0

The drag force is caused by the air flow around the moving panel. Like the resistance force, the drag force is proportional to velocity^{-2}. The panel velocity between 0 to 16 degree is very small. Even for 16 to 60 degree range the panel velocity will be less than 5 m/s. Therefore, we assumed:

F_D = drag force = 0.0

The external force is a combination of many forces.

F_e = external force = $F_g + F_P - F_w + F_s - F_r$

where:
F_g = gravitational force perpendicular to panel area,
F_P = Pressure force perpendicular to panel area,
F_w = Wind pressure force perpendicular to panel area,
F_s = Spring force applied to panel, and
F_r = Resistance force applied to panel.

Assume:

F_g = gravitational force perpendicular to panel area = $m \cdot g \cdot \sin\Theta$
m = mass of panel, kg
g = acceleration due to gravity = 9.80665 $m.s^{-2}$
F_P = Pressure force perpendicular to panel area = $\Delta P \cdot A \cdot \cos\Theta \cdot L_A / L_{cg}$
ΔP = Pressure difference across panel, Pa, $N.m^{-2}$, $kg.m^{-1}.s^{-2}$
A = Area of panel, m^2
L_A = Distance of the area centre of panel from hinges, m
F_w = Wind pressure force perpendicular to panel area = $\rho \cdot A \cdot (v^2 / 2) \cdot \cos\Theta \cdot L_A / L_{cg}$
v = Wind velocity toward panel face, $m.s^{-1}$
F_s = Spring force applied to panel = $K \cdot y = - K \cdot L_t \cdot \Theta_{sp} \cdot L_t / L_{cg}$
K = spring Hook's constant, $kg.s^{-2}$
L_t = Distance between spring location and hinges, m
Θ_{sp} = Angle of compression for spring = $\Theta_{s0} - \Theta_0 + \Theta$
Θ_{s0} = Initial angle of compression for spring at time = 0
Θ_0 = Initial panel angle at time = 0

The resistance force applied to panel has many components. Most notable of these components are resistance due to drag, resistance at hinges, resistance between panel frame and panel. The resistance force of the above component is proportional of the square of the panel velocity and can be given as $C_r\ (ds/dt)^2$, where C_r is resistance factor for panel and is a constant. Therefore:

$$F_r = C_r \cdot L_{cg}^2 \cdot (d\Theta/dt)^2 \qquad \text{(Equation 3)}$$

Therefore, the equation governing panel opening is:

$$m\, d^2 (L_{cg} \cdot \Theta) / d\, t^2 = m \cdot g \cdot \sin\Theta + \Delta P \cdot A \cdot \cos\Theta \cdot L_A / L_{cg} - \rho \cdot A \cdot (v^2 / 2) \cdot \cos\Theta \cdot L_A / L_{cg} - K \cdot L_t \cdot (\Theta_{s0} - \Theta_0 + \Theta) \cdot L_t / L_{cg} - F_r$$

or,

$$d^2\Theta/dt^2 = g \cdot \sin\Theta / L_{cg} + A \cdot (\Delta P - \rho \cdot v^2 / 2) \cdot \cos\Theta \cdot L_A / (m \cdot L_{cg} \cdot L_{cg}) - K \cdot (\Theta_{s0} - \Theta_0 + \Theta) \cdot L_t \cdot L_t / (m \cdot L_{cg} \cdot L_{cg}) - F_r / (m \cdot L_{cg}) \qquad \text{(Equation 2)}$$

It is possible but not feasible to find an exact solution for Equation 2. It is feasible to solve this equation using various numerical integration schemes. Due to trigonometric functions and sudden change in spring force, many program designs resulted in unstable solution. Four design approaches provide reasonable algorithms for designing this program. First two designs are based on semi exact solution and two are based on explicit integration. Each design has its merits and weaknesses.

4.1 Semi Exact Design for the Program

In Equation 2, g is a universal constant, v and ρ are constant parameters of outside air, L_{cg}, L_A, L_t, A, m, K, Θ_{s0} and Θ_0 are constant parameters of panel design, ΔP and F_r are transient quantities and Θ is the dependent variable.

If we assume that ΔP and F_r can be replaced by their average value during the integration time range, then the above equation can be integrated.

