11. Qualitative and Quantitative Effects of Fluid-Structural Coupling, *E. G. Schlechtendahl, U. Schumann (KFZ/Karlsruhe-Germany)*

INTRODUCTION

Many reactor components represent a coupled system of fluid and structure. For evaluation of the structural deformations caused by fluid loadings, a decoupled analysis procedure was common in the past.[1] First, the pressure field was calculated for rigid structures and then the reaction of the structure was determined subsequently. At present, advanced methods become available which treat the whole system as inherently coupled.[2,3]

In this paper, dimensionless groups are defined characterizing the effects caused by the coupling and criteria that indicate whether a coupled treatment gives significantly different results compared to the decoupled ones. The general statements are illustrated for the case of blowdown loadings on PWR vessel internals. Other examples are blast loadings on containment vessels in case of a hypothetical LMFBR core disruptive accident, loadings in the pressure suppression system of a BWR, sodium/water reaction in an LMFBR steam generator, or loadings on components in a fuel processing plant due to a chemical explosion.[4,5] Also, the behavior of a bursting pressure vessel would belong to this class of problems if one would have to analyze it in more detail. Our subject does not include flow-induced vibrations.[6] Also, the effect of large deformations is not discussed.[4]

EFFECT 1: REDUCED AND INCREASED EIGENFREQUENCIES

Because of the danger of resonance, one must be aware of the fact that the eigenfrequencies of the coupled system can differ essentially from those of the individual parts. This can be demonstrated by means of a simple model: a rigid gas-filled pipe open at one end and coupled to a flexible piston at the other end. To first order, the coupled system can be represented by[7,8]

$$\ddot{c} + \omega_S^2 c = -p/m_S, \quad \ddot{p} + \omega_F^2 p = \ddot{c}\,\omega_F^2 m_F \;, \qquad (1)$$

where c = deflection; p = pressure; ω_S,ω_F = eigenfrequencies, m_S,m_F = masses per unit area of the structure and fluid, respectively. The eigenfrequencies $\omega_{1,2}$ of this coupled system are

$$\left(\frac{\omega_{1,2}}{\omega_S}\right)^2 = \frac{1}{2}\left(1 + \left(\frac{\omega_F}{\omega_S}\right)^2 \frac{m_F + m_S}{m_S} \pm \left\{\left[1 + \left(\frac{\omega_F}{\omega_S}\right)^2 \frac{m_F + m_S}{m_S}\right]^2 - 4\left(\frac{\omega_F}{\omega_S}\right)^2\right\}^{1/2}\right) . \qquad (2)$$

We note that the coupled system possesses a reduced eigenfrequency in which structure and fluid oscillate in phase so that the inertia of both systems add together; it also has an increased eigenfrequency in which they oscillate in opposite phase so that the stiffnesses add together. This latter mode would vanish for incompressible fluids, in which case $\omega_F \rightarrow \infty$ and $(\omega/\omega_S)^2 = m_S/(m_S + m_F)$.

For more complicated geometries, m_F has to be replaced by the virtual fluid mass which is a function of the flow pattern. For instance, m_F is large if the fluid has to oscillate with large velocities through narrow passages. In case of the core barrel oscillations in a PWR, the virtual mass exceeds the actual fluid mass by orders of magnitude; in particular, with respect to the breathing mode where the fluid has to flow axially through the rather narrow downcomer.[8]

EFFECT 2: CHANGED AMPLITUDES UNDER PERIODIC FORCING

Using the same simple model, one can determine the response to an oscillating force with frequency ω. The difference between the decoupled and coupled solution amplitudes relative to the decoupled one is

$$D = \frac{m_F/m_S}{\frac{m_F}{m_S} + \left\{\frac{\omega_S^2}{\omega^2} - 1\right\}\left\{\frac{\omega^2}{\omega_F^2} - 1\right\}} . \qquad (3)$$

This difference can be small if $m_S/m_F \gg 1$ or if $(\omega_F^2 m_F)/(\omega_S^2 m_S) = s_F/s_S \ll 1$ ($s_{F,S}$ = stiffnesses). It can be small also if $\omega^2 m_S \gg s_F$ or $s_S \gg \omega^2 m_F$. The errors become extremely large in any case, however, when ω approaches one of the eigenfrequencies defined in Eq. (2). (In which case the denominator becomes zero.) In addition, the error amounts to 100% if ω equals one of the eigenfrequencies of the decoupled system.

