# Experimental Modal Analysis of the HDR Core Barrel

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Within the framework of code development for predicting the dynamic response of PWR-internals to the blowdown pressure transient a series of 7 blowdown and 16 snapback experiments was performed at the HDR experimental facility at Karlstein/Main. The task of these experiments was to study the transient pressure loading and the corresponding transient response of a HDR core barrel mockup installed in a HDR-pressure vessel. The transient displacement and acceleration signals, measured on the core barrel, were evaluated with the computer code EVA yielding a set of 32 eigenmodes of the core barrel-reactor pressure vessel system and a set of 44 eigenmodes of the core barrel-water charge-reactor pressure vessel system. The particular objective of the investigations described in the paper was the modal survey of the core barrel performed immediatelly before and during the blowdown test V32 (initial water temperature 311 $^{o}$C, initial system pressure 111 bar). The results obtained confirmed the feasibility of an experimental modal survey under conditions of constant temperature and pressure, yielding a set of 16 eigenfrequencies, mode shapes and critical damping ratios of the core barrel. The modal survey of the blowdown test V32 yielded a set of 16 eigenfrequencies and mode shape estimates, but there was no possibility to evaluate modal damping. An excellent consistency was obtained of eigenfrequencies related to time intervals shortly before and at the beginning of the blowdown; the mutual deviations are smaller than $\pm$ 0.5%. These eigenfrequencies are approximately 3-5% higher than those measured at room temperature. This increase is due to the temperature induced decrease of density in accordance with the theoretical expectations. An additional increase of eigenfrequencies due to the evaporation of the water charge during blowdown was likewise observed. In contrast to eigenfrequencies, the mutual deviations between "high temperature" and "low temperature" critical damping ratios are substantially greater. It is supposed that the higher temperature considerably changes prestressing of the core barrel and of the reactor pressure vessel, thus modifying damping. The critical damping ratios and the eigenfrequencies are plotted over the circumferential order of the modes identified; the eigenfrequencies are compared with the corresponding theoretical predictions calculated with the coupled fluid/structure-interaction code FLUX. Several typical mode shapes as well as the total displacement response of the core barrel reconstructed from the modal data extracted are also presented in the paper.

## 1. Introduction

In 1980 and 1982, 7 blowdown and 16 snapback experiments were performed at the HDR experimental facility at Karlstein/Main in order to determine the dynamic response of the HDR-core barrel mockup /¯1,2_7. The common objective of this series has been the experimental verification of the coupled fluid/structure-interaction codes currently being developed to assess the dynamic response of the PWR core barrel in the hypothetical loss-of-coolant accident (LOCA). A brief review of the codes developed and of the results obtained in the blowdown experiments is given in /¯1_7. The results of the modal-analytic evaluation of four snapback experiments performed at room temperature in 1980 are summarized in /¯2_7. The objective of the paper submitted is:

1. to demonstrate the applicability of the step relaxation procedure combined with the computer code EVA /¯2_7 to an experimental modal survey under hostile environmental conditions;
2. to present modal data of the HDR core barrel, obtained in the "high-temperature" snapback test V59.05 and in the blowdown test V32 as well as to compare these data with the corresponding results of the "room-temperature" snapback tests and with the theoretical predictions.

## 2. Experimental setup and modal evaluation procedure

The HDR experimental facility where the "high-temperature" snapback- and blowdown-tests were performed comprises among others the reactor pressure vessel, the core barrel mockup, the rupture disc device, and the hydraulic deflection (snapback) device, used to generate the transient dynamic response of the core barrel (fig. 1). The reactor pressure vessel is approx. 11 m high and has an inside diameter of nearly 3 m. The cylindrical shell of the core barrel is 7570 mm long (high); its inside diameter equals 2614 mm and its wall thickness 23 mm. The mass of the mass ring bolted onto the bottom of the shell is 13500 kg.

To measure the transient dynamic response the core barrel was instrumented with 25 inductive displacement transducers and 7 piezoelectric accelerometers, connected via amplifier to the central HDR data acquisition system, where digital magnetic tapes are produced with the simultaneously measured response signals. The transducers used were calibrated individually before and after installation on the HDR-core barrel; the calibration facilities as well as the qualification tests made on several prototypes to verify their performance characteristics in a blowdown environment are described in /¯3_7.

