DESIGN AND MAINTENANCE IN AN IAEA TECHNICAL GUIDELINES ON FLUID-STRUCTURE INTERACTION

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Background

- In nuclear power plants, FSI occurring in component and systems can cause mechanical damage so that FSI had been considered can be important ~~issues~~ for design and maintenance and ~~. They~~ are related to safety issues.
- Authors cannot find comprehensive guidelines to correspond to FSI phenomena which can be important in the design and maintenance of nuclear power plants.
- Based on the background, International Atomic Energy Agency (IAEA) has drafted guidelines on FSI, and the contents are shown by Kim and Ainsworth.
- This paper summarizes: general description of FSI (Section 2) and design and maintenance against FSI (Section 3).

Contents

This paper summarizes general description of FSI (Section 2) and design and maintenance against FSI, in which the following matters are ~~were~~ described:

- Added mass, damping and stiffness
- Vortex induced vibration including design guidelines of thermo-well
- Self-excited vibration including design guidelines for fluid elastic vibration of steam generator tubes and criteria for acoustic resonance at branch pipe
- Forced vibration including design for nuclear fuel assembly and steam generator tubes
- Maintenance method for pipe vibration downstream of pressure control valve and pumps
- Water hammer
- Valve issues
- Pipewhip, which can be an issue at pipe break

Added mass, damping , and stiffness coefficients

- The motion of the surrounding fluid induced by the body motion generates unsteady fluid forces.
- The fluid force:
  - Extraneous fluid force independent of the cylinder motion such as random excitation by turbulence
  - Induced by the cylinder motion itself ⟹ Added mass, damping and stiffness
- **Added mass**: ~~It is lowering~~ lowers the natural frequency, which generally leads to a decrease in the safety margin.
- **Added damping**: It can sometimes be negative for ~~the~~ cases with a mean flow, which causes self-excited vibrations.
- **Added stiffness**: It can be negative for ~~the~~ cases with mean flow, which causes the divergence.

  Cross-coupling of the added stiffness can ~~could~~ sometimes result in occurrence of self-excited vibration and flutter.

Vortex induced vibration including design guidelines of thermo-well

Single cylinder

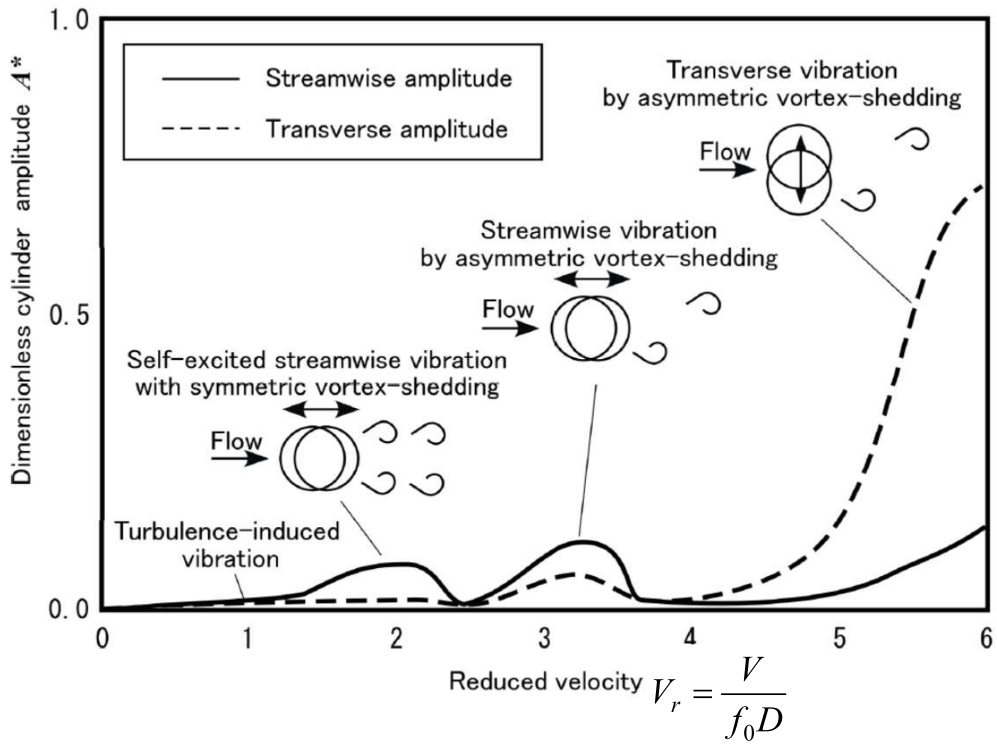
- Thermometer wells and nozzles
- One of the sources causing high-cycle fatigue
- Shedding frequency:

$$f_w = \mathrm{St}\frac{V}{D}$$

- Circular cylinder:

