FLUID/STRUCTURE INTERACTION AND TUF CODE VALIDATION

T. Toong
Senior Design Specialist
Ontario Hydro
700 University Avenue
Toronto, Ontario

SUMMARY

In the course of analysis of Steam Generator (SG) divider plate integrity under Loss-Of-Coolant-Accident (LOCA) conditions, it became clear that the pressure differential across the divider plate is strongly affected by the ensuing movement of the divider plate. The effect of the divider plate movement on the thermal-hydraulics has been studied in detail at Ontario Hydro. In this paper, emphasis is placed on the fundamental physics involved in the phenomena.

Two physical problems, which can be solved analytically, are presented in this paper, which may be used for code validation:
1) The first one relates to the fundamental physics of pressure wave propagation generated by the motion of a piston in a pipe,
2) The second one deals with a lumped volume (or node in simulation codes) with inlet and outlet pipes, which is representative of the bowl of a SG with the tubes and the nozzle as inlet and outlet.

Fluid/structure interaction modeling for SG divider plate integrity study has been implemented in the TUF code at Ontario Hydro. The structure-to-fluid part of the coding is tested against these two physical problems. The results have demonstrated the code capability for simulations of fluid/structure interaction problems.

PHYSICAL PROBLEMS

1) Pipe with piston

Consider a pipe filled with liquid with a piston at one end, Figure 1a. Initially the liquid is at rest and at pressure P0. A step change in velocity v is applied to the piston. The resulting pressure wave travels to the right at sonic velocity c. The fluid between the piston and the wave front moves at velocity v and is at pressure P0+ΔP. The fluid beyond the wave-front is of course still at rest and at pressure P0. It can be shown from first principles that ΔP is given by the Joukowski's equation:

$$\boxed{\Delta P = \rho v c} \qquad (1)$$

2) Lumped volume with inlet and outlet pipes

Consider a SG outlet bowl with the tubes and the nozzle as inlet and outlet, Figure 2a. Let V be the volume of the bowl and A′ and A″ be the areas of the inlet and outlet respectively. Let $\dot{V}$ be the rate of volume change due to the movement of the divider plate in the direction shown, ($\dot{V}$=-$\dot{V}$). The increase in pressure in the bowl will cause the fluid to move out via the inlet and the outlet, at a common velocity v. Eventually, the *rate* of volume displaced by the divider plate must be equal to the *rate* of volume of fluid moved out via the inlet and outlet. Therefore

$$\dot{V} = vA \qquad \text{where } A = A' + A'' \tag{2a}$$

Since the pressure waves in the inlet and outlet pipes are governed by (1), substituting v into (1), we get for the final pressure increase ΔP in the bowl

$$\boxed{\Delta P = \rho c \dot{V}/A} \tag{2b}$$

Note that V does not enter into the equation, although V does affect the time it takes for the pressure to reach to that value. This result is significant in that it converts a pressure wave travelling in a pipe to a pressure swell in a lumped volume. It justifies the use of thermal-hydraulic codes for modeling the SG bowl as a lumped volume, or a node, (provided that the LOCA transient pressure wave does not vary too fast.)

TUF CODE VALIDATION

1) Long pipe with plate in center

The pipe is modelled by the TUF code with nodes of equal volumes and lengths, Figure 1b. The plate is situated between nodes 50 and 51, (the pipe is long enough so that there is no reflection coming back from the ends of the pipe in the first milli-second.) The pressure on the left is 9 MPa and on the right is 7 MPa. The plate is given a step change in velocity .9 m/s at time zero. The resulting pressure and velocity transients in the vicinity of the plate are shown in Figures 1c & 1d.

The fluid velocity eventually approaches .9000 m/s, which is the plate velocity, as expected.

The pressure change on the left hand side approaches 788.7 kPa. Comparing this with (1), we have ρ= 793.5 kg/s and c= 1104.9 m/s at average pressure ~8600 kPa, [initial P= 9000, H=1120, T=257.0], therefore ΔP= 789.1 kPa. The difference is therefore .05%.