The snapback test V59.05 and the blowdown test V32 were consecutively performed on the same day; the initial temperature and pressure measured in the upper plenum of the reactor water charge, were 311 $^{o}$C and 111 bar, respectively. To extract from the response signals recorded the eigenfrequencies, the mode shapes and the critical damping ratios of the HDR core barrel, the computer code EVA has been used. Basic equations and several important subroutines of this code have been summarized in paper /¯4_7; a detailed description is given in report /¯2_7. The theoretical basis of this code implies the existence of the free vibration responses $X_r(t)$ (r=1, 2,...,R) of a linear, linearly damped multiple degree-of-freedom system, mathematically modelled by equation

$$X_r(t) = \sum_{n=1}^{2N} C_{rn} \exp(\lambda_n t) \tag{1}$$

In eq. (1)

$$\lambda_n = -\zeta_n \omega_n + i\Omega_n = \omega_n \left(-\zeta_n + i\sqrt{1-\xi_n^2}\right) \tag{2}$$

is the complex eigenvalue of the n-th vibration mode; $\omega_n$ and $\Omega_n$ are the corresponding natural angular frequencies of the undamped and damped systems, respectively; $\zeta_n$ is the corresponding critical damping ratio, and $C_{rn}$ is the complex initial value of the contribution of the n-th mode to the total response measured at time t=0 at the r-th location; R is the number of the measuring chains available. The set of the response signals $X_r(t)$ serves as a basis for the evaluation with the computer code EVA.

In case of the blowdown-test, the continuous energy flow through the evaporating water charge overlaps the energy dissipation in the structure and continuously modifies damping. Furthermore, the continuous decrease in water density continuously increases the eigenfrequencies of the core barrel. Therefore, application of eq. (1) to describe the dynamic response of the core barrel is no longer justified. However, it turned out to be useful to apply the computer code EVA to evaluating very short (approx. 2 sec) portions of the response signals which yields rough estimates of the eigenfrequencies and of the mode shapes of the core barrel. Reliable estimates of eigenfrequencies, mode shapes and critical damping ratios, which are necessary to verify the coupled fluid/structure-interaction codes mentioned in the Introduction, were extracted from the response signals of the snapback tests.

## 4. Experimental results

The modal characteristics of the core barrel extracted in the frequency range 0-100 Hz are summarized in table 1. The first three columns contain the number, the axial order $\mu$ and the circumferential order $\nu$ of the corresponding mode, respectively. The next two columns contain the natural frequency f and the critical damping ratio $\zeta$, extracted from the signals of the "room-temperature" snapback tests V59.2.3 and V59.4.3 /‾2_/. The next two columns contain the f- and $\zeta$-values related to the "high temperature" snapback test V59.05 and finally the last column contains the f-values relating to the blowdown test V32. Abbreviation n.i. indicates that in the given test the corresponding value could not be reliably identified. The modal data of the snapback-test V59.05 relate to the time interval 0-8 sec, those of the blowdown test V32 relate to the time interval 0-2 sec. The eigenfrequency values obtained from these two experiments are practically identical; the mutual deviations are smaller than $\pm$ 0.5%. All eigenfrequency values summarized in table 1 as well as the corresponding theoretical predictions calculated with the computer code FLUX /‾4_/ are plotted over the circumferential order $\nu$ in fig. 2. This diagram shows that the "high temperature" eigenfrequency values are systematically about 3-5% higher than the corresponding "room-temperature" values. This is due to the reduction in density of the coupled fluid which is in accordance with the theoretical expectations. The calculated eigenfrequency values of the beam modes ($\nu$=1) and of several shell modes ($\nu$=4,5) agree well with the corresponding values extracted; the eigenfrequencies of the shell modes of the second ($\nu$=2) and higher circumferential orders ($\nu$> 5) reveal small deviations from the corresponding experimental values.

