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NUMERICAL SIMULATION OF HYDROELASTIC MOTION WITH

APPLICATION TO THE FULL-SCALE HDR TESTS

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SUMMARY

The K-FIX(3D,FLX) code for coupled fluid-structure interaction simulation has been undergoing extensive testing in preparation for the full scale blowdown and snapback tests in the German HDR Project (Fig. 1). K-FIX(3D)[1] solves the three-dimensional, two-fluid equations for two phase flow to describe the fluid dynamics. FLX[2] solves the three-dimensional, linear-elastic shell equations to describe the core barrel dynamics. The shell equations and features of the FLX code are given in Figs. 2-4. The results of several calculations have been compared with analytic solutions[3] for the core barrel motion in vacuum. The comparisons include frequencies and mode shapes of torsional and lateral vibrations and the stiffness to lateral displacement. The core barrel motion is excited by prescribed displacement, as will occur in the snapback tests, and by horizontal shaking of the vessel produced through the codes' option to simulate seismic disturbances. The calculated motion of the core barrel bottom is shown in Figs. 5 and 6 following its release from an initial 3.5 mm deflection and in response to a horizontal harmonic vessel motion. The radial displacement histories are well described by $W = -3.5 \cos(35.8\,\pi t)$ and $W = -0.93\,[\cos 10\pi t - \cos 35.2\,\pi t]$, respectively, which

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yield frequencies of 17.9 Hz and 17.6 Hz compared with the analytic determination of 17.0 Hz. Without the mass ring, similar calculations produce the bottom motion shown in Figs. 7 and 8, which exhibit frequencies of 38.6 Hz and 37.9 Hz, respectively, compared with the analytic value of 35.5 Hz.

The analytic results are obtained by a perturbation solution[4] of the Timoshenko beam equations[5] that include the effects of shear and rotary inertia. Solution of the classical beam equations, which neglect both these effects, yields a frequency of 45.2 Hz without the mass ring. Most of the 22% reduction associated with the solution of the Timoshenko equations is due to the softening effect of shear. The significance of shear is likely to be even greater for a U.S. PWR where the length-to-diameter ratio of the core barrel is much smaller than in the HDR. The deflection profiles for the fundamental mode associated with the Timoshenko and classical beam equations' solutions and the FLX solution are compared in Fig. 9. The FLX solution and the solution to the Timoshenko equations are in quite good agreement.

The ratio of the force applied at the core barrel bottom to the deflection there is defined as the stiffness, which depends on the size and material properties of the core barrel. For a deflection of 3.5 mm, the FLX solution indicates a force of 0.67×10^{11} dyn is needed, which implies a stiffness of 1.91×10^{11} dyn/cm. Solution of the Timoshenko equations yields 1.81×10^{11} dyn/cm.

The frequency and mode shape of core barrel motion initiated by torsion about the longitudinal axis has been determined analytically including the mass ring. The FLX calculation exhibits a torsional frequency of

22.0 Hz, which agrees precisely with the analytic solution. The mode shapes are compared in Fig. 10 at the end of one period and are also in excellent agreement.

The analytic solutions have provided a valuable standard against which to compare the numerical results without introducing the uncertainties and added complexities associated with the realities of experiments. These comparisons augment parameter and sensitivity studies to provide insight into the relative significance and origin of departures between calculated results and data.

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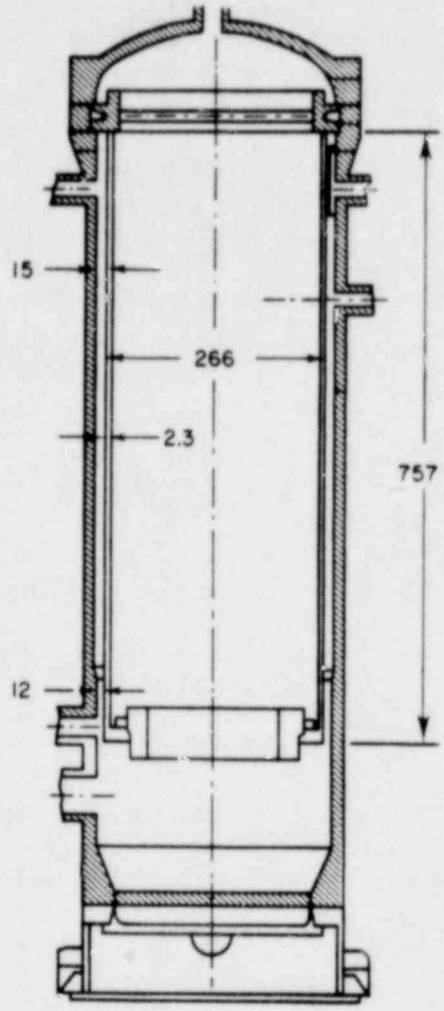


