LOCA-Calculations with and without Account of Nonlinearities and Hydrodynamic Coupling

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Summary

Up to now most of the calculations for the design of nuclear power plants against internal and external dynamic loadings are done using linear elastic methods and neglecting any influence of geometric or material nonlinearities.
We have performed a study for the case of a loss-of-coolant accident (LOCA) in the reactor coolant system of a PWR-type reactor, to work out the influence of geometric nonlinearities (gaps).
The coupling of motion between reactor pressure vessel and core-barrel due to the water in the downcomer is taken into account using a nondiagonal mass-matrix.
The study was restricted to consideration of a double-ended cold-leg guilloutine-break, which is the most severe load-case for the RPV-support.

The consideration of geometric nonlinearities and hydrodynamic coupling results in a reduction of the horizontal moments for the RPV-support - but increases the horizontal support forces.

1. Introduction

Calculations for loss-of-coolant accidents (LOCA) in a PWR- reactor coolant system have usually been performed using linear methods. It was assumed that this approach was conservative with respect to the calculated loads.
We have performed a comparison of linear and nonlinear LOCA-calculations to study the influence of (simple geometric -) nonlinearities and hydrodynamic coupling between vessel and core-barrel.

2. Model description

A simplified model of the RCS was used in the calculations, which only consists of a two-beam model of the RPV and the internals, while the loops and components have only been represented by a stiffness matrix.
A schematic of this model is shown in figure 1.
The vessel is supported in the height of the nozzles with 4 vertical pads and 8 horizontal (tangential acting) stops. (see fig. 2)
The calculations have been performed, using the following modifications of the model :

model 1 : full linear, core-barrel free at the lower end (infinite "gap")

model 2 : linear vessel support, gap between vessel and core-barrel at the lower end of the core-barrel

model 3 : vessel support with gaps, gap between vessel and core-barrel at the lower end of the core-barrel

2.1 Modeling of gaps

model 1 : no gap at the vessel support, infinite gap between vessel and core-barrel at the lower end of the core-barrel

model 2
and
model 3 : finite gap between vessel and core-barrel at the lower end of the core-barrel (gap-size : o.oo3 m)

model 3 : (in addition) gapped vessel support
vertical gaps at the support pads (size : + o.oo1 m)
horizontal (tangential) gaps at the horizontal stops
(gap-size : ± o.ooo4 m)
(see fig. 2 for a schematic drawing of the support-model)

2.2 Hydrodynamic coupling between vessel and core-barrel

The influence of the water in the downcomer on the relative motion of vessel and core-barrel (hydrodynamic coupling) is taken into account by using a nondiagonal mass-matrix (virtual coupling mass), the elments of which have been calculated as done by Mc. Donald /1/ and Kiss /2/ for the motion of "concentric cylinders".
Vertical coupling was neglected.
For comparative calculations without hydrodynamic coupling only a diagonal mass-matrix without virtual terms was used.

3. Calculation method

The time-history-analysis was performed using direct integration (THDI) method /4/.
For the linear calculations without hydrodynamic coupling a comparison was made with modal-analysis (THMA) /3/, showing excellent agreement for the maximal values and even for the response time-histories, which have been identical within a tolerance of 1% maximal deviation. (see table 1)

4. Load-case considered

The force input was taken from a calculation of transient hydrodynamic loadings following a circumferential (guilloutine) break in the cold leg (fig. 3).
The analysis was restricted to this single load-case, which is the most severe load-case for the vessel support.

4.1 Consideration of forces in the loops

The excitation forces were calculated for a more complex model including pipes and components.
Before the break occurres, the forces from all four loops (bend-forces) acting on the RPV are in equilibrium and need not to be considered.
After break opening there is an unbalanced force acting on the RPV due to the missing bend-force from the broken (cold-) leg.
This unbalanced force has to be taken into account in addition to the pressure forces acting on the RPV and core-barrel directly.

5. Results - influence of nonlinearities (gaps) and hydrodynamic coupling

5.1 Linear calculations

Hydrodynamic coupling was found to reduce the relative motion of vessel and core-barrel slightly and mainly remove vibrations of higher frequencies. This can be seen from the displacement response-time-history (fig. 4) and from the corresponding acceleration response-spectra as well (fig. 5).
The reduction of relative motion results in a reduction of the horizontal moments at the RPV-support as can be seen in table 2 (model 1 : reduction of moments to 7o% of the reference value)

5.2 Nonlinear calculations

For models 2 and 3 the gap-size of the gap between vessel and core-barrel at the lower end of the core-barrel limits the relative motion of vessel and core-barrel.
The effect of this limitation is a significant reduction of the horizontal moments at the RPV-support to about 5o% of the reference value (model 1 without hydrodynamic coupling).
The additional consideration of the gaps at the RPV-support results in an increase of the RPV-support forces (horizontal) of about 35%, while the moments (horizontal) become 5o% (with hydrocoupling) or 35% (without hydrocoupling) of the reference value (see table 2).
Calculated response-spectra show (e. g. fig. 6) that the gapped RPV-support causes an increase of the higher-frequency content of the response time-histories.
Again one can see the influence of the hydrodynamic coupling, which reduces the peak-values in the high-frequency range significantly (see fig. 7).
Since the peak-frequencies are shifted towards lower frequencies due to the hydrodynamic coupling,. this can lead to a partially increase of spectral amplitudes even in the lower frequency range (compared with the linear reference - model 1 without hydrodynamic coupling (fig. 8).