The increase of the eigenfrequencies of the core barrel, caused by the evaporation of the water charge during blowdown, is illustrated in fig. 3. The extraction of the corresponding natural frequency values was performed in six time intervals, beginning at 0, 2, 4, 6, 8 and 10 sec, repectively, each of them lasting 2 sec. The remarkable increase of eigenfrequency values of the shell modes indicates intense evaporation of the water in the shell region. The water evaporation in the lower plenum which influences primarily the fundamental beam mode, obviously begins approx. 11 sec after the start of the blowdown. At that time, only the eigenfrequency of the fundamental beam mode was identified; the contribution to the total response

of the remaining modes had already been immersed in the noise.
The values of the critical damping ratio $\zeta$ summarized in table 1 are plotted over the circumferential order $\nu$ in figs. 4 and 5. The agreement between the corresponding $\zeta$-values is not so good as for the natural frequencies in fig. 2. Two circumstances are supposed to contribute to this phenomenon. One of them is the overwhelming numerical inferiority of the real part (damping term) $\zeta_n \omega_n$ with respect to the imaginary part $\Omega_n$ in eq. (2), which causes numerical uncertainties impairing the extraction of the $\zeta$-values. The other is the strong variability of structural damping due to variable prestressing of the mutually rubbing surfaces (such as flanges), caused by the thermal stresses.
The shapes of the five modes significantly contributing to the total response of the core barrel in the snapback test V59.05 are illustrated in fig. 6. The first diagram in the upper left corner presents the basic meshed network of the developed core barrel shell in state of rest; the arrow indicates the location and the direction of the pull rod of the snapback device. The deformed network on the right illustrates the fundamental beam mode. The subroutine MODAP was used to calculate and plot these networks. MODAP has been developed to approximate the sets of R-extracted initial values $C_{rn}$ by a three-dimensional surface $C_n\ (z,\phi)$ /5/.
The other diagrams in fig. 6 illustrate three shell modes of first axial order ($\mu$=1; $\nu$=3,2 and 4, respectively) and one mode of the second axial and fourth circumferential orders ($\mu$=2, $\nu$=4).
Knowledge of the extracted modal data $\Omega_n$, $\zeta_n$ and $C_{rn}$ can be utilized to reconstruct the original response according to eq. (1). This possibility is used in fig. 7, illustrating the dynamic response of the core barrel at six successive times, t = 0, 3, 6, 9, 12 and 15 msec. Such a reconstructed response can be compared and/or correlated with the corresponding theoretical prediction and thus offers an objective quality criterion for the comparison and evaluation of different computer codes.

## 4. Conclusions

The work presented demonstrates the feasibility of an experimental modal survey in a hostile environment. The experimental procedure used is based on the application of the step relaxation technique in combination with the computer code EVA. This procedure yielded a set of 16 natural frequencies, mode shapes and critical dmaping ratios, which are consistent with the corresponding modal data obtained at room temperature. The modal data extracted can be used to verify the coupled fluid/structure-interaction codes. A preliminary comparison of the extracted natural frequencies with the corresponding theoretical values calculated with the computer code FLUX revealed satisfactory agreement.

## References

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Table I: Natural frequencies f and critical damping ratios ζ extracted (n.i. = not identified in this experiment)