EFFECT 3: ENERGY EXCHANGE

In a decoupled analysis the structure experiences a prescribed forcing. If the forcing spectrum contains components at frequencies close to the structural eigenfrequencies, then the structural oscillations will grow soon without limits unless a damping process is present in the structure. Thus, energy is transferred into the structure without accounting for the energy reduction in the fluid, thus violating the energy balance. For an oscillating driving force outside of the resonance range of the coupled system the decoupled analysis will give, therefore, larger amplitudes than the coupled one after a sufficient number of cycles. This difference becomes important, in particular if the process is not driven by an external forcing (as assumed above) but rather if the energy stems from the initial reservoir contained in the fluid. This is the case, e.g., in the blowdown problem where the pipe break represents only the trigger. A decoupled analysis would tend to overestimate the structural motion, especially if the initial energy in the fluid is small. In the simple model problem this is the case if s_F/s_S is large. In more complicated situations, the fluid energy is also a function of its volume V_F.

These general considerations are verified by excessive coupled and decoupled computations which have been performed for PWR blowdown conditions.[3,8] These studies have been prepared with respect to the HDR experiments[1] that are scheduled for 1979. Figure 1 shows, for example,

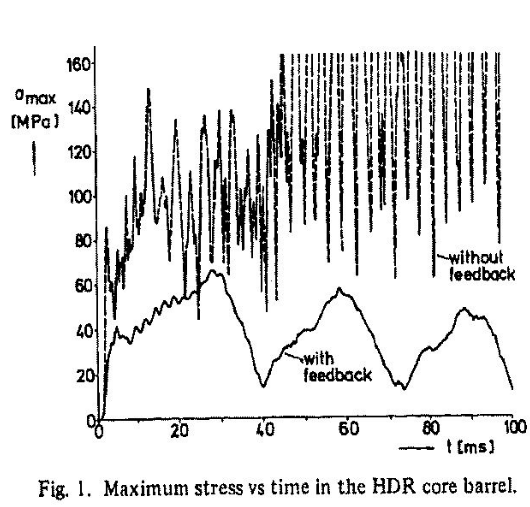

Fig. 1. Maximum stress vs time in the HDR core barrel.

TABLE I

Uncoupled Analysis Is Allowed Only if All Following Conditions Are Satisfied

structure (S) / fluid (F)		stiff	weak	
			thin	thick
stiff		$s_S >> s_F$ (1)	$\omega^2 \rho_S L_S >> s_F$ (4)	$\omega \rho_S a_S >> s_F$ (7)
weak	thin	$s_S >> \omega^2 \rho_F L_F$ (2)	$\rho_S L_S >> \rho_F L_F$ (5)	$\rho_S a_S >> \omega \rho_F L_F$ (8)
	thick	$s_S >> \omega \rho_F a_F$ (3)	$\omega \rho_S L_S >> \rho_F a_F$ (6)	$\rho_S a_S >> \rho_F a_F$ (9)

s = stiffness, ω = frequency of external loads, ρ = density, L = thickness, a = speed of sound.

the maximum stress magnitude versus time for the case of the HDR core barrel with and without structural feedback. In this case, the decoupled analysis overestimates the stresses by a factor of about 2.5 initially due to the neglected inertia of the coupled system and by even much larger factors at later times due to the "one-way" energy transfer.

On the other hand, if the initial energy in the fluid is large, both the coupled and decoupled analyses have the potential to result in large structural deformations which can by far exceed the deformation one would expect from a static analysis. In this respect, a blowdown from saturated conditions may give larger amplitudes than from subcooled initial values. It is another question how much of the initial energy can be converted into structural energy. This fraction certainly depends on the ratio of characteristic eigenfrequencies of the structure and the fluid alone. At least in one-dimensional cases, examples can be constructed[7] where this fraction comes close to the theoretical limit. It follows that a coupled analysis is required if $\omega_S \approx \omega_F$ and $s_F \gg s_S$.