Fig. 1. Geometry of the HDR vessel (dimensions in cm).

$$\rho h\,\ddot{U} = N_\phi^0 + N_{\phi z}' - M_\phi^0/a + M_{z\phi}'/a + \rho h(\ddot{x}\sin\phi - \ddot{y}\cos\phi) \quad ,$$

$$\rho h\,\ddot{V} = N_z' + N_{\phi z}^0 - \rho h\,\ddot{z} \quad ,$$

$$\rho h\,\ddot{W} = q - M_z'' + 2M_{z\phi}^{0'} - M_\phi^{00} - N_\phi/a - \rho h(\ddot{x}\cos\phi + \ddot{y}\sin\phi) \quad ,$$

$$N_z = C(V' + \nu U^0 + \nu W/a) \quad ,$$

$$N_\phi = C(U^0 + W/a + \nu V') \quad ,$$

$$N_{\phi z} = C(1-\nu)(V^0 + U')/2 \quad ,$$

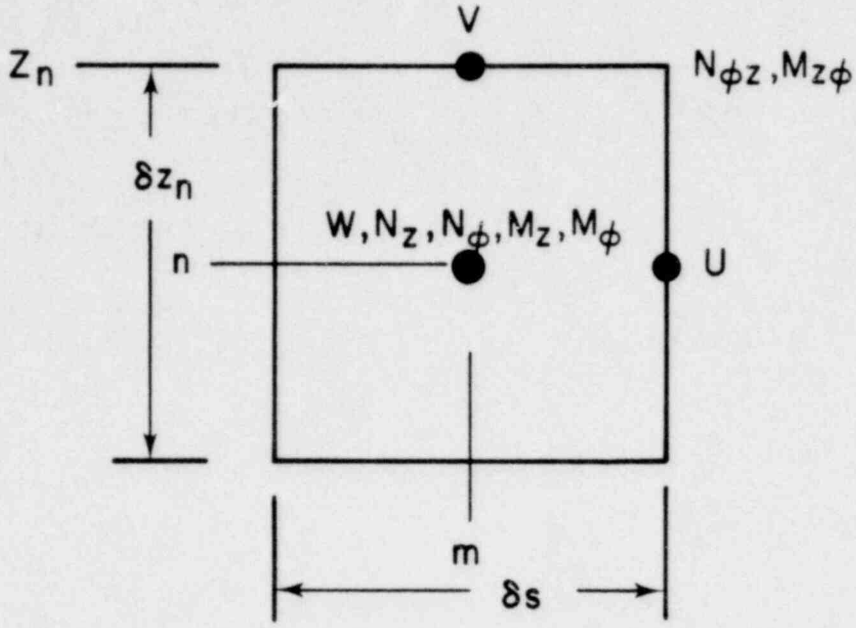
$$M_z = D(W'' + \nu W^{00} - \nu U^0/a) \quad ,$$