2) SG bowl with moving divider plate

The TUF nodalization scheme is shown in Figure 2b. Node 51 is the SG bowl, the inlet and outlet flow areas are .2 and .07 m^2 respectively. The divider plate is given a step change in volumetric rate of change .25 m^3/s. The resulting pressure and velocity transients are shown in Figures 2c and 2d.

The flow velocity in the inlet and outlet eventually approach ∓.9260 m/s. From (2a), we obtain v=.25/(.2+.07)=.9259 m/s. The difference is negligible.

The pressure swell approaches 940.3 kPa. Comparing this with (2b), we have ρ= 894.5 kg/s and c= 1135.8 m/s at final presure 9540 kPa, [initial P=8600, H=1040, T=247.8], therefore ΔP= 894.48*1135.82* .9259/1000=940.7 kPa. The difference is .05%.

Notes on Spatial and Temporal Convergence

The resolution in a transient simulation is determined by the node size. For pressure wave applications, it is inversely proportional to the node length L. If c is the sonic velocity, then the time resolution Δt is given by

$$\Delta t \sim L/c \tag{3}$$

which is the time it takes for the pressure wave to travel the node. This sets the limit to the detail to which the simulation can reveal. If the time-step dt used is very small compared to Δt, say dt < $\Delta t/10$, the simulation results will show wiggles or fine structures having a width of about $2\Delta t$. Since these wiggles are nodalization effects and are therefore fictitious, it is desirable to eliminate them. This can be done by not using too small a time-step. A suggested time-step is

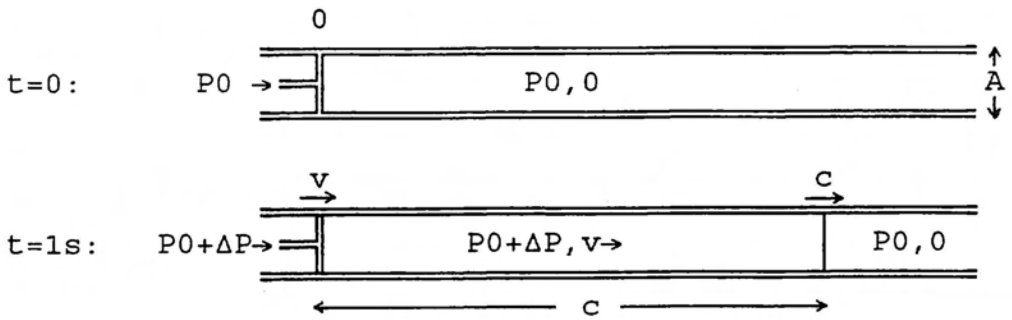
$$dt \sim \Delta t/2. \tag{4}$$

This is the time-step used in the two TUF runs, .05 ms and .5 ms respectively. However it should be noted that using a larger time-step increases the numerical diffusion.

CONCLUSION

The TUF code is validated against the two theoretical physical problems. The results checked out to be better than .1%.

Figure 1a. Physical problem #1: Pipe with piston

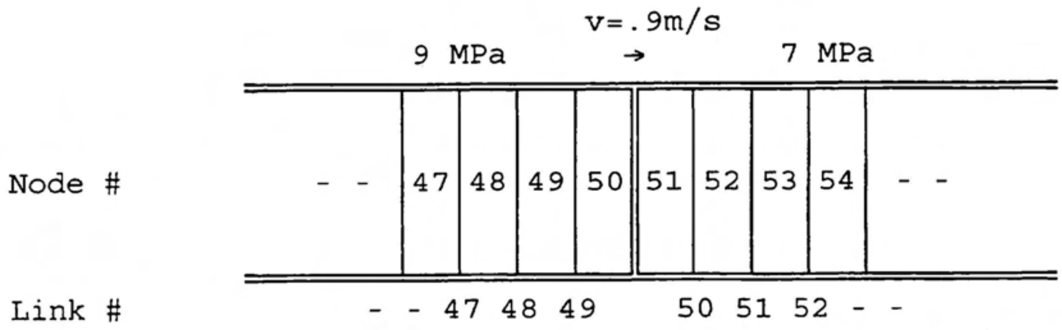


Net force = rate of change of momentum

$$\Delta P * A = A c \rho * v$$

$$\therefore \quad \boxed{\Delta P = \rho v c} \quad \text{Joukowsky's formula}$$