  St = 0.2

  for 300<Re<2x10^5



The rules of JSME to avoid resonance

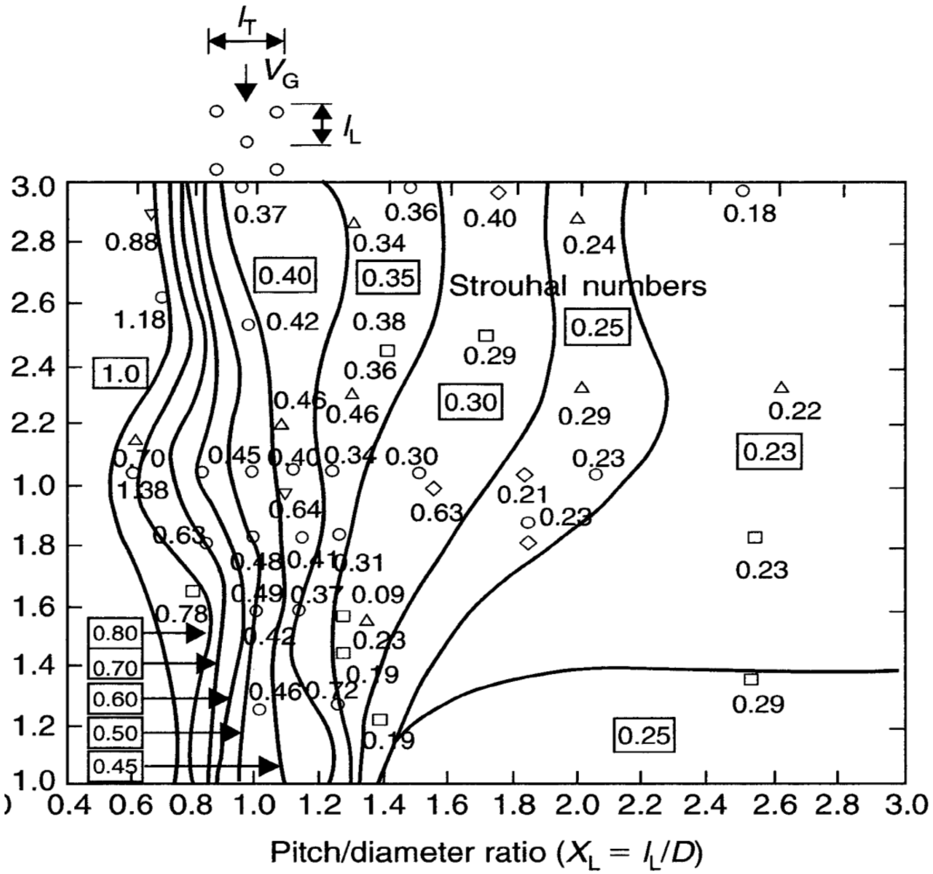
Cond.	ASME	JSME	Remarks
1	$V_r \leq 1$		To avoid resonance
2	$C_n \geq 64$		To prevent resonance
3	$V_r \leq 3.3$ & $C_n \geq 1.2$	$V_r \leq 3.3$ & $C_n \geq 2.5$	To avoid resonance in lift, and to prevent it in drag
4	$\frac{f_0}{f_w} \leq 0.7$ or $\frac{f_0}{f_w} \geq 1.3$	None	To avoid resonance in lift

Vortex-induced vibration of a tube bundle

- St is known to be a function of P/D, and to be a weak function of Re.