6. Conclusion

The consideration of gaps at the RPV-support and the lower core-barrel limitation tends to rise the horizontal RPV-support forces and to reduce the horizontal moments at the support - compared to the simple linear calculation.
The reduction of moments at the RPV-support can be clearly identified

as caused by the limitation of the relative motion between vessel and core-barrel due to the finite gap between vessel and core-barrel at the lower end and/or due to the hydrodynamic coupling.
The consideration of gaps at the RPV-support is of minor influence for the horizontal moments at the support, since there is no uplift of the support pads.

The increase of the horizontal support forces (model 3) caused by the RPV- impact to the horizontal stops should not be overestimated, since not the forces but the moments are critical for the integrity of the RPV-support.

At the other hand this may result in an increase of loads for the loops and components and for the internals in the upper part of the RPV as must be exspected from a comparison of the horizontal response-spectra for the calculation with gapped RPV-support and for the linear reference (see fig.8).

References :

/ 1 / Seismic analysis of vertical pumps enclosed in liquid filled containers C. K. Mc Donald, ASME 75-PVP-56

/ 2 / Analysis of the fundamental interaction frequency of a radial vane internal steam seperator structure
E. Kiss, ANL 7685, May 197o

/ 3 / MRI - Stardyne theoretical manual
CDC - publication 866163oo

/ 4 / Dynamic analysis of piecewise linear structures
J. S. Lien, R. P. Kassawara, H. B. Smith
ASCE second speciality conference of structural design of nuclear power plant facilities (New Orleans 1975)

Table 1 : RPV-support loads (model 1 without hydrocoupling)

Method	max. horizontal force (KN)	max. horizontal moment (KNm)
THMA	21200	48244
THDI	21134	48790

Table 2 : RPV-support loads

load (max. value)	without hydrocoupling	with hydrocoupling	model No. (type)
horizontal force (KN)	21134	18615	1 (full linear)
	21096	-	2 (gap: RPV-CB)
	28863	25800	3 ("full" nonlinear)
horizontal moment (KNm)	48790	34000	1 (full linear)
	21294	-	2 (gap: RPV-CB)
	17294	21277	3 ("full" nonlinear)

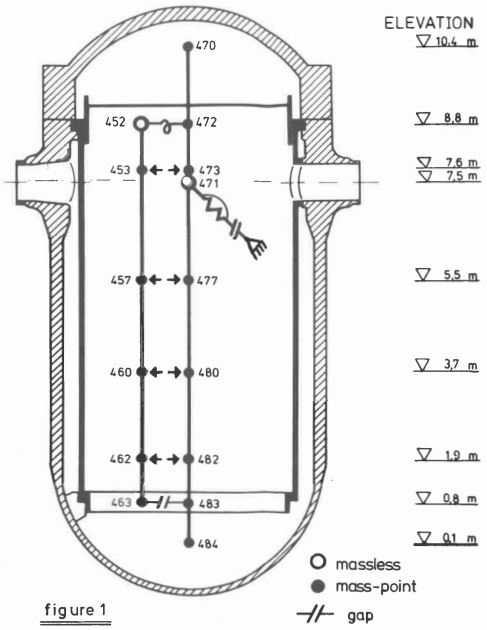
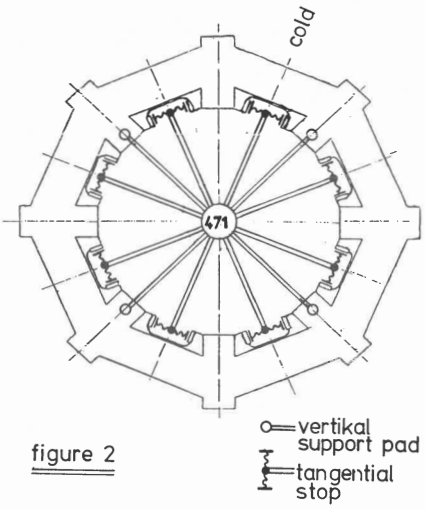


figure 1



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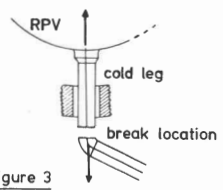

