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FLUID AND STRUCTURAL-DYNAMIC PIPING SYSTEM ANALYSIS

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1. Introduction

Fluid hammers in piping systems can cause high dynamic loads which affect the holding fixtures; especially when part of the piping system, because of its temperature expansion, is hanging in springs, resonance effects can cause additional loads which may be a multiple of the static load. Therefore it is important to know in advance the loads for certain operating conditions in order to duly adjust the support concept. For that purpose a fluid-dynamic analysis was conducted for the load case. The results, transient forces, are used for the dynamic structural analysis and are given as force/time curves. Due to their complexity and the related great computing efforts, such analyses are conducted by means of efficient computer systems.
This paper shall demonstrate that quite exact advance analyses can be conducted also for complex, greatly meshed systems with a major number of valves, as is shown by the comparison with measured values.

2. Fluid dynamics

2.1 Bases

Today's software solves the equations for mass, impulse and energy conservation which are given as partial differential equations by appropriate numerical methods such as the finite-difference method or the characteristics method. For that purpose the whole piping system is discretized into small sections and is analyzed with very short time steps in the millseconds range for the whole time in question. The forces then result from integration of the pulse between directional changes, e.g. piping bends. The quality of the results is decisively influenced by modelling of the valves which are to be mapped in the computer as really as possible in order to simulate an exact pattern of valve movement and the related influence on the flow. In addition, the physical boundary conditions of the system limits towards the outside as well as inside boundary conditions must be recorded by the user with sufficient accuracy to minimize the unavoidable deviations.

2.2 System and modelling

The piping system to be analyzed is the low-pressure cooling system of a nuclear power plant in Germany. To establish a computer model the whole system was discretized in sections of 0.5-1 m length. The problem time was fixed at 3 sec. for the pressure waves begin to decay within that time as a result of damping. With a time discretization of 0.3 ms it was necessary to analyze the whole system modelled ten thousand times. The load case for re-analysis of the cooling system in the four-pump mode assumes failure of pump 1 while the freely swinging, weight-loaded non-return damper on the pump discharge side closes. Calculations were conducted with damper weights of 49 kgs and 98 kgs and compared with measured values.

2.3 Results

The reflux through the slowly moving non-return damper in the event of pump failure leads to hammering with related pressure surges. Figure 1 shows the pressures as a function of time in comparison with the values measured at a damper weighing 49 kgs. The precision of the analysis is largely influenced by damper modelling. In this case it was, for example, necessary to exactly consider the high gland friction of the damper shaft at the penetration of the casing to duly cover all attacking moments of the motion equation for the damper disk. It was shown that this friction moment was also responsible for the late closure of the damper and thus caused considerable dynamic loads. To reduce the loads, additional measurements were made with twice the damper weight of 98 kgs and were re-analyzed later. The results show a clear reduction of the hammer amplitudes and the related loads on the system, for due to weight doubling, the damper closes more quickly and there is only a small reflux. Figure 2 depict the pressure together with the appropriate values measured. The good agreement between the analysis and the tests demonstrated sufficient precision of system modelling so that good results were expected for further fluid-dynamic analyses of several load cases with subsequent structural-dynamic analyses to optimize the support concept of the whole system.

3. Fluid-dynamic system analyses

According to its process purposes, the whole low-pressure cooling system of a nuclear power plant was modelled for conducting the fluid-dynamic analyses. Figure 3 shows the scheme of the low-pressure cooling system and reveals the modelling complexity resulting from the simultaneous interaction of:

- 14 suction lines with 12 freely swinging non-return dampers
- 6 pumps
- 8 discharge lines with 4 freely swinging non-return dampers and 6 undamped non-return valves
- 2 minimum-flow lines with 2 undamped non-return valves.

The system was subdivided into 1100 sections with 395 pipe forces. Problem times between 3 and 20 sec. were needed in dependence on the various load cases. It was necessary to analyze 10000 to 40000 time steps.

3.1 Selection of load cases

The process purposes of the low-pressure system are controlled recirculation and feeding of cooling water into the nuclear power plant. The flow as well as the pressure conditions to be overcome depend on the operating state of the plant. From the multitude of tasks of the low-pressure cooling system and the resulting operating conditions, three dominating and enclosing load cases were selected for the fluid-dynamic system analysis. The analysis of these load cases which have been selected under process engineering viewpoints results in force/time curves which serve as exciting variables for the structural piping analyses.