| mode number | μ | ν | (V59.2.3, V59.4.3) f [Hz] | ζ [%] | V59.05 f [Hz] | ζ [%] | V32 f [Hz] |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 6.42 | 1.5 | n.i. | n.i. | n.i. |
| 2 | 1 | 1 | 6.48 | 0.46 | 6.78 | 0.16 | 6.79 |
| 3 | 1 | 3 | 12.66 | 0.094 | 13.25 | 0.15 | 13.20 |
| 4 | 1 | 2 | 12.99 | 0.14 | 13.59 | 0.16 | 13.61 |
| 5 | 1 | 4 | 20.31 | 0.073 | 21.27 | 0.095 | 21.19 |
| 6 | 2 | 1 | 26.58 | 0.48 | 27.34 | 0.36 | 27.31 |
| 7 | 2 | 1 | 26.73 | 0.24 | n.i. | n.i. | n.i. |
| 8 | 2 | 3 | 27.90 | 0.095 | 29.07 | 0.18 | 29.12 |
| 9 | 2 | 4 | 28.92 | 0.069 | 30.03 | n.i | n.i. |
| 10 | 2 | 2 | 32.85 | 0.34 | 34.62 | 0.35 | 34.67 |
| 11 | 2 | 2 | 32.97 | 0.40 | n.i. | n.i. | n.i. |
| 12 | 1 | 5 | 35.28 | 0.061 | 36.77 | 0.067 | 36.74 |
| 13 | 2 | 5 | 40.01 | 0.083 | 41.48 | 0.16 | 41.53 |
| 14 | 1 | 2 | 41.02 | 0.57 | n.i. | n.i. | n.i. |
| 15 | 3 | 4 | 45.35 | 0.079 | 47.16 | n.i. | 47.07 |
| 16 | 3 | 3 | 49.98 | 0.094 | 51.88 | 0.13 | 51.91 |
| 17 | 3 | 5 | 50.67 | 0.097 | 52.45 | n.i. | 52.70 |
| 18 | 1 | 6 | 56.57 | 0.072 | 58.45 | 0.09 | n.i. |
| 19 | 3 | 1 | 57.37 | 0.45 | n.i. | n.i. | n.i. |
| 20 | 3 | 1 | 58.00 | 0.35 | n.i. | n.i. | 59.14 |
| 21 | 2 | 6 | 59.71 | 0.064 | n.i. | n.i. | 61.72 |
| 22 | 3 | 2 | 60.02 | 0.19 | 61.67 | 0.15 | 62.62 |
| 23 | 4 | 5 | 65.96 | 0.074 | 68.23 | 0.14 | 68.01 |
| 24 | 4 | 4 | 66.18 | 0.087 | 69.00 | n.i. | n.i. |
| 25 | 3 | 6 | 66.75 | 0.11 | n.i. | n.i. | n.i. |
| 26 | 4 | 3 | 74.60 | 0.30 | n.i. | n.i. | n.i. |
| 27 | 4 | 6 | 77.43 | 0.072 | 79.94 | 0.088 | n.i. |
| 28 | 2 | 2 | 79.60 | 1.1 | n.i. | n.i. | n.i. |
| 29 | 1 | 7 | 83.75 | 0.044 | 86.27 | 0.079 | n.i. |
| 30 | 2 | 7 | 86.29 | 0.062 | 88.87 | 0.11 | n.i. |
| 31 | 3 | 7 | 91.80 | 0.10 | 94.45 | n.i. | n.i. |
| 32 | 4 | 7 | 99.79 | 0.12 | n.i. | n.i. | n.i. |

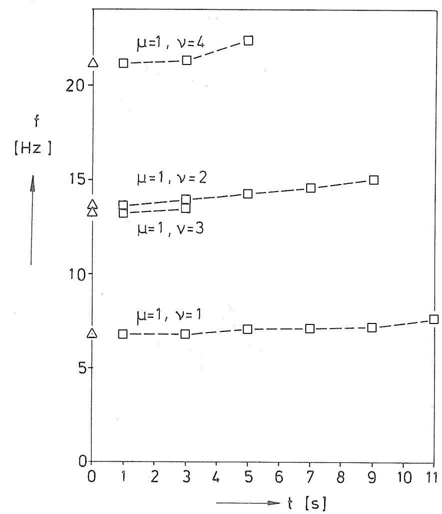


Fig. 3: Time dependence of the natural frequencies of the core barrel during blowdown

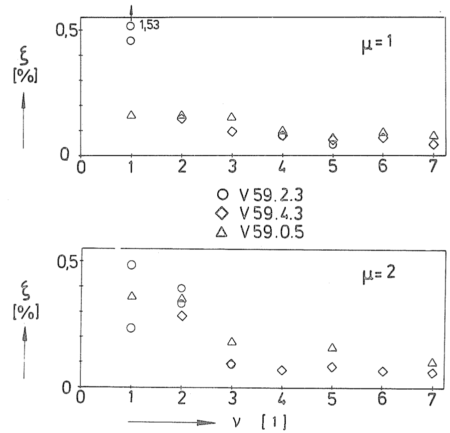


Fig. 4: Critical damping ratios extracted ($\mu$ = 1 and 2)