Assume

$$d\Theta/dt = \alpha$$

Then

$$d^2\Theta/d t^2 = d\alpha/dt = d\alpha/d\Theta \ . \ d\Theta/dt = \alpha \ . \ d\alpha/d\Theta$$

$$\alpha \ . \ d\alpha/d\Theta = g \ . \ \sin\Theta / L_{cg} + A \ . \ (\Delta P - \rho \ . \ v^2 / 2) \ . \ \cos\Theta \ . \ L_A \ / (m \ . \ L_{cg} \ . \ L_{cg}) - K \ . \ (\Theta_{s0} - \Theta_0 + \Theta) \ . \ L_t \ . \ L_t \ / (m \ . \ L_{cg} \ . \ L_{cg}) - F_r \ / (m \ . \ L_{cg})$$

Integrating the above equation.

$$\alpha^2/2 = - g \ . \ \cos\Theta / L_{cg} + A \ . \ (\Delta P - \rho \ . \ v^2 / 2) \ . \ \sin\Theta \ . \ L_A \ / (m \ . \ L_{cg} \ . \ L_{cg}) - K \ . \ (\Theta_{s0} \ . \ \Theta - \Theta_0 \ . \ \Theta + \Theta^2 / 2) \ . \ L_t \ . \ L_t \ / (m \ . \ L_{cg} \ . \ L_{cg}) - F_r \ . \ \Theta / (m \ . \ L_{cg}) + \text{Constant} \qquad \text{(Equation 4)}$$

The initial boundary condition is that panel is at rest at time zero i.e. $\alpha=0$ at $\Theta = \Theta_o$.

4.1.1 First design for the Program

Assume that the ΔP and F_r can be replaced by their average value for the duration of the panel opening time. Substituting $\alpha = 0$ at $\Theta = \Theta_o$:

$$0 = - g \ . \ \cos\Theta_0 / L_{cg} + A \ . \ (\Delta P - \rho \ . \ v^2 / 2) \ . \ \sin\Theta_0 \ . \ L_A \ / (m \ . \ L_{cg} \ . \ L_{cg}) - K \ . \ (\Theta_{s0} \ . \ \Theta_0 - \Theta_0 \ . \ \Theta_0 + \Theta_0^2 / 2) \ . \ L_t \ . \ L_t \ / (m \ . \ L_{cg} \ . \ L_{cg}) - F_r \ . \ \Theta_0 / (m \ . \ L_{cg}) + \text{Constant}$$

and

$$\alpha^2 = 2 \ . \ g \ . \ (\cos\Theta_0 - \cos\Theta) / L_{cg} + 2 \ . \ A \ . \ (\Delta P - \rho \ . \ v^2 / 2) \ . \ (\sin\Theta - \sin\Theta_o) \ . \ L_A \ / (m \ . \ L_{cg} \ . \ L_{cg}) + 2 \ . \ K \ . \ (\Theta_0 - \Theta) (\Theta_{s0} + \Theta/2 - \Theta_0/2) \ . \ L_t \ . \ L_t \ / (m \ . \ L_{cg} \ . \ L_{cg}) - F_r \ . \ (\Theta - \Theta_0) / (m \ . \ L_{cg})$$

Therefore:

$$d\Theta/dt = [\ 2\ .\ g\ .\ (\cos \Theta_0 - \cos \Theta) / L_{cg}\ + 2\ .\ L_w\ .\ (\Delta P - \rho\ .\ v^2 / 2)\ .\ (\sin \Theta - \sin \Theta_o)\ .\ L_A\ .\ L_A\ / (m\ .\ L_{cg}\ .\ L_{cg}) + 2\ .\ K\ .\ (\Theta_0 - \Theta)\ (\Theta_{s0} + \Theta/2 - \Theta_0/2)\ .\ L_t\ .\ L_t\ / (m\ .\ L_{cg}\ .\ L_{cg})\ - F_r\ .\ (\Theta - \Theta_0) / (m\ .\ L_{cg})\ ]^{0.5}$$

(Equation 5)

where

L_w = width of the panel, m
ΔP = (pressure in node1 - g * density in node1 * column height from panel centre to node1 centre) - (pressure in node2 - g * density in node2 * column height from panel centre to node2 centre)
g = acceleration due to gravity

The spring is not attached to panel. When Θ_{sp} (Angle of compression for spring) becomes zero at $\Theta = \Theta_{sx} = \Theta_0 - \Theta_{s0}$, no more force is exerted by the spring. For this angle range Equation 2 becomes:

$$d^2\Theta/dt^2 = \quad g\ .\ \sin \Theta / L_{cg}\ + A\ .\ (\Delta P - \rho\ .\ v^2 / 2)\ .\ \cos \Theta\ .\ L_A\ / (m\ .\ L_{cg}\ .\ L_{cg}) - F_r\ / (m\ .\ L_{cg})$$

Integrating the above equation

$$\alpha^2/2 = \quad - g\ .\ \cos \Theta / L_{cg}\ + A\ .\ (\Delta P - \rho\ .\ v^2 / 2)\ .\ \sin \Theta\ .\ L_A\ / (m\ .\ L_{cg}\ .\ L_{cg}) - F_r\ .\ \Theta / (m\ .\ L_{cg}) + \text{Constant}$$