3.2 Description of load cases

To analyze the load cases, all freely swinging non-return dampers and non-return valves were dynamically modelled at the same time. To cover the behavior of the operating and the failing pump these were integrated into the fluid-dynamic model with their specific-speed characteristics, driving torque, startup moments, flywheel effects and moments of mass inertia of the motor, coupling and rotor as well as the rotating fluid mass.

To determine the pipe forces all pump failure variants have been analyzed for the following operating conditions:

- operation with 1 pump, total mass flow 278 kg/s = 1000 t/h,
- operation with 3 pumps, total mass flow 917 kg/s = 3300 t/h,
- operation with 6 pumps, total mass flow 2128 kg/s = 7660 t/h,

3.3 Load case results

The order of magnitude of the force/time curves is mainly influenced by the motion behavior / closing behavior of the valve on the pump discharge side. The time curve of the closing process depends on the flow behavior of the fluid in the pipe branch of the failing pump which determines the attacking moments on the damper disk. The analyses have shown that relevant pipe forces, which as exciting loads are of such an order that they are able to dynamically load the piping system, appear only if fluid flows back through the closing freely swinging non-return damper.

For the condition with one operating pump, a transient fluid hammer analysis has been conducted for failure of one pump. The freely swinging non-return damper with an initial opening angle of 23.0 degrees closes after 17.5 sec. Refluxes and related major pressure ramps do not occur since the flow behavior is only determined by the failing pump.

The result of the load case: failure of one pump in the three-pump mode is a closing time of 9 sec. for the non-return damper. The reduction of the damper closing time is caused by the pumps continuing in operation which counter a pressure drop according to the characteristic curve of the failing pump. Refluxes have not been analyzed since the counterweight of the freely swinging non-return damper causes this latter to close before the flow is reversed.

For the condition with six operating pumps, the results of the fluid hammer analyses for failure of one pump while the remaining five pumps continue in operation, with a damper closing time of 1.2 sec., show a reflux through the closing non-return damper. In this load case, the dominating fluid hammers of all analyzed load conditions of the system are appearing.
During operation with six pumps with maximum throughput and speeds of 1435 min^{-1}, the maximum delivery head of some 200 m is achieved. If one of the pumps fails, the closing time of the discharge-side freely swinging non-return damper is shortest with 1.2 sec. As the remaining pumps continue in operation, the high delivery heads and the existing pressure differences lead after a closing time of abt. 1.1 sec. to a reversal of the flow, that is a negative flow of 25.6 kg/s maximum through the closing non-return damper, Figure 4. This abrupt deceleration of the flow is reflected in the

pressure ramps and the related force/time curves as maximum fluid hammer of all analyzed load conditions.

4. Structural-dynamic piping system analysis

4.1 Modelling - Boundary conditions of the calculation model

A special eigenvalue calculation is provided for the fluid hammer analysis. It is assumed that the fluid hammer consists of dynamic axial forces which are given in form of force/time functions, Figure 5. To avoid major deviations from reality, it is important that the physical boundary conditions of the structured model are recorded as exactly as possible.

Essential boundary conditions are, besides the correct mass distribution, the piping support concept and system damping.

- The supports (sliding supports, partially fixed points) are assumed in their direction of action while the spring stiffness of the supports as well as the stiffnesses of the following components such as pump and vessel branches are also taken into account.
- Another important system variable is damping which comprises material and system damping.
  As only one damping value is assumed for all natural forms, a value will be specified which leads to high loads for the lower natural forms. 4 % system damping was assumed in accordance with KTA 2201.4.