- To avoid lock-in the following empirical equation is suggested for design usage in the ASME rules for instance.

$$0.7\,(\text{or}\ 0.8) \le f_w/f_s \le 1.3(\text{or}\ 1.2)$$



Self-excited vibration

- Strong FSI
- One-degree-of-freedom system: the total damping of the combined fluid-structural system vanishes = negative-damping
- Multi-degrees-of-freedom system: Coupled-mode self-excited vibration can also occur
- Major phenomena:
  - **Flutter of pipe containing fluid flow**: whipping of broken pipe
  - **Fluid-elastic vibration of tube bundle** in single-phase flow and two-phase flow: Steam generator tube bundle
  - **Leakage flow induced vibration**: feed-water spargers and jet pumps
  - **Vibration by over flow weir**: Super-Phenix-I LMFBR
  - **Acoustic resonance at branch pipe**: Dryer fatigue at EPU

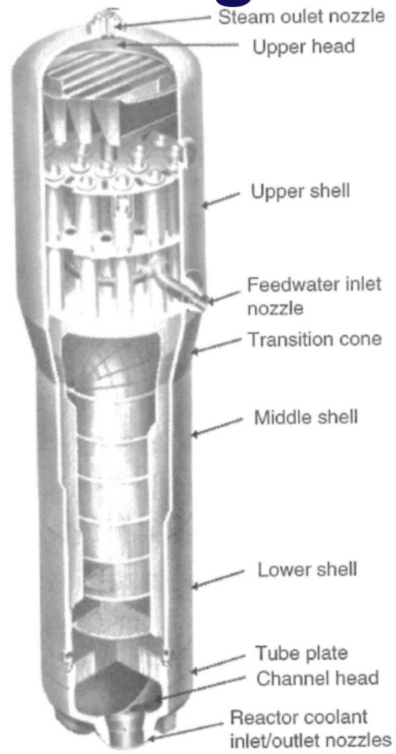
Fluid-elastic vibration of tube bundle in single-phase flow and two-phase flow

- One of the most dangerous vibration mechanisms and the root cause of many problems in industry, i.e. SG tube bundle
- Simple criterion by Connors:

$$\frac{V_c}{f_s D} = K\left[\frac{m\delta}{\rho D^2}\right]^{1/2}$$

δ: logarithmic decrement of damping in vacuum

K has been obtained experimentally for arrangements



Steam generator

- Non-uniform flow:

$$SR = \frac{V_e}{V_c} < 1$$

$$V_e = \left[\frac{\int_0^L \frac{\rho(x)}{\rho_{averge}} V_G(x)^2 \phi(x)^2 dx}{\int_0^L \frac{m(x)}{m_{averge}} \phi(x)^2 dx}\right]$$