$$M_\phi = D(W^{00} + \nu W'' - U^0/a) \quad ,$$

$$M_{z\phi} = -\,D(1-\nu)(W^{0'} - U'/a) \quad ,$$

$$C = Eh/(1-\nu^2) \quad , \quad D = Eh^3/12(1-\nu^2) \quad .$$

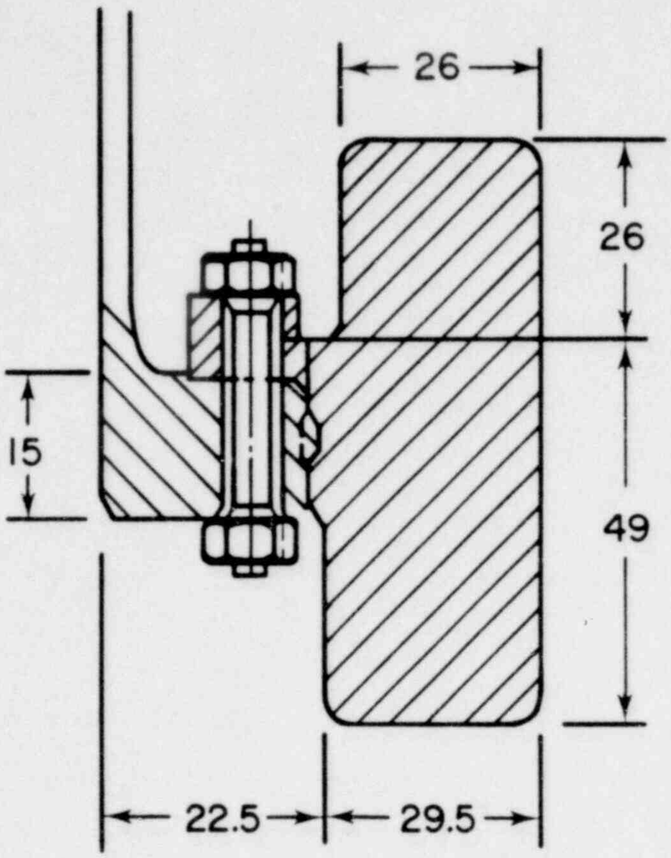
Fig. 2. The three-dimensional, elastic shell equations. In these equations, U, V, and W are the circumferential, axial, and radial displacements, respectively; ρ is the density; ($\rho = 7.9\ g/cm^3$); h is the thickness (h = 2.3 cm); a is the radius of the middle surface (a = 131.85 cm); ν is Poisson's ratio ($\nu = 0.3$); q is the differential pressure between the inside and outside of the core barrel; and E is Young's Modulus (E = 1.95 x 10^{12} dyn/cm^2).



$$\rho h \ddot{V} = N_z' + N_{\phi z}^{0}$$

$$N_z = C(V' + \nu U^0 + W/a) \qquad N_{\phi z} = C(1 - \nu)(V^0 + U')/2$$

Fig. 3. Location of variables for a computational cell in the FLX code.



FLX Ring Model

- Location
- Mass
- Volume
- Stiffness

Fig. 4. Detail of the HDR mass ring and features of the FLX mass ring model.

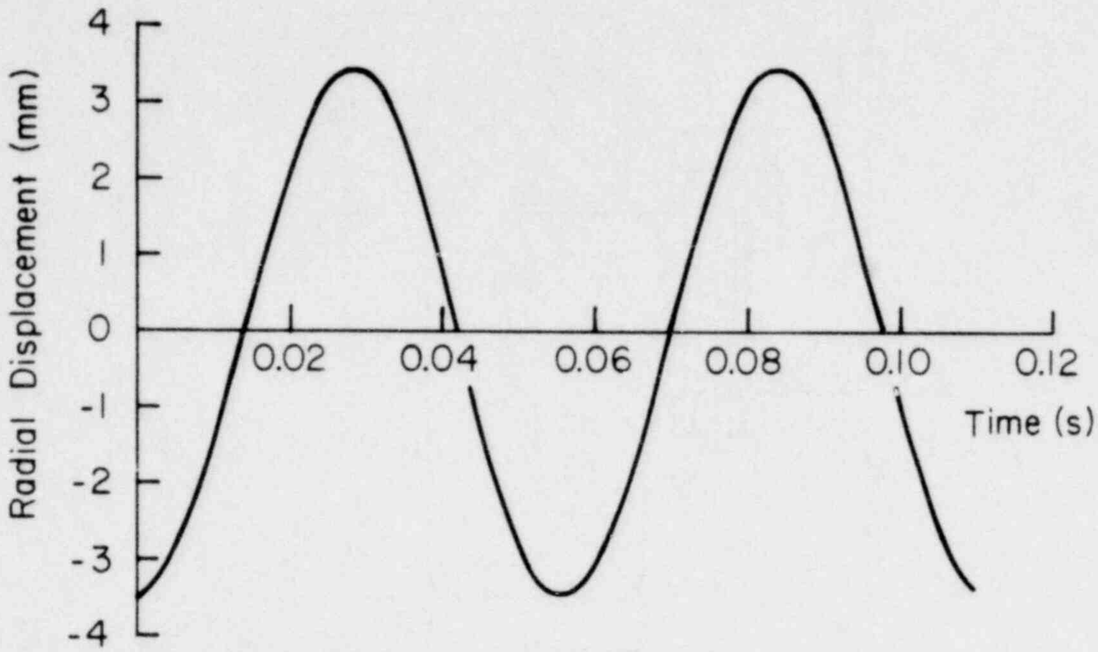


Fig. 5. Calculated radial displacement history of the core barrel bottom after release from a static configuration in which the core barrel bottom is deflected 3.5 mm. The frequency is 17.9 Hz.