figure 3

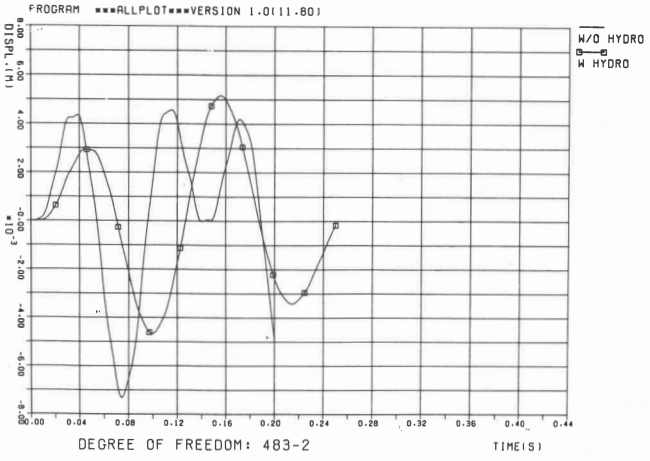

figure 4

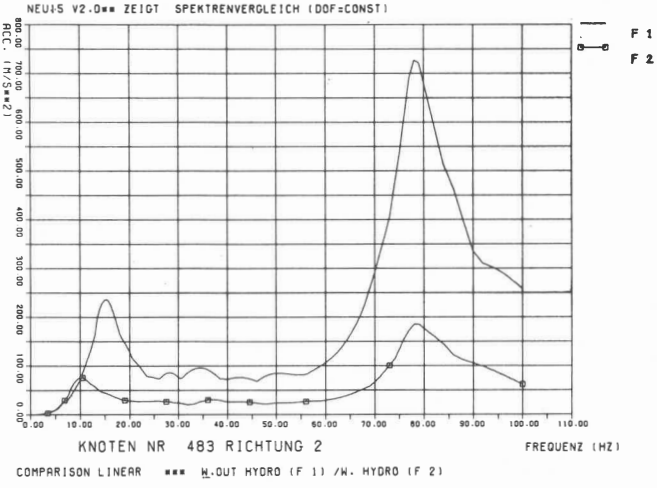

figure 5

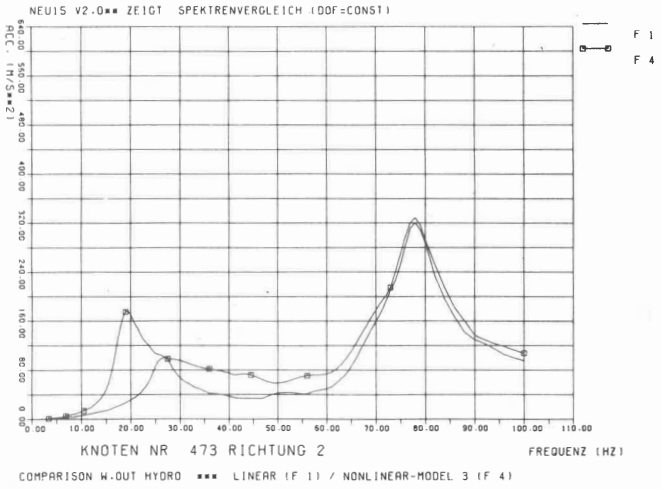

Figure 6

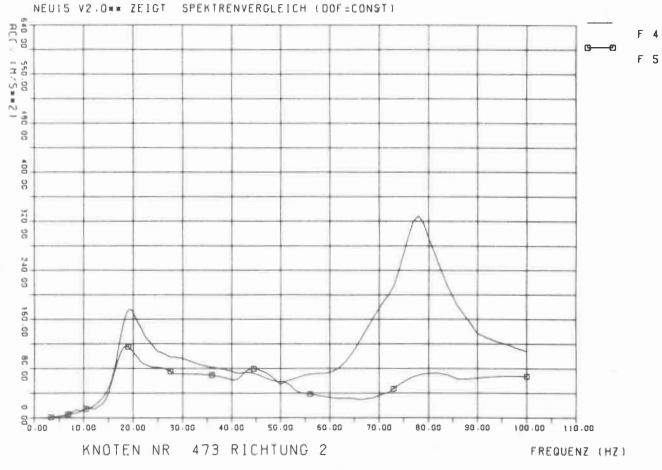

Figure 7

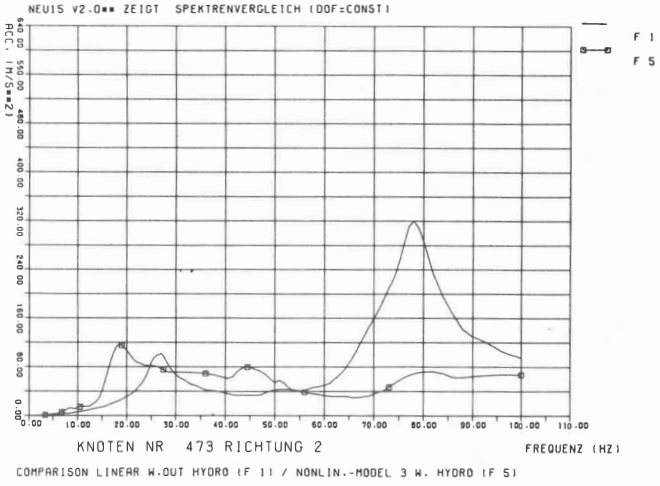
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figure 8