V_e : Effective flow velocity

V_G is gas phase velocity

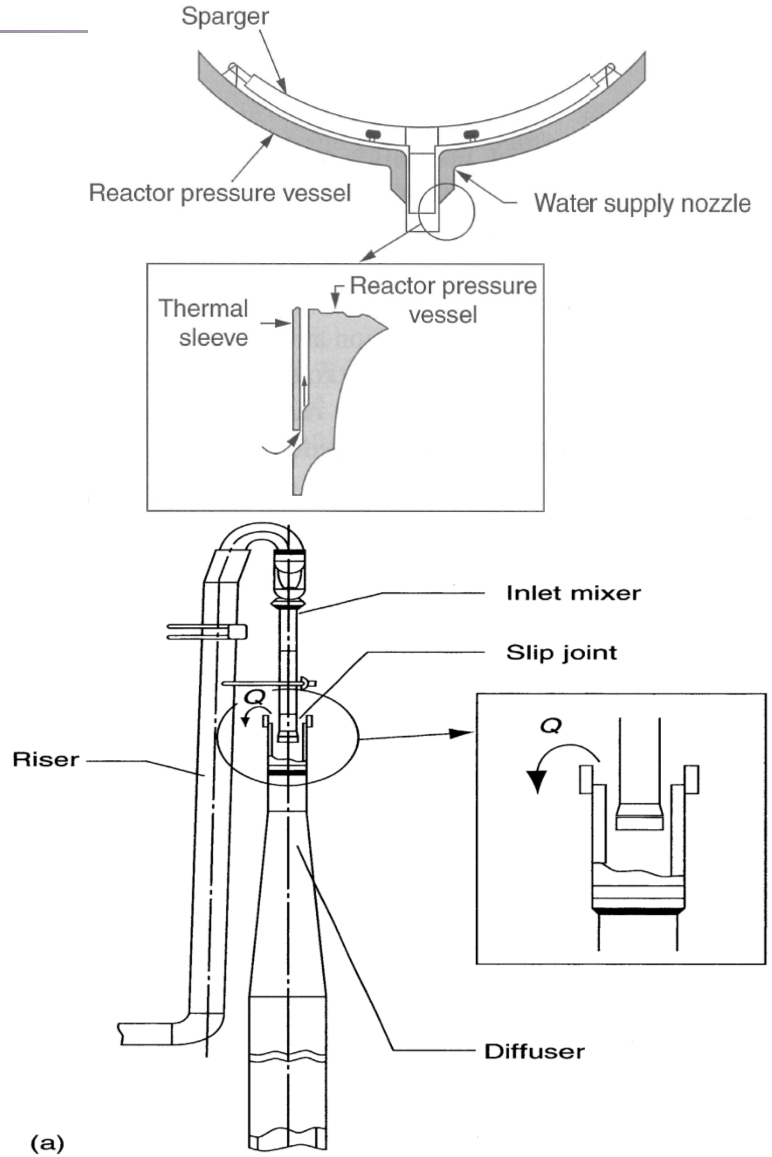
ϕ: mode function of tubes

ASME: K=3.0 for most conservative value

JSME: K=7.3 for best estimation

Leakage flow induced vibration

- **No steady flow**: Added mass and damping, which can be very large because of the squeeze film effect.
- **Steady flow**: Flow resistance variation generates oscillations of the leakage-flow velocity, which can also induce large added damping/stiffness forces.
- **Self-excited vibration can easily occur if the flow resistance is larger in the entrance side such as the divergent passage**
- In the case of divergent passage, flow separation can also induce large amplitude turbulent induced vibration.



Acoustic resonance at branch pipe

- Pressure fluctuation induced by the acoustic resonance of SRVs propagates MSLs, and it excites the dryer, which can lead to fatigue damage while operating at EPU conditions.
- Occurrence of acoustic resonance can be judged by the following relationship:

$$\mathrm{St} = f\frac{d+r}{U}$$

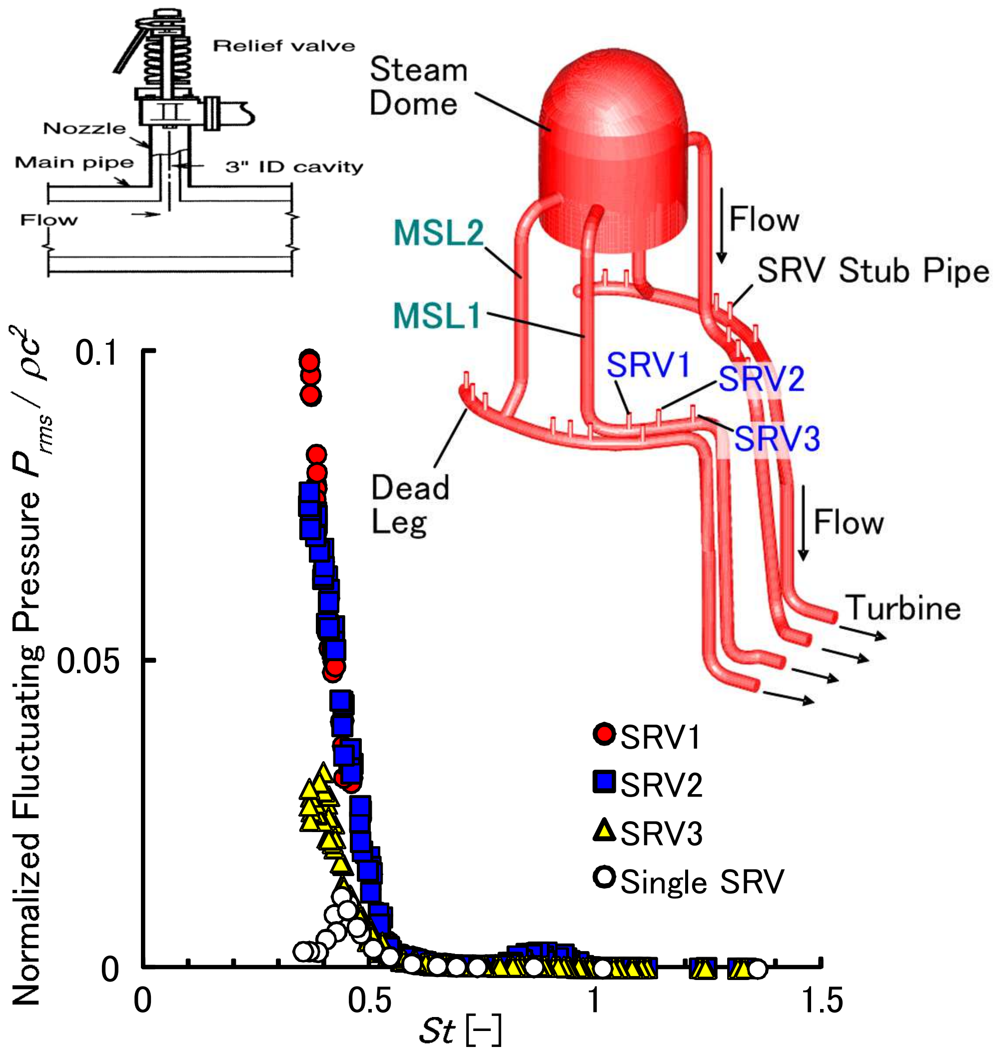
$$U_L > 1.49 f(d+r)$$

d: stub pipe inner dia.

r: stub entrance radius

U: mean velocity in the main pipe

f: Acoustic resonance frequency



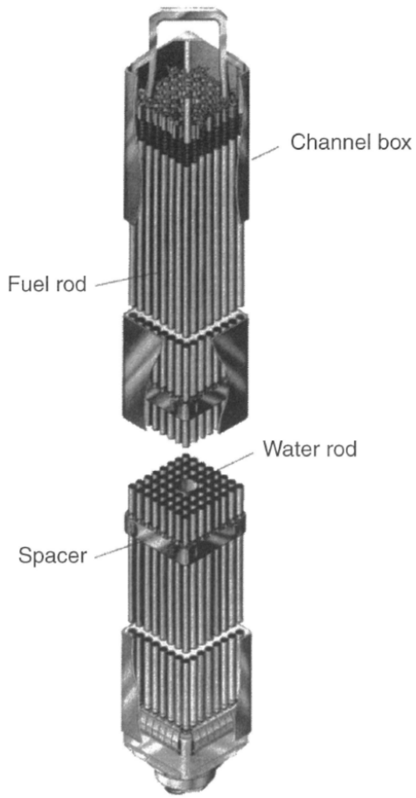
An example of CFD method for acoustic resonance at branch pipes

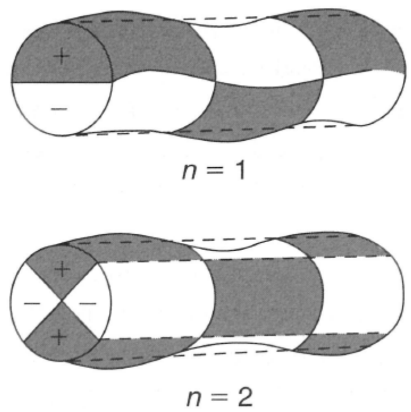
◆It was confirmed that resonance in SRV stub pipes could be simulated by using high spatial precision and Large Eddy Simulation (LES).

Code	3D Compressible Flow Code
Turbulence Model	Large Eddy Simulation (LES)
Time Integration Method	2^{nd}-order Temporal Precision Scheme with Newton Iterative Procedure and LU-SGS Algorithm
Discretization Method of Convective Term	5^{th}-order Upwind Scheme or 4^{th}-order MUSCL-TVD Scheme
Discretization Method of Viscous Term	4^{th}-order or 6^{th}-order Central Difference

Forced vibration - 1

- Turbulence-induced vibration of a tube and tube bundle
  - The amplitude should be evaluated at the design to adjust the support position.
  - A cylinder in single-phase flow: ASME rules and JSME rules
  - Two-phase flow: Full-scale tests are required to design important equipment~~s~~.
- Pipe vibration downstream of pressure control valve
  - A vibration source of the valve and the downstream small bore piping under partial valve opening
  - When the valve is fully opened, normally the vibration reduces
  - A high-frequency (several hundred Hertz) acoustic mode can be excited in ~~the~~ large diameter piping.