If panel is at moving at the speed of α_{sx} at $\Theta = \Theta_{sx}$ then

$$\alpha_{sx}^2/2 = \quad - g\ .\ \cos \Theta_{sx} / L_{cg}\ + A\ .\ (\Delta P - \rho\ .\ v^2 / 2)\ .\ \sin \Theta_{sx}\ .\ L_A\ / (m\ .\ L_{cg}\ .\ L_{cg}) - F_r\ .\ \Theta_{sx} / (m\ .\ L_{cg}) + \text{Constant}$$

and

$$d\Theta/dt = \alpha = \quad [\ 2\ .\ g\ .\ (\cos \Theta_{sx} - \cos \Theta) / L_{cg}\ + 2\ .\ L_w\ .\ (\Delta P - \rho\ .\ v^2 / 2)\ .\ (\sin \Theta - \sin \Theta_{sx})\ .\ L_A\ .\ L_A\ / (m\ .\ L_{cg}\ .\ L_{cg}) - F_r\ .\ (\Theta - \Theta_{sx}) / (m\ .\ L_{cg}) + \alpha_{sx}^2\ ]^{0.5}$$

(Equation 6)

The algorithm to solve the above equations is:

1) calculate the angle of compression for spring by the equation $\Theta_{sp} = = \Theta_{s0} - \Theta_0 + \Theta$

If Θ_{sp} is less than zero

2-1) calculate $(d\Theta/dt)_t$ using Equation 5
2-2) store value of Θ as possible value of Θ_{sx}
2-3) store value of α as possible value of α_{sx}

else

3-1) calculate $(d\Theta/dt)_t$ using Equation 6

end if

4) calculate $\Theta_{t+\Delta t} = \Theta_t + \Delta t\ .\ (d\Theta/dt)_t$

Note that $d\Theta/dt$ is zero at $t = 0$. Step 4 of the algorithm will result in $\Theta_{0+\Delta t}$ being zero, at the next integration step. Step 2-1 will again predict $d\Theta/dt = 0$ and thus the panel will not move from their initial position. Therefore, the numerical integration for Θ as a function of time is not feasible using the above design without arbitrarily assuming that at $t = 0$, $\Theta = \Theta_o + \varepsilon$ where ε is a small number. The disadvantage of using ε is that the time for panels to move from Θ to $\Theta_o + \varepsilon$ is assumed zero, resulting in a small under prediction of opening time. This under prediction of opening time will increase with an increase in the assumed value of ε. However, because initial force of spring will decrease with increasing values of ε the effect will not be very significant.

The above design needs a value for ε (a small initial offset to start panel moving). Various values starting from one micro degree to 0.1 degree are tested with the above design. The pressure, wind and resistance forces were not modelled. As expected, the predicted panel opening time decreases with an increase in this value. For size less than 0.001 the under prediction is less than 1 millisecond. Therefore, a value of 0.000010 is selected for this design.

The size of time steps will have more significant effect than the value of ε. The value of $\Theta_{t+\Delta t}$ in step 4 is calculated by using the size of time step Δt and the velocity at the start of the time step $(d\Theta/dt)_t$. Given an angle Θ_t the value of $(d\Theta/dt)_t$ is calculated by exact solution. However, the speed is increasing with time, therefore, the average value of speed over the time step will be slightly higher than at the start of the time step. Thus, the opening time will be over predicted. The larger the size of the time step greater will be the error. The design will break down if the size step is larger than the panel opening time (it will still predict some stable number).

We studied the effect of integration time step using an initial offset angle of 0.00001 ° on the time for panel to drop to 60° from vertical. The pressure, wind and resistance forces were not modelled. As expected, the predicted values were higher for higher values for the time step. For time steps less than 0.001 s, the variation in the time for panel opening is within 4 milliseconds. To ensure that the PRESCON2 large time steps will not over penalizes the panel behaviour, and to ensure that the application of pressure force and the wind force will not further deteriorate the situation, the maximum time step for this model is restricted to less than 0.0001 s.

There is a known weakness in this design, if used with very large time steps, that the sudden large jump across $\Theta_{sp} = 0$ can result in not having sufficient velocity to cross the $\Theta = 0$ threshold to ensure that the gravity force will open the panel. This weakness will not have any effect if the pressure force is much stronger than wind force. The use of 0.0001 s maximum time step ensures that this will not happen in drop test predictions. Therefore, no algorithm is designed to ensure smooth transition across $\Theta_{sp} = 0$.