4.2 Conductance of structural-dynamic analysis

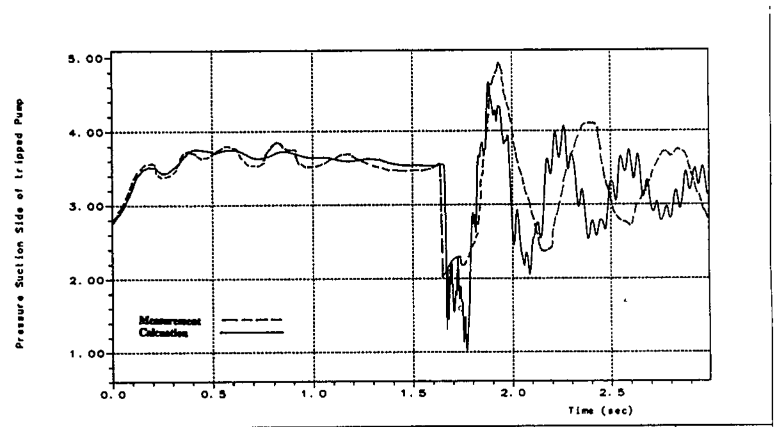
For all load cases considered for the fluid-dynamic analysis a fully dynamic piping system analysis was conducted according to the time/history method. To avoid some vibration peaks not being covered by the time steps of the time/history method, a plus/minus 10 % frequency shift is used, Figure 6. At the end of the analyses the analyzed load cases were classified according to KTA 3201.2.

4.3 System qualification

- All supports were checked with the extra loads. Some support structures had to be reinforced or anti-lifting devices had to be fitted.
- All flange connections at pumps and valves have been re-analyzed and the restraint graph was adjusted to the internal forces determined by us for pump failure.
- Acceptability of stresses at the vessel, cooler and pump branches was proved so that also these components fulfill the dynamic requirements.
- A detailed stress analysis was conducted for some piping elements, such as not reinforced Tees, according to the finite-element method so that the acceptability of the fluid-dynamic loads was ultimately proven.

5. Summary

By means of the fluid and structural-dynamic analyses conducted, the cooling system was qualified for all fluid-dynamic processes in normal and anomalous operation and in case of accidents. The boundary conditions assumed by us for the fluid and structural-dynamic analyses were confirmed by the forces and movements measured time for some operating conditions as a function of time. Expensive hardware measures such as additional supports or replacement of Tees were not necessary as we combined the fluid and structural-dynamic analyses and then demonstrated safety of the supports, connected components and some of the piping elements as such.



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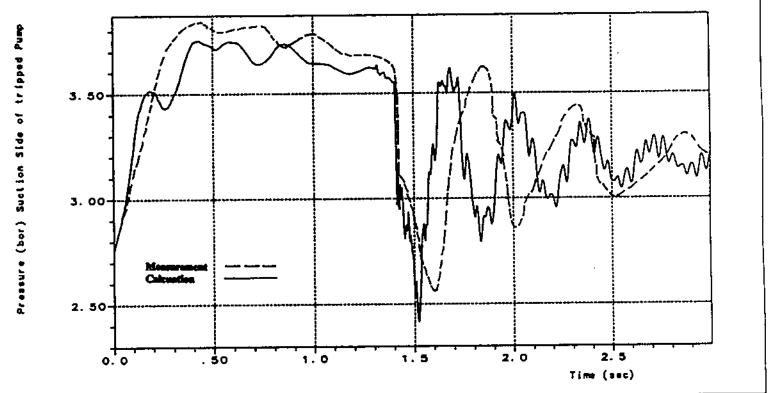
Calculation and Measurements
Trip of Pump 1 of 4 Pumps in a Emergency-Coolingsystem
Check Valve closes with a Weight of 49 kg

Figure:1



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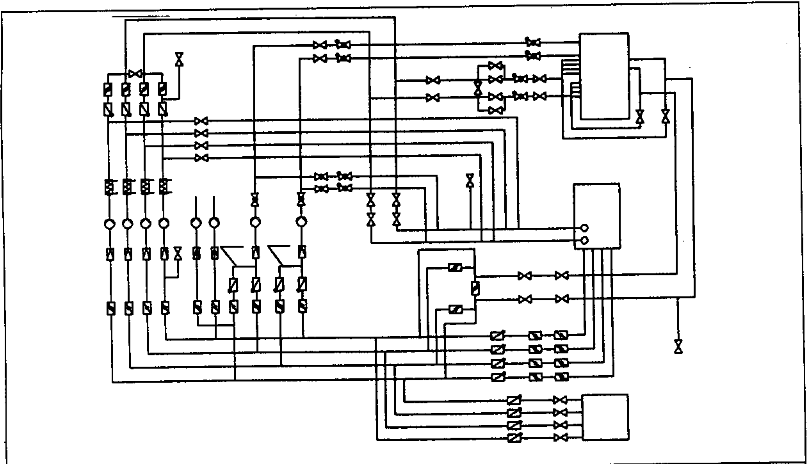
Calculation and Measurements
Trip of Pump 1 of 4 Pumps in a Emergency-Coolingsysten
Check-Valve closes with a Weight of 98 kg