GENERALIZED CRITERIA INCLUDING WAVE EFFECTS

In the simple model problem, wave propagation in either fluid or structure has not been treated. Either material was taken as thin compared to the length of pressure waves. In general, however, the maximum pressure exerted on the interface from stiffness, acoustic, and inertia effects is given by terms of the form cs_i, $\dot{c}\rho_i a_i$, $\ddot{c}\rho_i L_i$, where ρ = density, a = speed of sound, L = thickness, and i = S,F. For oscillations with amplitude c_0 at frequency ω, an upper bound can be formulated as $c_0\,(s_i + \omega\rho_i a_i + \omega^2\rho_i L_i)$. In an uncoupled analysis this term is neglected on the fluid side. Hence, uncoupled analysis can be valid only for

$$s_F + \omega\rho_F a_F + \omega^2\rho_F L_F \ll s_S + \omega\rho_S a_S + \omega^2\rho_S L_S \quad . \quad (4)$$

This criterion may be written in a tabular form if we distinguish between "stiff" [$s_i > \text{Min}\,(\omega\rho_i a_i, \omega^2\rho_i L_i)$] or "weak," and "thick" [$a_i < \omega L_i$] or "thin" material layers.

Criteria 1, 2, 4, and 5 coincide with $|D| \ll 1$ in Eq. (3).

Note that these criteria are *necessary* to permit an uncoupled analysis but they are not sufficient. In addition: the frequency of external loads must not be near the *eigen*frequencies of the *coupled* system.

From this analysis, we conclude:

Problem	Violates Criterion
BWR pressure suppression	2
Blowdown effects in reactor vessel	1 and 5
Local fuel-coolant interaction in LMFBR subassemblies	5
Slug impact on LMFBR vessel head	8
LMFBR vessel reaction on a hypothetical core disruptive accident	6
Pressure vessel rupture	9

Therefore, coupled analysis is mandatory for all these examples.

1. R. KRIEG, E. G. SCHLECHTENDAHL, and K.-H. SCHOLL, "Design of the HDR Experimental Program on Blowdown Loading and Dynamic Response of PWR-Vessel Internals," *Nucl. Eng. Design*, **43**, 419 (1977).

2. T. BELYTSCHKO, "Methods and Programs for Analysis of Fluid-Structure Systems," *Nucl. Eng. Design*, **42**, 41 (1977).

3. E. G. SCHLECHTENDAHL, R. KRIEG, U. SCHUMANN, and C. W. HIRT, "Analyse der fluid-strukturdynamischen Wechselwirkung von Reaktordruckbehältereinbauten beim Blowdown," KFK 2570, p. 127, Kernforschungszentrum Karlsruhe (1977).

4. N. E. HOSKIN and M. J. LANCEFIELD, " 'The COVA Programme' for the Validation of Computer Codes for Fast Reactor Containment Studies," *Nucl. Eng. Design*, **46**, 17 (1978).

5. R. KRIEG, "Coupled Problems in Transient Fluid and Structural Dynamics in Nuclear Engineering, Part 1," *Appl. Math. Modeling*, **2**, 81 (1978).

6. Y. S. SHIN and M. W. WAMBSGANSS, "Flow-Induced Vibration in LMFBR Steam Generators: A State-of-the Art Review," *Nucl. Eng. Design*, **40**, 235 (1977).

7. U. SCHUMANN, "Fluid-Structure Interactions in One-Dimensional Linear Cases," Kernforschungszentrum Karlsruhe, to be published (1978).

8. U. SCHUMANN, "Effektive Berechnung Dreidimensionaler Fluid-Struktur-Wechselwirkung beim Kühlmittelverluststörfall eines Druckwasserreaktors–FLUX," KFK 2645, Kernforschungszentrum Karlsruhe (1978).