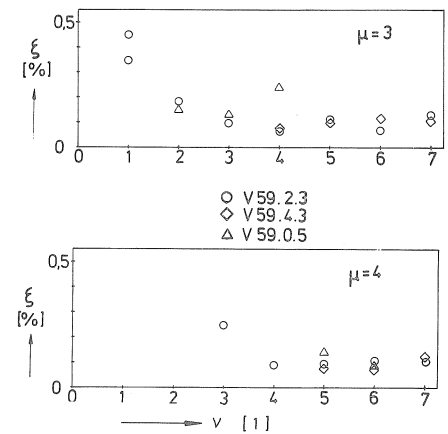


Fig. 5: Critical damping ratios extracted ($\mu$ = 3 and 4)

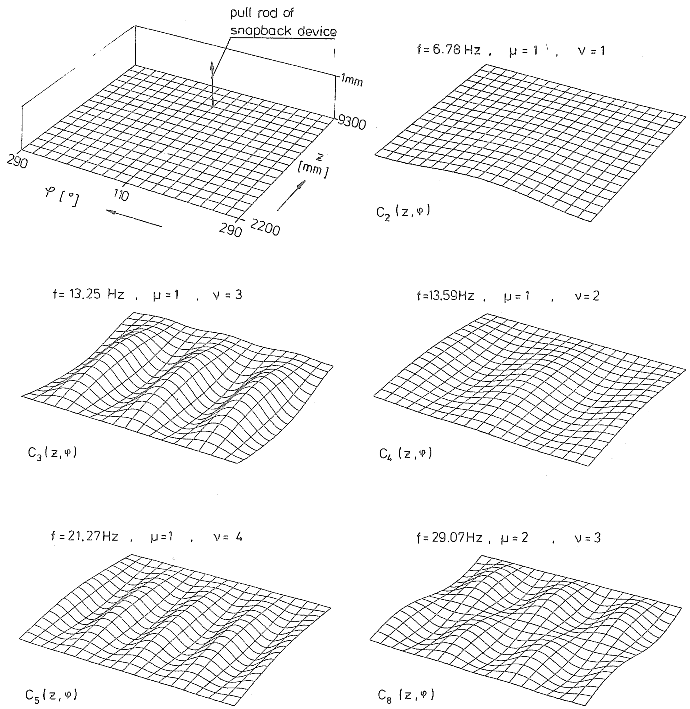


Fig. 6: Typical mode shapes extracted of the core barrel

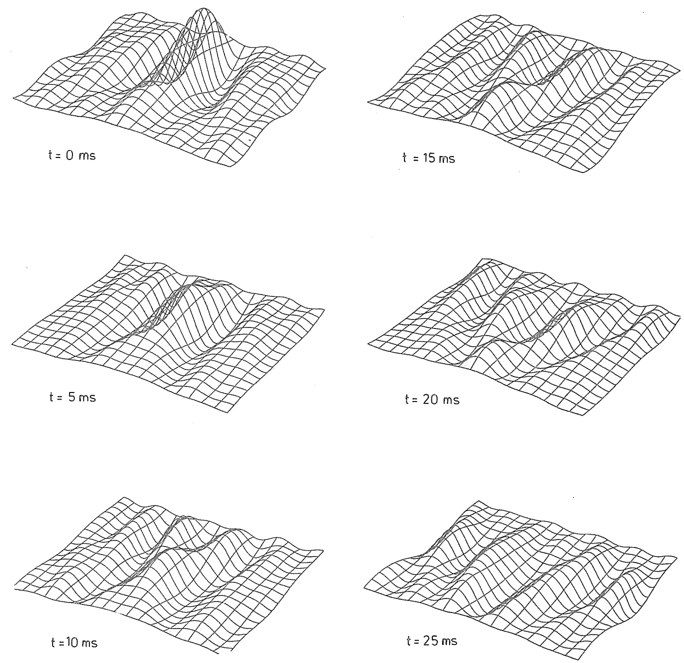


Fig. 7: Reconstructed time-relaxation response of the core barrel