Forced vibration - 2

- Pipe vibration downstream of pump
  - Fluctuating pressures generated by centrifugal pumps

    f=mN/60, m=1,2,3··· where N is pump rotating speed (rpm)
  - Acoustic frequency of a simple pipe

    fn=(c/2L)n n=1,2,3 ··· for open-open or closed-closed ends

    fn=(c/4L)(2n-1) n=1,2,3 ··· for open-closed ends

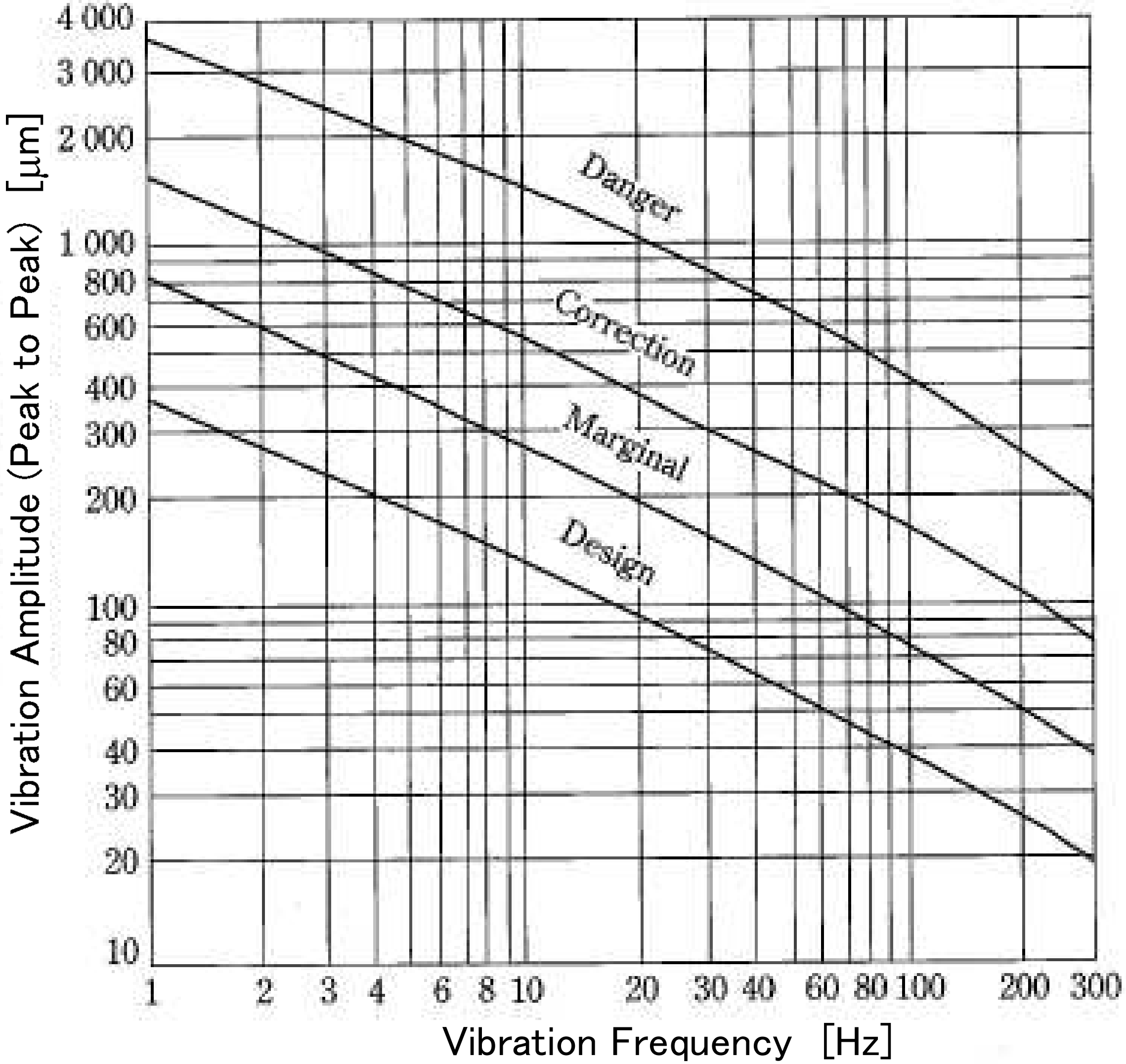
    L: pipe length, c: speed of sound
  - Sound speed of two-phase flow

    $$c = 1/\sqrt{\{\alpha/P + (1-\alpha)/K + d/Eh\}\{\alpha\rho_g + (1-\alpha)\rho_l\}}$$

    Note: Sound speed is reduced by mixing of a little void
  - Example: BWR jet pump instrumentation pipes for flow rate measurements

    They were damaged by fluctuating pressures caused by the reactor PLR pumps.