Figure 1b. TUF Nodalization - Long pipe with moving plate



Node length .1m

Figure 1c. TUF Simulation - Long pipe with moving plate
Pressure transient

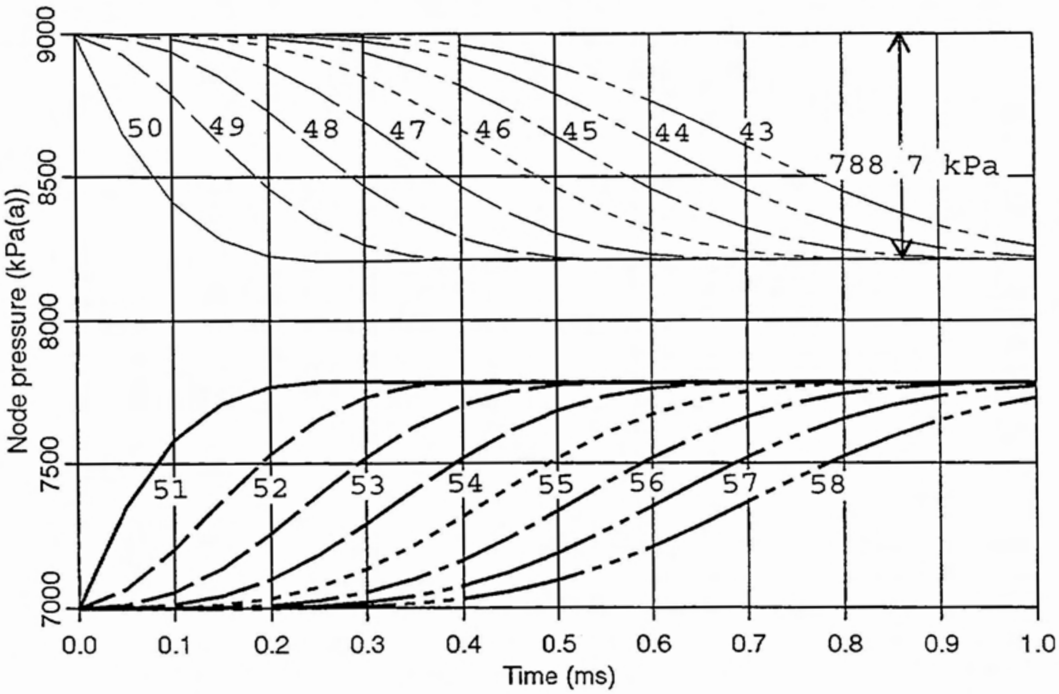


Figure 1d. TUF Simulation - Long pipe with moving plate