This design is stable, fast and accurate but has two serious restrictions. Exact solution assumes that pressure and resistance force are constant. During the drop test the value of pressure force will be very small and the variation in pressure force will be negligible. During an accident, the value will vary from 1 to 3 kPa. Therefore, using an average of pressure force from 0 to t for calculating velocity will not have major variation. If the resistance force is small it will also have no affect on predictions. However, if resistance force is so large that it can change results of the drop test from 1 second to 2 seconds the above design will not predict a defendable result. The resistance force is zero at time zero and increases with time as given by Equation 3.

4.1.2 Second design for the Program

The weakness of the first design can be partially removed by assuming that the pressure and resistance force are only constant across the time step but can vary from the present time step to the next time step. This is most widely method used in the numerical integration program. If we assume that Equation 2 is integrated from t-Δ to t, then we can write Equation 4 as:

$$\text{Constant}_{t-\Delta t} = 2 \cdot \text{Constant} = (\alpha^2)_{t-\Delta t} - 2 \cdot [- g \cdot \cos\Theta / L_{cg} + A \cdot (\Delta P - \rho \cdot v^2 / 2) \cdot \sin\Theta \cdot L_A / (m \cdot L_{cg} \cdot L_{cg}) - K \cdot (\Theta_{s0} \cdot \Theta - \Theta_0 \cdot \Theta + \Theta^2 / 2) \cdot L_t \cdot L_t / (m \cdot L_{cg} \cdot L_{cg}) - F_r \cdot \Theta / (m \cdot L_{cg})]_{\Theta \text{ at } t-\Delta t}$$

(Equation 7)

and

$$(\alpha^2)_t = 2 [- g \cdot \cos\Theta / L_{cg} + A \cdot (\Delta P - \rho \cdot v^2 / 2) \cdot \sin\Theta \cdot L_A / (m \cdot L_{cg} \cdot L_{cg}) - K \cdot (\Theta_{s0} \cdot \Theta - \Theta_0 \cdot \Theta + \Theta^2 / 2) \cdot L_t \cdot L_t / (m \cdot L_{cg} \cdot L_{cg}) - F_r \cdot \Theta / (m \cdot L_{cg})]_{\Theta=\Theta t} + \text{Constant}_{t-\Delta t}$$

(Equation 8)

Because, it is normal practice in integration techniques that the integration constant is assumed constant over the range of integration i.e. $\text{Constant}_t = \text{Constant}_{t-\Delta t}$.

The algorithm to solve the above equations is:

1) calculate the angle of compression for spring by the equation $\Theta_{sp} = = \Theta_{s0} - \Theta_0 + \Theta$

2) If Θ_{sp} is less than zero
   calculate spring force
   else
   spring force is zero
   end if

3) calculate $(d\Theta/dt)_t$ using Equation 8 using new values of gravitational, pressure, wind, spring and resistance forces at t and Θ_t but previous value of Constant_t.

4) calculate Constant_t for next time step using Equation 7. (The value will change because pressure and resistance forces will change).

5) calculate $\Theta_{t+\Delta t} = \Theta_t + \Delta t \cdot (d\Theta/dt)_t$

Note that this algorithm is not self starting and Constant_t at t=0 and $\Theta_t = \Theta_0$ must be calculated. Furthermore, velocity is zero at t = 0, thus a small offset (similar to first design) in initial angle will be needed to start panel movement.

The above design is tested to decide an appropriate vale for ε (a small initial offset to start panel moving). The tested values ranged from one micro degree to 0.1 degree. The pressure, wind and resistance forces were not modelled. As expected, the predicted panel opening time decreases with an increase in this value. For size less than 0.001, the under prediction is less than 1 millisecond. Therefore, a value of 0.000010 is selected for this design.

The size of the time step will have much more effect on predicted values in comparison to the first design. Basically we are solving $\Theta_{t+\Delta t}$ in step 5 by using the velocity at the start of the time step $(d\Theta/dt)_t$ calculated in step 3 using the $\text{Constant}_{t-\Delta t}$. Not only the average velocity within a time step will be higher than $(d\Theta/dt)_t$. The value of "Constant" being a function of $(d\Theta/dt)_t$ and Θ_t will also be affected by this under prediction of the velocity.

Because the values are calculated at each time step, the effect of these deviations will be additive and will result in severe over prediction of panel opening time.

We studied the effect of integration time step using an initial offset angle of 0.00001 ° on the time for panel to drop to 60° from vertical. The pressure, wind and resistance forces are not modelled. As expected, the predicted values are much higher when compared with first design. The effect of the time step is small because accuracy gained by using small time steps is balanced by additive nature of error in $Constant_t$. The design failed for time steps 0.05 and 0.1 seconds because of a large jump across $\Theta_{sp} = 0$, resulting in the prediction of no panel opening. The use of 0.0001 s time steps will ensure that this will not happen (but still this design will over predict the opening time by 40%).