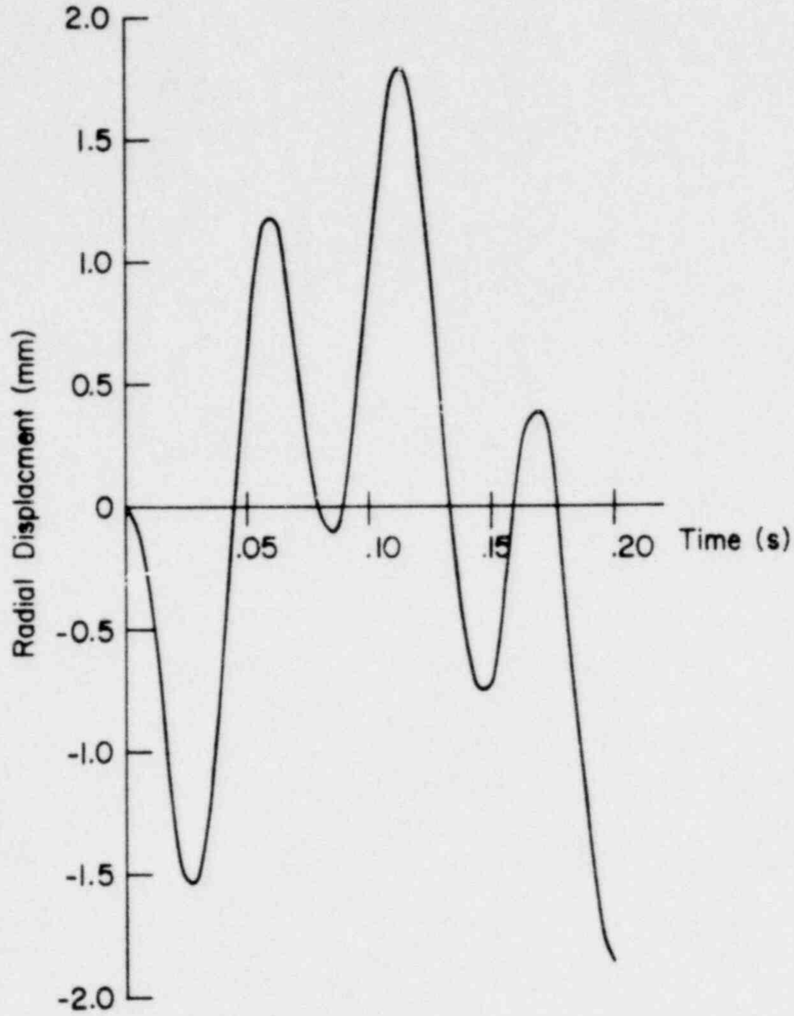


Fig. 6. Calculated radial displacement history of the core barrel bottom in response to a horizontal harmonic vessel acceleration $\ddot{x}$ = 980 cos 10 πt. The frequency is 17.6 Hz.