Flow velocity transient

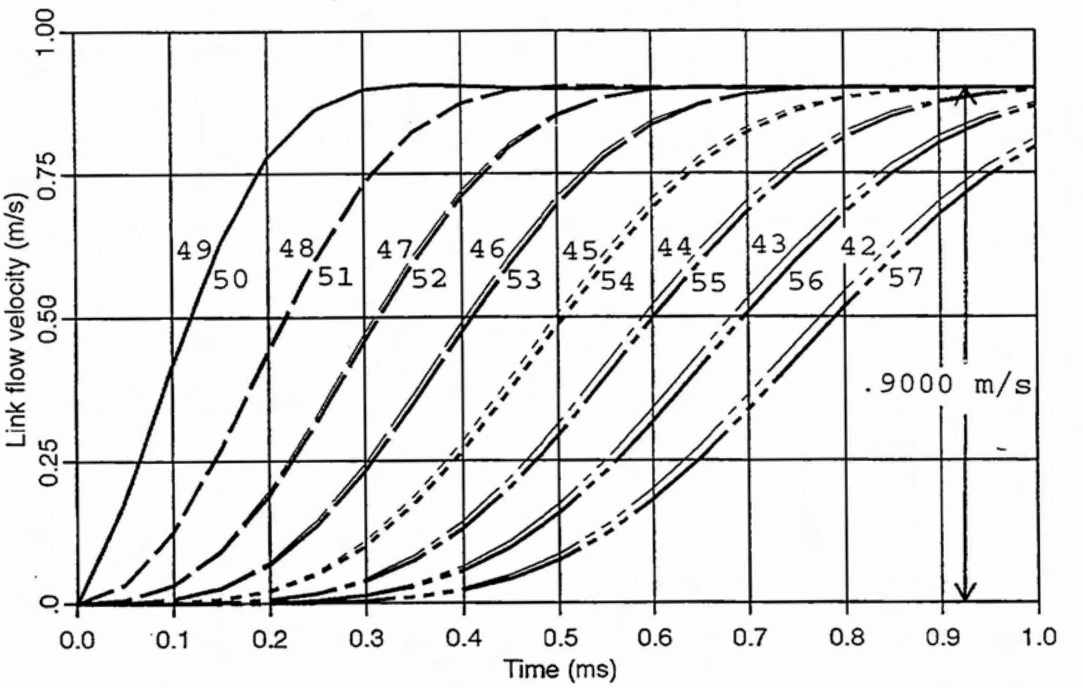


Figure 2a. Physical problem #2:
Lumped volume with inlet and outlet pipes

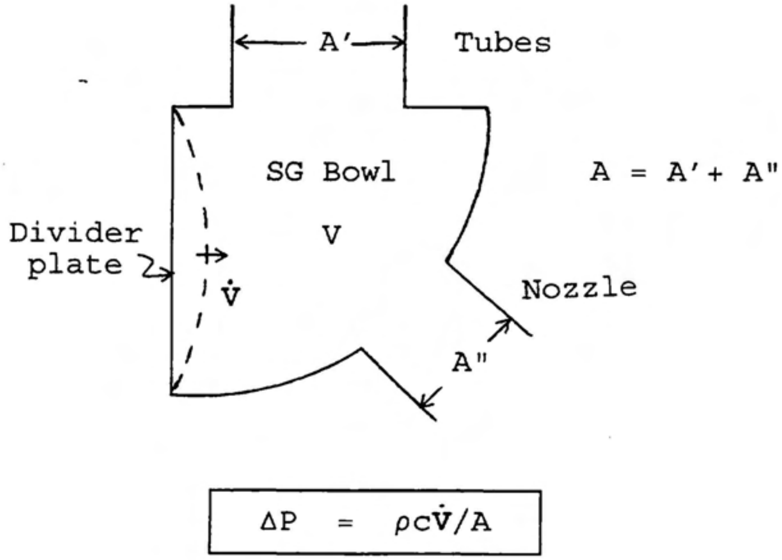
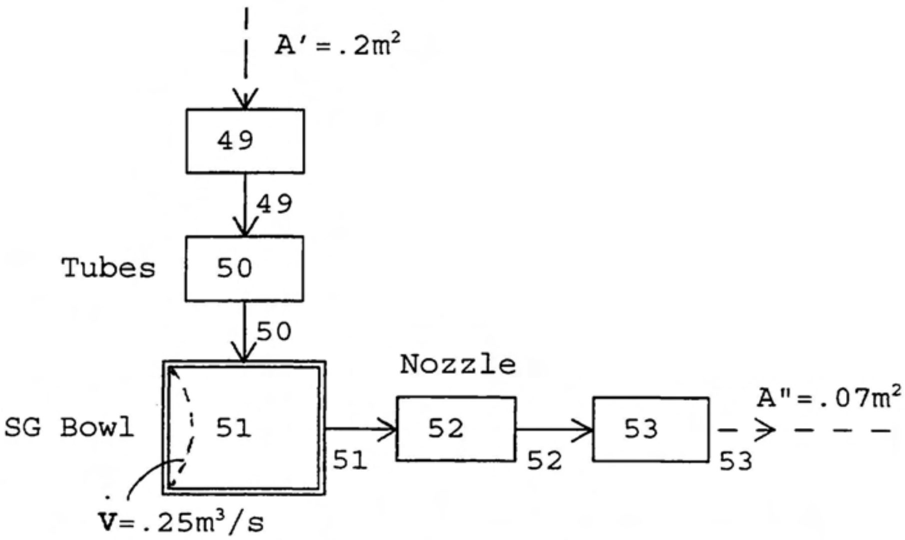