4.2 Explicit Integration Design for the Program

In Equation 2, g is a universal constant, v and ρ are constant parameters of outside air, L_{cg}, L_A, L_t, A, m, K, Θ_{s0} and Θ_0 are constant parameters of panel design, ΔP and F_r are transient quantities and Θ is the dependent variable. By combining Equation 2 and Equation 3 we can write:

$$d^2\Theta/dt^2 = g \,.\, \sin\Theta / L_{cg} + A \,.\, (\Delta P - \rho \,.\, v^2/2) \,.\, \cos\Theta \,.\, L_A \; / (m \,.\, L_{cg} \,.\, L_{cg}) - K \,.\, (\Theta_{s0} - \Theta_0 + \Theta) \,.\, L_t \,.\, L_t \; / (m \,.\, L_{cg} \,.\, L_{cg}) - C_r \,.\, L_{cg} \,.\, (d\Theta/dt)^2 / m$$

$$(d^2\Theta/dt^2)_t = F[\,\Theta,\ (d\Theta/dt),\ \Delta P\,]_t$$

$$(d^2\Theta/dt^2)_t = F_t$$

(Equation 9)

Using forward difference formulation, Equation 9 becomes:

$$(d\Theta/dt)_{t+\Delta t1} = (d\Theta/dt)_t + \Delta t_1 \,.\, F_t$$

(Equation 10)

where:

$$(d\Theta/dt)_t = (\Theta_{t+\Delta t1} - \Theta_t) / \Delta t_1$$

(Equation 11)

$$(d\Theta/dt)_{t+\Delta t1} = (\Theta_{t+\Delta t1+\Delta t2} - \Theta_{t+\Delta t1}) / \Delta t_2$$

(Equation 12)

therefore:

$$\Theta_{t+\Delta t1+\Delta t2} = (1 + \Delta t_2 / \Delta t_1)\, \Theta_{t+\Delta t1} - (\Delta t_2 / \Delta t_1)\, \Theta_t + \Delta t_2 \,.\, \Delta t_1 \,.\, F_t$$

(Equation 13)

Equation 13 is not self starting and need values for two previous time steps. Similar expressions are formulated if we used central difference or backward difference techniques. Even with more complex formulation, we cannot formulate a second order differential to be solved for $\Theta_{t+\Delta t1}$ only using the value of Θ_t.

The known boundary conditions are $\Theta_t = \Theta_0$ and $(d\Theta/dt)_t = 0$ at t = 0. There are various designs and most of them will work with small time steps. All of these designs are based on solving d((dΘ/dt)/dt) for (dΘ/dt), and solving (dΘ/dt) for Θ, using a combination of forward, central, backward and more complex numerical formulations for variable step solutions. All these formulations originate from Taylor's theorem which state that if Y and its derivatives are single valued continuous functions of X, then:

$$Y(X+a) = Y(X) + a\, d(Y(X))/dt + 1/2\, a^2\, d^2(Y(X))/dt_2 + 1/6\, a^3\, d^3(Y(X))/dt_3 + ...$$

$$Y(X-b) = Y(X) - b\, d(Y(X))/dt + 1/2\, b^2\, d^2(Y(X))/dt_2 - 1/6\, b^3\, d^3(Y(X))/dt_3 + ...$$

where a and b are small variation from the X value. Thus the forward difference formula, with an error of the order of a, is:

$$Y(X+a) = Y(X) + a\, d(Y(X))/dt$$

(Equation 14)

and the backward difference formula, with an error of the order of a, is:

$$Y(X-b) = Y(X) - b\, d(Y(X))/dt$$

$$Y(X) = Y(X-b) + b\, d(Y(X))/dt$$

$$Y(X+b) = Y(X) + b\, d(Y(X+b))/dt$$

substituting b=a

$$Y(X+a) = Y(X) + a\, d(Y(X+a))/dt$$

(Equation 15)

and the central difference formula (by subtracting second Taylor's expansion from the first), with an error of the order a.b (i.e. a^2 because a and b are very close in numerical value), is:

$$Y(X+a) = Y(X-b) + (a+b)\, d(Y(X))/dt$$

$$Y(X+a+b) = Y(X) + (a+b)\, d(Y(X+b))/dt$$

substituting a+b=x and b=x/2

$$Y(X+x) = Y(X) + x\, d(Y(X+x/2))/dt$$

substituting x=a

$$Y(X+a) = Y(X) + a\, d(Y(X+a/2))/dt$$

(Equation 16)

Among all the designs tested, most designs have a tendency of under prediction of panel opening time. However, proper combination of forward, backward and central difference in the design of a program can control the direction of error (over or under prediction).

4.2.1 Third design for the Program

This design is based on forward difference scheme. Because force is decreasing in early stage of the panel opening and increasing at the later stage of the panel opening, the velocity is over predicted at the early stage (small time step) and will result in under prediction of the panel opening time.