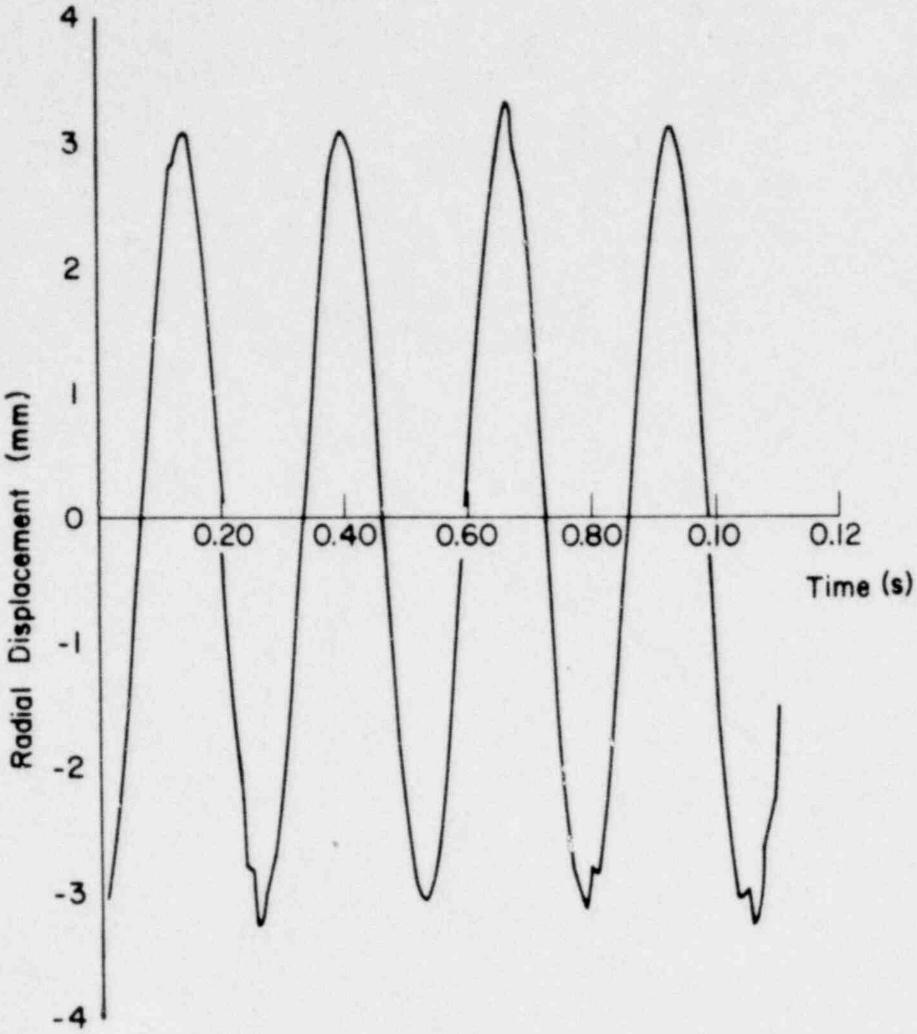


Fig. 7. Calculated radial displacement history of the core barrel bottom without the mass ring. The motion is initiated by prescribing the three components of the displacement field from solution of the Timoshenko beam equation. The frequency is 38.6 Hz.

