Considerable Reduction of Loads in Piping Systems after Pump Failure by Coupled Fluid/Structure-Calculation

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Abstract

An approximated representative part of a PWR-feed-water-line was modelled and used to calculate the displacements of the piping system and the loads on it, caused by pressure pulse due to pump failure and subsequent check valve closure.

The computation was performed with the code SAPHYR which contains the fluid code KOLAST and the structure code SAPIENS, calculating simultaneously and interactively. The results were compared with an uncoupled calculation without fluid/structure interaction.

It was shown that neglecting the fluid/structure interaction can lead to considerable overestimations - in some cases up to a factor of 3 - of the loads on the structures.

1. Introduction

In the analysis of the mechanical loads on complex piping systems the structure dynamics, caused by pressure pulses due to pump failure and subsequent check-valve closure plays an important role. The displacements, caused by the excitation of vibrations of the piping systems lead to loads on snubbers, hangers, nozzles and elbows.

Up to now, loads usually are calculated in two steps. First, the transient pressure field is calculated by a one-dimensional fluid-dynamic code. Here, a rigid pipe-wall is assumed, or, at most, the radial movement of the pipe is taken into account either explicitly or implicitly by the reduction of the sound velocity.

Secondly, the axially acting unbalanced forces on consecutive pipe elbows, branches, closed ends or changes in pipe diameter caused by the above calculated pressure field, are used as input for a structure dy-
namic calculation which computes the desired loads.

In these uncoupled calculations the secondary pressures pulses, as induced by the piping movement, are not taken into account, because the structure dynamics cannot influence the pressure-time-history. However, as soon as the energy transfer from the fluid to the structure becomes appreciable in comparison to the energy content of the pressure pulses, it is obvious that neglecting this feed-back of structure on fluid must lead to an over-estimation of the loads and a wrong description of the pressure pulses.

This effect may be quite severe in case of resonance, i.e. when the hydrodynamic transients lead to the production of standing pressure waves, such that its dominant frequency is near to a structure eigenfrequency and the corresponding eigenmode contains components parallel to the fluid forces, see Kellner, Schönfelder, Voss /1, 2/.

In this case, fluid energy is fed into the structure system permanently, and the missing coupling supports an unlimited increase of the structure loads.

2. Model system used for calculation

In order to assess the magnitude of the over-estimations, coupled and uncoupled calculations were performed with the fluid/structure code SAPHIR for a piping system, which is an approximated representative for a feed-water-line of a PWR.

The model piping system consists of a single line (with several elbows), outer diameter 580 mm, wall-thickness 32 mm, leading through the main pump and damped check-valve to the inlet header of three parallel steam generators. In this line, water with the temperature of approximately 150 °C, is fed by the main pump to a pressure of 85 bar. The distance between the check valve and the inlet header is 76 m, and between the inlet header and the steam generators 18, 21 and 25 m.

The piping system is supported by a number of snubbers and hangers, which are connected via other support systems to the wall of the building.

The fluid part of the SAPHIR model includes:
- fully dynamic pump, which is assumed to fail at the start of the calculation, such that the pump continously slows down during the run.
- fully dynamic damped check valve, interacting with the fluid motion
- piping system between pump and steam generator, including the branches at the inlet header
- the steam generators and the feed water reservoir are modelled as constant pressure boundary conditions.

The structure part of the SAPHYR model includes
- 2-node-pipe-modelling of straight and bent pipes
- modelling of snubbers and hangers and additional support systems to which the snubbers are attached by one-dimensional springs
- modelling of steam generators by fixed points.

The piping system is shown in figure 1 (without support system), a typical model for snubbers and support system in figure 2.

3. The fluid/structure code SAPHYR

The fluid/structure code SAPHYR consists of the interactively calculating codes ROLAST and SAPIENS.

The fluid code ROLAST solves the 1-dimensional hydrodynamic equations (continuity of mass and momentum) by a finite-difference-scheme; it is capable of modelling a large number of hydraulic components, such as pumps, check-valves, air chambers etc., for arbitrarily branched piping systems. The finite-element structure code SAPIENS (linear analysis) contains a large class of finite-elements, so that it is capable to describe all structure components of a complex piping system.

In SAPHYR, both codes are calculating interactively: at each time step, forces due to the transient pressure field calculated by ROLAST are used as input-data to SAPIENS, which in return feeds back the calculated axial pipe velocities, elbows, branches, closed ends etc., as boundary conditions to ROLAST.

4. Results of calculations

Two calculations were performed: a coupled one, using SAPHYR, and an uncoupled one, as described above.

In both cases the pump failure caused the fluid flow to decelerate and, after the onset of return flow, the check-valve closed, producing standing waves between the valve and the steam generators. The relatively high amplitude of the first pressure peak is primarily determined by the fluid deceleration and velocity at the moment of valve closure, see figure 3. But already here in the uncoupled case the maximum pressure is about 7 % higher than in the coupled case.
The following peaks are only slightly decreasing with time due to friction in the uncoupled case, whereas they are drastically reduced in the coupled calculation due to periodic energy-exchange with the piping. This is reflected by the behaviour of the snubber loads (fig. 4) which are reduced by up to a factor 2, the largest difference between coupled an uncoupled case existing at the L-shaped part of the line just upstream of the inlet header (fig. 5). The picture clearly shows resonance in the uncoupled calculation, which is due to the fact that the frequency of the relevant eigenmode ($\approx 3.4$ Hz) is quite near to the dominant frequency of the standing pressure wave. Fig. 3 shows that in the coupled calculation the frequency of the pressure wave is lower than in the coupled case.

5. Conclusions

This comparison shows that the uncoupled calculation can lead to considerable overestimations of the loads on a PWR feed-water line in case of pump failure - an effect, which has also been found to hold for other piping configurations and loads and which has been proved experimentally as well /1, 2/.

Literature

/1/ Kellner, A., Schönheder, C.

/2/ Kellner, A., Voß, J., Schönheder, C.
Fluid/Structure - Interaction in Piping Systems: Experiment and Theory Trans. 7th Int. Conf. on Structural Mech. in Reactor Techn.
Chicago 1983, Vol B4/3
Figure 1:
model piping system

Figure 2:
model of support structure
Figure 3:
pressure/time-history at $P_1$ pressure
(see fig. 1)

Figure 4:
spring-force/time-history at $F_1$
(see fig. 1)

Figure 5:
spring-force/time-history at $F_2$
(see fig. 1)