Figure:2



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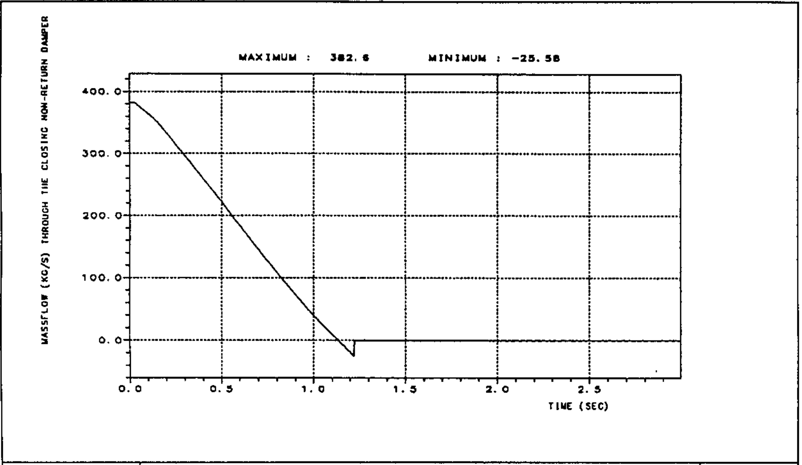
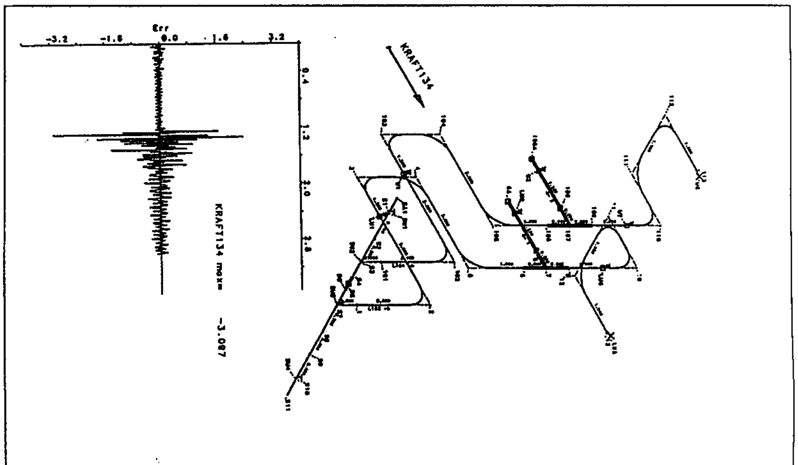
MODELL OF THE LOW-PRESSURE-COOLING-SYSTEM

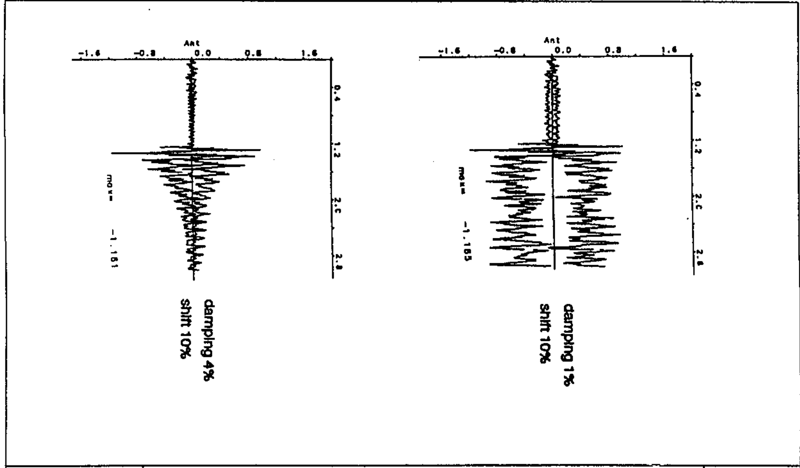
Figure: 3



BABCOCK Rohrleitungsbau GmbH Oberhausen	OPERATING WITH 6 PUMPS	Figure: 4



BABCOCK Rohrleitungsbau GmbH Oberhausen	Load time function of force 134	Figure: 5



BABCOCK Rohrleitungsbau GmbH Oberhausen	Responses of the load time function 134 with damping and shift	Figure: 6