The algorithm to solve the Equation 9 is:

1) calculate the angle of compression for spring by the equation $\Theta_{sp} = \, = \Theta_{s0} - \Theta_0 + \Theta$

2) If Θ_{sp} is less than zero

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        calculate spring force
else
        spring force is zero
end if
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3) calculate $F = F[\, \Theta_t, (d\Theta/dt)_t, \Delta P_t \,]$

4) calculate $\Theta_{t+\Delta t} = \Theta_t + \Delta t \, . \, (d\Theta/dt)_t$

5) calculate $(d\Theta/dt)_{t+\Delta t} = (d\Theta/dt)_t + \Delta t \, . \, F$

We tested the effect of the integration time step on the time for the panel to drop to 60° from the vertical. The pressure, wind and resistance forces were not modelled. As expected, the predicted values start slightly higher, for very small time steps, than first design but are decreasing with an increase in time step size. For a time step of 0.0001 the values are 3 milliseconds smaller than the first design.

4.2.2 Fourth design for the Program

This design is based on calculating velocity using a partial backward difference scheme and angle of opening using a forward difference scheme. Because force is decreasing in the early stage of the panel opening (and increasing at the later stage of the panel opening), the velocity is under predicted in the early stage (small time step) and will result in a slight over prediction of the panel opening time.

The algorithm to solve the Equation 9 is:

1) calculate the angle of compression for spring by the equation $\Theta_{sp} = \, = \Theta_{s0} - \Theta_0 + \Theta$

2) If Θ_{sp} is less than zero

```
        calculate spring force
else
        spring force is zero
end if
```

3) calculate $\Theta_{t+\Delta t} = \Theta_t + \Delta t \, . \, (d\Theta/dt)_t$

4) calculate $F = F[\, \Theta_{t+\Delta t}, (d\Theta/dt)_t, \Delta P_t \,]$

5) calculate $(d\Theta/dt)_{t+\Delta t} = (d\Theta/dt)_t + \Delta t \, . \, F$

We tested the effect of the integration time step on the time for the panel to drop to 60° from the vertical. The pressure, wind and resistance forces were not modelled. As expected, the predicted values start slightly higher, for very small time steps, than the first and third design and are increasing very gradually (because of a partial backward scheme) with an increase in the time step size. The increase is so slow that for a time step of 0.0001 the values are 2 milliseconds smaller than the first design.

5 SELECTION OF DESIGN FOR PROGRAMMING THE PANEL MODEL

The first design is most accurate of all the designs reported in this paper. However, this design is not suitable for present needs because it cannot properly handle the resistance forces.

The second design is suitable for our purpose but is highly "conservative". It will grossly over predict the panel opening time up to the point that it can predict that the panels will not open even if they will open during the field test.

The third design is suitable for our purpose but this design slightly under predicts the panel opening time for the panel drop test. The reason for this under prediction is related to the spring force that is decreasing with time while the increase in gravitational force during the early stage of panel opening is very slow. Because the panel opening speed is slow during the early stage of opening, this early behaviour does have a significant influence on the predicted panel opening time.

The fourth design is also suitable for our purpose and does slightly over predict the panel opening time for drop test. The reason of over prediction of panel drop time for gravity drop test is decreasing force with time during early stage of panel opening.

For incorporation in PRESCON2 and to develop a stand alone program to use for the prediction of the gravitational panel drop test, the third design is selected. This design slightly under predicts (by few milliseconds) the time for gravitational panel drop without resistance force because combined forces applied to panel is decreasing with time in early stage of panel opening. In accident condition the pressure force will be stronger than spring force and will be increasing with time (for aged panels resistance force will also increase with increasing speed of panel opening). Therefore, for PRESCON2 analyses of a secondary circuit break in the turbine building using the third design will over predict the panel opening time.

6 PREDICTIONS OF TIMING FOR GRAVITY DROP TESTS

It is not feasible to test the installed panels with a controlled sustained pressure difference. However it is possible to open the installed panels by selecting the panel's local hand switch to "OPEN" and letting the panel open by a combination of spring force and gravitational force. The time a panel takes to go from the stationary position to its full extension is called the panel drop test opening time or the panel drop time.

A stand alone program based on selected design is used to study the effect of input parameters on the predicted results. For no pressure differential, no wind and no significant resistance to open the panel is predicted to open from closed position to 60° drop (fully open position) in 0.96 s. This time is consistent with the measured time of 1.2 seconds with no spring force and 0.7 second for a push by a pulse pressure (Test 8 and Test 5 in Table 1 of Reference 1).