Figure 2b. TUF Nodalization - SG bowl with moving divider plate



SG Bowl V= .5575 m^3, Node length 1m (for all links)

Figure 2c. TUF Simulation - SG bowl with moving divider plate
Pressure transient

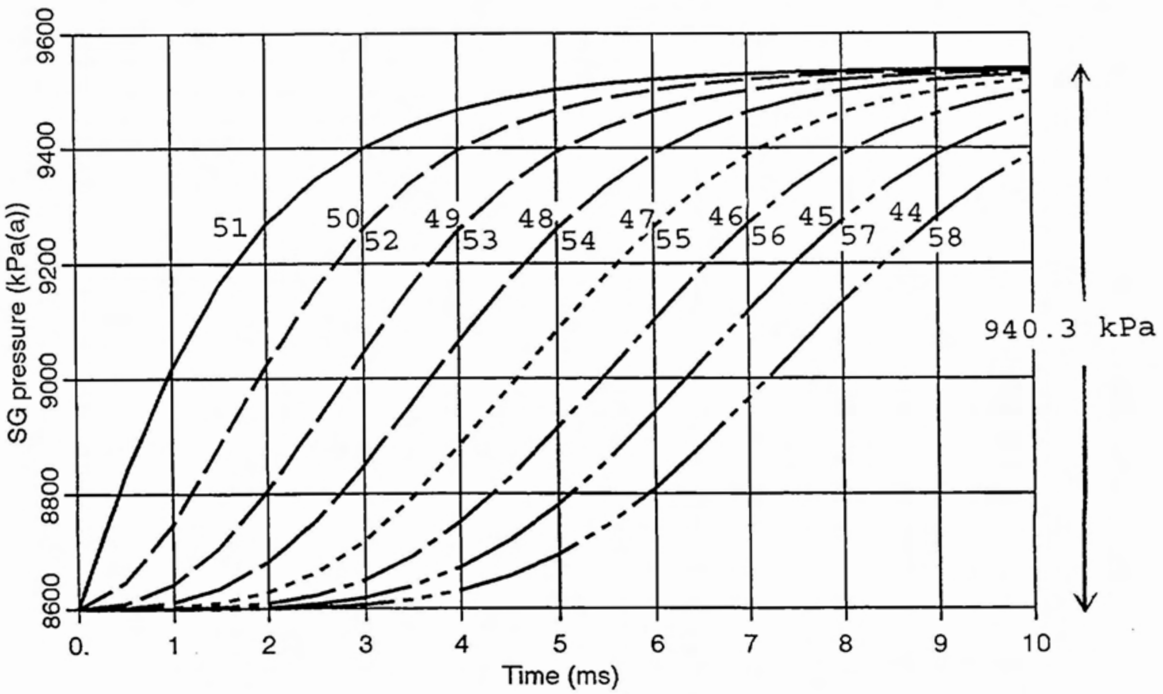


Figure 2d. TUF Simulation - SG bowl with moving divider plat
Flow velocity transient