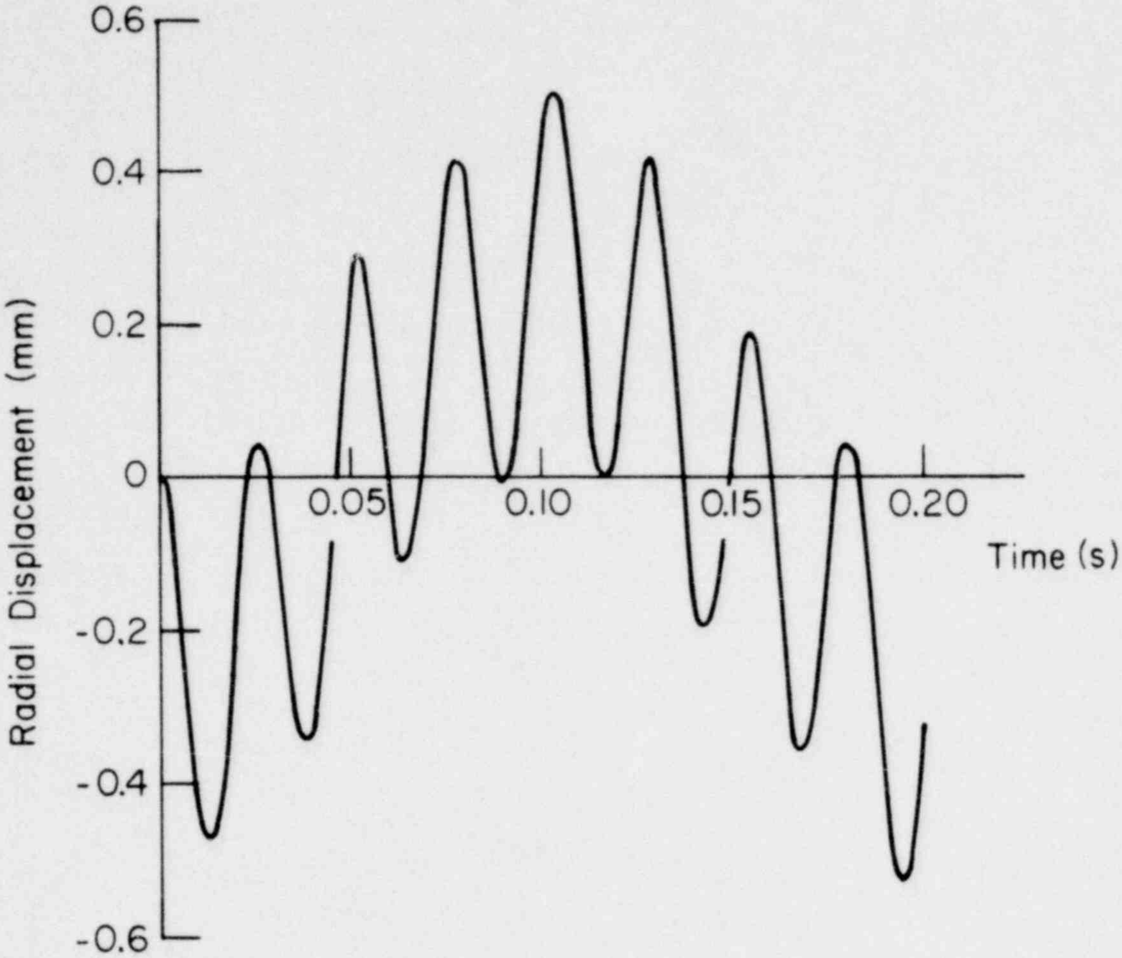


Fig. 8. Calculated radial displacement history of the core barrel bottom without the mass ring in response to a horizontal harmonic vessel acceleration $\ddot{x}$ = 980 cos 10 πt. The frequency is 37.9 Hz.