These panels will be tested in their installed locations. Variation in turbine hall atmospheric condition (e.g. plant operating vs. shutdown) and variation in weather condition will cause a difference in pressure between the inner and the outer face of the panel and can increase or decrease the panel drop time. The pressure difference across the panel at the time of the test will be a sum of the pressure difference due to changes in the environment and the wind pressure. A differential pressure indicator (PDI) is installed near the panels, to measure net pressure across the panel. Therefore, the parameter effecting the panel drop time becomes the reading of PDI value and Resistance Factor.

The effect of small pressure differential is shown in Table 1. Positive pressure inside turbine hall decreases the panel opening time and negative pressure increase the panel opening time. At a pressure of -0.358 kPa(g), the panel opening time is 3.1 s but at -0.359 kPa(g) the panel stopped at 8.76° at 1.64 s.

Table 2 shows the effect of wind velocity. The higher is the wind velocity; the higher is the opening time. At a wind velocity of 27.2 km/h opening time increased to 2.49 s. At a wind speed of 27.4 km/h panel stopped at 8.38° at 1.26 s.

Table 3 documents the effect of the large pressure differentials. The predicted opening time at 1 kPa(g) is 0.243 which agrees with the design specification of 0.25 s for new panels. The opening time at 2.5 kPa(g) is 0.16 s that is well within the operational requirement of within 0.5 s for basement panels. The opening time at 3 kPa(g) is 0.15 s that is well within the operational requirement of within 0.5 s for deaerator tower panels. These time are consistent with the experimentally measured opening time of 0.15 to 0.22 s for large pressures (Test 10 to 12 in Table 1 of Reference 1).

Table 4 shows the effect of wind on the opening time of these panels when the pressure is 1 kPa(g) as specified for the opening set point. The panel opens in 0.32 s for a wind velocity of 100 km/h. At a wind velocity of 146 km/h opening time increased to 1.25 s but at a wind speed of 148 km/h panel stopped at 3.55° at 0.35 s.

Table 5 documents the dependence of the turbine hall panel's drop test timing on the "resistance factor". A value of 200 increases time by a factor of 2. For a threefold increase a value of 450 will be required and a value of 800 will increase drop test time by a factor of four.

REFERENCES

(1) E.E. Dainty, G. Lobay, W. Vincent, G. Plume and R. Morris. "An Investigation of Explovent Panels for New Brunswick Power Corporation", Canada Centre for Mineral and Energy Technology (CANMET), Mining Research Laboratories Report MRL-93-001(CR). 1993 January.

TABLE 1 TIMING FOR PANEL DROP TEST, EFFECT OF SMALL PRESSURE DIFFERENTIAL
Wind velocity = 0, Resistance Factor = 0

Pressure across panel kPa(g)	Opening time s	Opening Angle Degrees
.05	0.7080	60.0
.03	0.7803	60.0
.01	0.8850	60.0
.00	0.9596	60.0
-.01	1.0625	60.0
-.03	1.5638	60.0
-.032	1.7101	60.0
-.034	1.9675	60.0
-.035	2.2381	60.0
-.0354	2.4533	60.0
-.0358	3.0651	60.0
-.0359	(1.6399)	8.7572
-.036	(1.1989)	8.2679
-.038	(0.6675)	6.2490

TABLE 2 TIMING FOR PANEL DROP TEST, EFFECT OF WIND VELOCITY
Pressure Difference = 0, Resistance Factor = 0

Wind Velocity Toward Panel Face, km/h	Opening time s	Opening Angle Degrees
0.0	0.9596	60.0
4.0	0.9663	60.0
10.0	1.0042	60.0
14.0	1.0550	60.0
20.0	1.2055	60.0
27.0	2.2088	60.0
27.2	2.4871	60.0
27.4	(1.2640)	8.380
29.0	(0.5393)	5.3093

TABLE 3 TIMING FOR PANEL DROP TEST, EFFECT OF LARGE PRESSURE DIFFERENTIAL
Wind velocity = 0, Resistance Factor = 0

Pressure across panel kPa(g)	Opening time s	Opening Angle Degrees
.00	0.9596	60.0
1.0	0.2431	60.0
2.0	0.1765	60.0
3.0	0.1456	60.0
4.0	0.1267	60.0
5.0	0.1137	60.0

TABLE 4 TIMING FOR PANEL DROP TEST, EFFECT OF PRESSURE DIFFERENTIAL AND WIND
Pressure Difference = 1.0 kPa(d), Resistance Factor = 0

Wind Velocity Toward Panel Face, km/h	Opening time s	Opening Angle Degrees
0.0	0.2431	60.0
20.0	0.2453	60.0
40.0	0.2520	60.0
60.0	0.2647	60.0
80.0	0.2862	60.0
100.0	0.3237	60.0
120.0	0.4002	60.0
140.0	0.6765	60.0
144.0	0.9081	60.0
146.0	1.2488	60.0
148.0	(0.3551)	3.5548
150.0	(0.1979)	1.7029