Screening criteria of pipe vibration in the operating plant: SwRI criteria



Water hammer

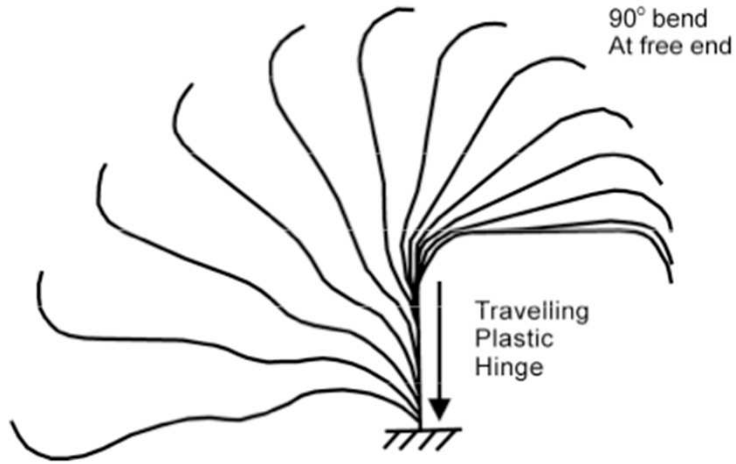
- When a rapidly closed valve suddenly stops water flowing in a pipeline, shock waves are set up within the system because of the sudden change of momentum. The pressure rise can be the order of $\rho c \Delta V$, which was derived by Joukowski.
- Four common events that typically induce water hammer:
  - Vapor column separation and the collapse of cavities
  - A rapid change in flow by pump power failure
  - Sudden valve closure
  - over sizing the surge relief valve or improperly selecting the vacuum breaker-air relief valve
- Since it can sometimes lead to ~~the~~ pipe rupture events, designer should take it into account including the case of equipment malfunction.
- Though the phenomena are recently well understood, it can still occur in plants if the operators do not operate the pumps, valves, etc. as described in the manual.

Valve issues

- High speed flow can be generated in the valve, so that valves are one of the major sources of damage of the valve itself and in downstream piping.
- phenomena of which we should take care and take countermeasures against are:
  - Turbulence-induced valve vibration
  - Self-excited vibration of flow-restriction valves
  - Small bore pipe vibration by steam control valve
  - Cavity tone excitation of relief valve

Pipe whip

- Thrust exerted by the escaping fluid at ~~the~~ pipe break events can generate an accelerating rotational displacement of the break pipe.
- The EDF Energy R3 procedure
  - Establish break locations.
  - Derive the thrust applied to a broken pipe as a result of rupture.
  - Establish by simplified methods the motion of a pipe in advance of considering whether there is a need for non-linear FEM to determine:
    - The location of a plastic hinge, assuming the pipe material to be rigid- perfectly plastic,
    - The rotation about the hinge to define a zone of influence,
    - The associated velocity, energy and momentum at a target within that zone.



  - If numerical methods of analysis are needed then perform a rigorous pipework analysis.
  - Assess damage caused by the whipping pipe.
  - Consider the need for pipe restraints, or assess existing restraints.

Summary and conclusions

- When we calculate the natural frequency, the added mass should be estimated.
- Vortex induced vibration can occur at a single cylinder, a tube bundle, and plate of reactor internal immersed in cross flow.
- Self-excited vibration can cause large amplitude vibrations, and it is one of the most dangerous vibration mechanisms.
  - The phenomena: Fluid elastic vibration, acoustic resonance at branch pipe, leakage flow induced vibrations, vibration by overflow weir etc.
- Forced vibration:
  - Turbulent induced random vibration should be evaluated at the design.
  - Pressure fluctuation induced by a steam control valve and centrifugal pumps can be a cause of fatigue of small bore pipes and the reactor internals. Screening criteria of pipe vibration can be effective.
- Water hammer can sometimes lead to ~~the~~ pipe rupture, and designer should take it into account.
- The extent of the hazard zone and the kinetic energy of ~~the~~ a whipping pipe are required to assess potential damage to objects within the hazard zone.