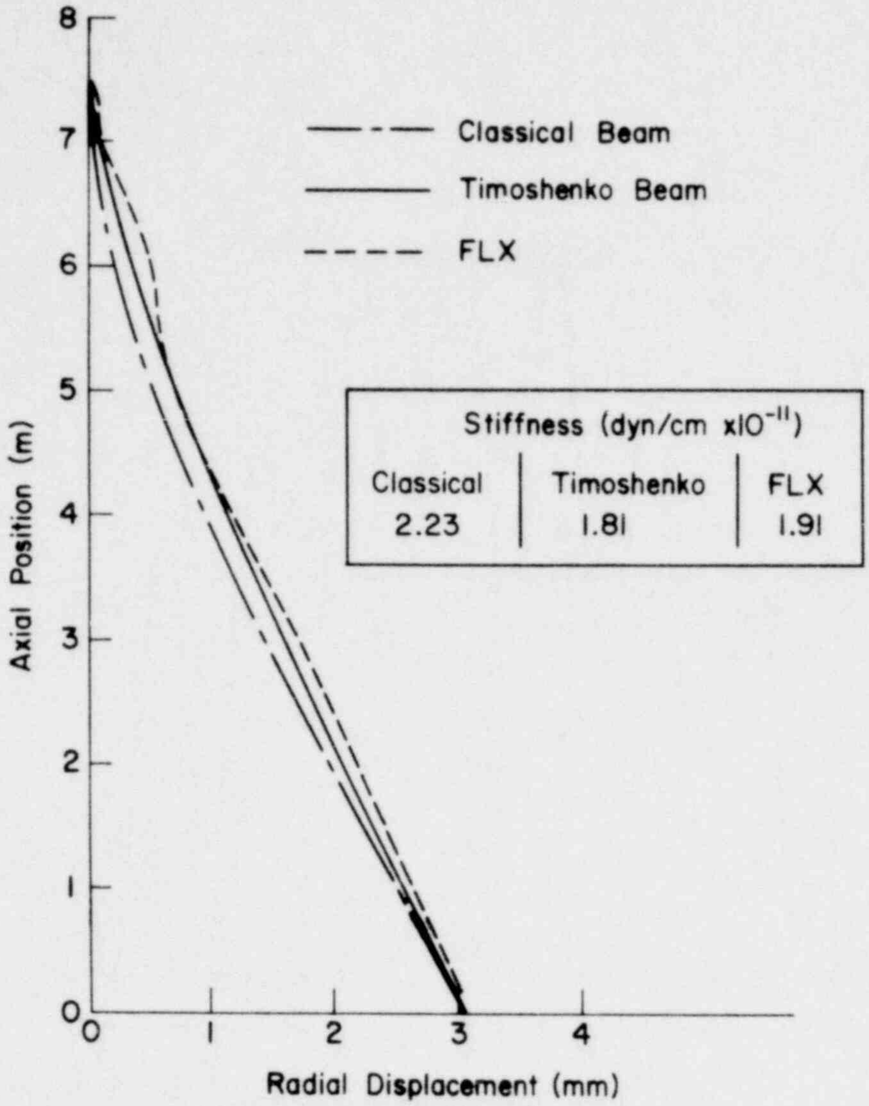


Fig. 9. Fundamental mode shape calculated with FLX compared with analytic results for solutions of the classical and Timoshenko beam equations.

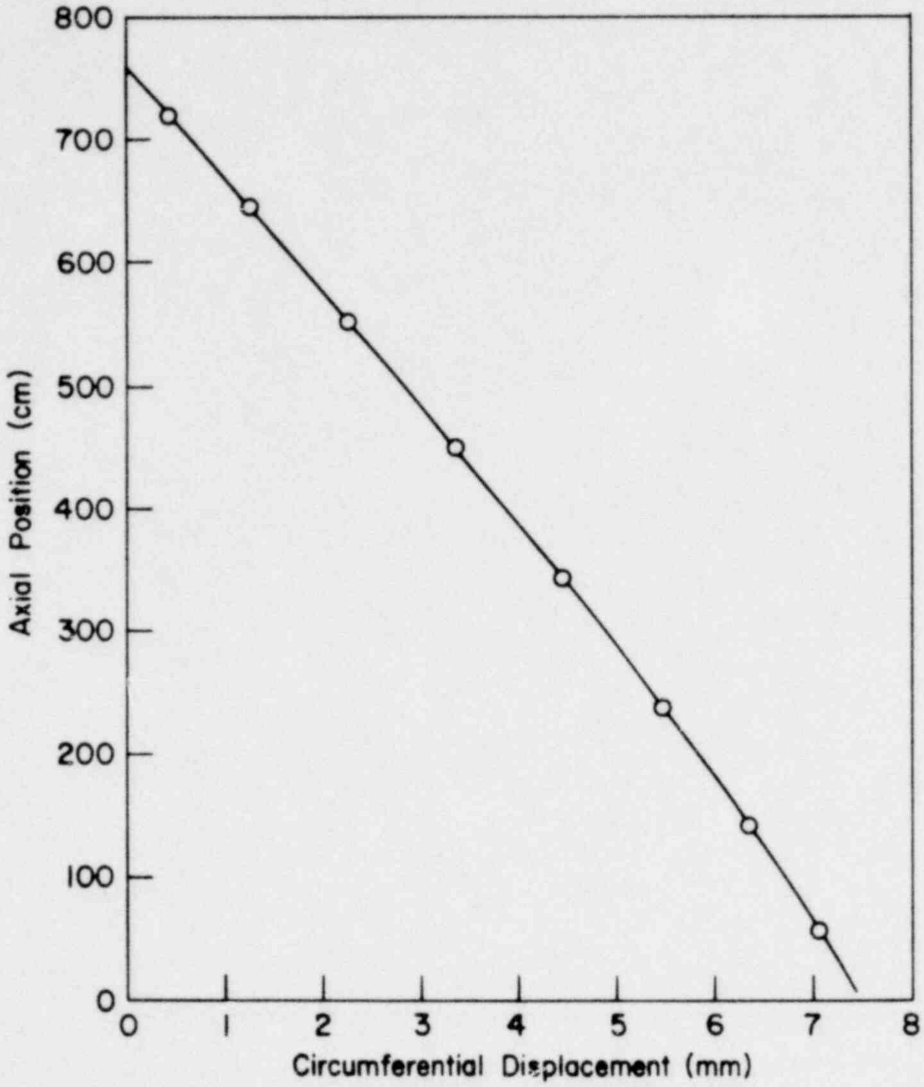


Fig. 10. Fundamental torsional mode shape calculated with FLX compared with the analytic result. The calculated torsional frequency is 22.0 Hz, which agrees precisely with the analytic solution.