TABLE 5 TIMING FOR PANEL DROP TEST, EFFECT OF RESISTANCE FACTOR

Pressure Difference = 0, Wind velocity = 0

Resistance Factor	Opening time s	Opening time increased by a factor
0	0.9596	1.0000
100	1.5234	1.5875
200	1.9811	2.0645
300	2.3721	2.4720
400	2.7198	2.8343
500	3.0366	3.1644
600	3.3299	3.4701
700	3.6046	3.7564
800	3.8640	4.0267
900	4.1106	4.2837
1000	4.3462	4.5292

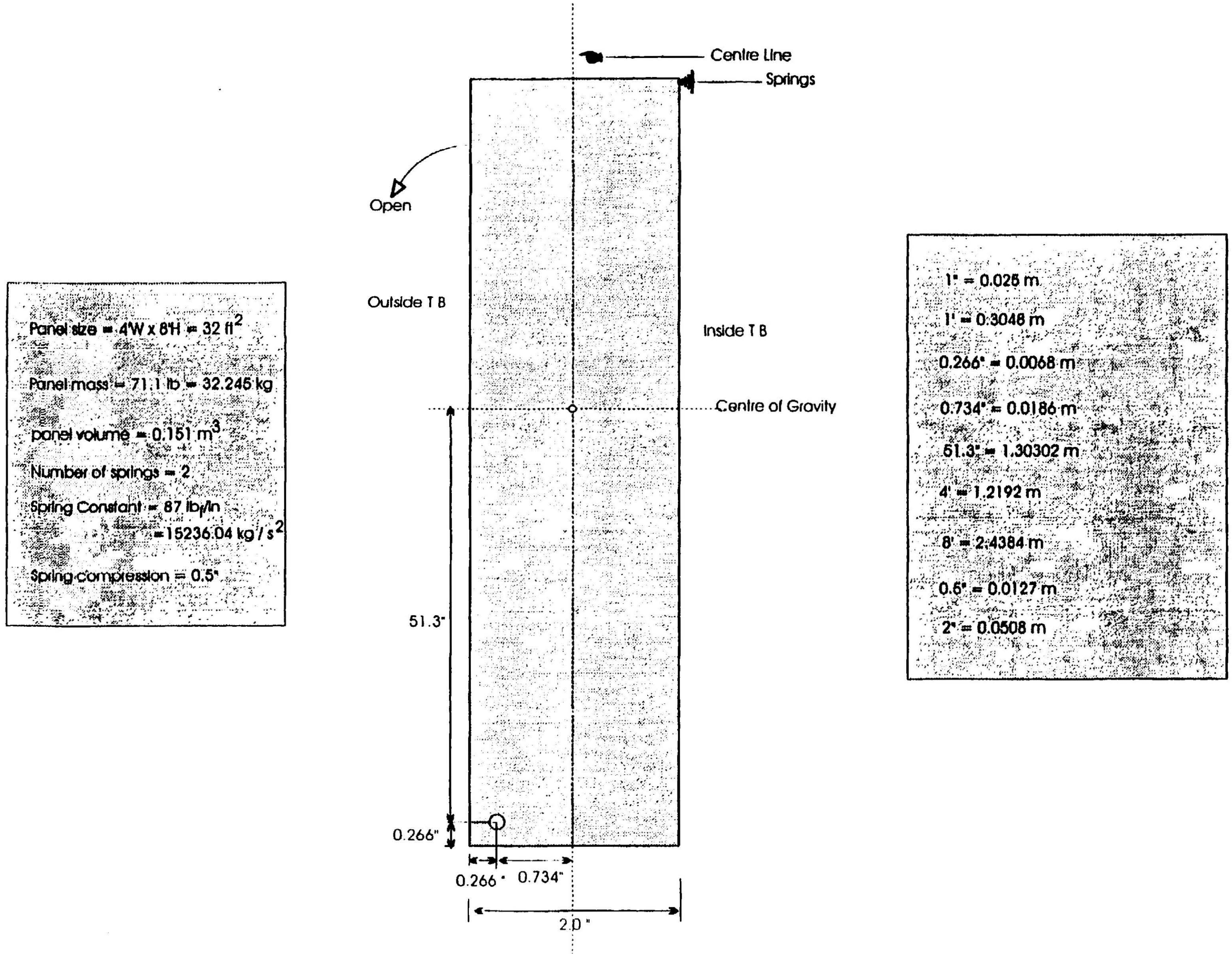

FIGURE 1 TURBINE HALL PRESSURE RELIEF PANEL MODELLING DETAILS