

Three-Dimensional Coupled Responses of a Vertical Deep-Ocean Pipe: Part I. Excitation at Pipe Ends and External Torsion

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ABSTRACT

For the simulation of three-dimensional (3-D), nonlinear, coupled axial, bending and torsional responses of a very long pipe system, a new nonlinear FEM code is developed, and a 4,000-ft-long vertical ocean-mining pipe is analyzed. The pipe top is pinned to a ship, while the bottom end of the pipe is connected to equipment on the seafloor. The pipe system is subject to a vertically varying current in establishing the static (initial) equilibrium configuration. For dynamic analysis, the pipe is excited by periodic horizontal, as well as vertical, ship motions at the pipe top and the periodic vertical motion of the equipment on the seafloor. It is also subject to the internal slurry flow and the external hydrodynamic forces. For torsional coupling, a consistent mass-matrix formulation is used. The external flow-induced torsional moment induces the biaxial bending in response to the ocean current and causes appreciable pipe twist. Excitation with concurrent axial and horizontal motions reduces the mean pipe deflections from the static equilibrium. Resonance frequencies for the present nonlinear coupled responses are different from those of the linear vibrations. Varying axial forces and bending moments change the natural frequencies of vibrations of a pipe column. The excitation frequency dominates the pipe vibration frequency, except for the torsional vibration. The period of the coupled torsional vibrations is the torsional resonance, which is twice the fundamental period of the linear system. The mean internal upward slurry flow reduces the axial stress and increases the mean bending deflection. Stability of the solutions is sensitive to the specific sequence of load steps, large torsional moment, excitation frequencies, and excessive axial excitation amplitudes. The biaxial bending (y -) and torsional vibrations are most sensitive to the time-step size. Part II presents the case of the free pipe bottom, which shows some response characteristics different from Part I.

INTRODUCTION

The importance of the axial stress for design was first pointed out by Chung and Whitney (1981), for which only uncoupled axial stress was investigated for deep-ocean manganese nodule mining with an 18,000-ft vertical pipe. The present paper points out the necessity of the three-dimensional (3-D) modeling coupled with the torsional deformation for the pipe design. A recent Pacific survey (Yamazaki, 1993) indicates that the seafloor slopes can be as steep as 20° in the area of cobalt-rich manganese crust reserves. Crust reserves also found beneath the sediment layer were as rich as the surface crust. The preliminary findings indicate that the crust mining (or recovery) would require a more complex technology than that for the nodule recovery from the seafloor of 3,000-6,000 m depth (Chung, Huttelmaier and Cheng, 1994).

One of the most crucial technological problems for the slow, continuous movement of a ship and seafloor mining system is the development of a reliable pipe system, which connects the seafloor to the ship. Chung (1994) presented new pipe system

concepts and the engineering evaluation of seafloor crust-fracturing equipment that can recover the seafloor-surface crust and buried crusts and operate on a steep slope. Among many possible problems, dynamic axial stresses were found to be a very critical design parameter for such a deep-ocean pipe (Chung et al., 1981a). Since then, Aso (1992), among much research on axial vibrations and stresses, proposed an axial vibration absorber, using analysis with an uncoupled solution for the crust mining pipe. Huang (1991) formulated a 3-D model without torsional coupling for the analysis of marine risers.

Recently, Chung and Whitney (1993) reported the external flow-induced torsional moments caused by asymmetric arrangement of cables and equipment around the long pipe. Deep-ocean mining pipe may be equipped with power cables for underwater equipment such as a buffer at the pipe bottom, compressed-air pipe, and pump-power cables. However, there were no solutions of the dynamic problems, such as the 3-D deformations coupled with the torsional deformation. While implicit time integration and a finite element model (FEM) (Chung et al., 1980, 1981b, 1981c) were regarded by many as a most advanced model, they did not account for the torsional moments and also had some drawbacks of causing numerical instability beyond a critical pipe velocity. Moreover, details of this proprietary technology have not been made available to the literature.

In order to evaluate mining system concepts and their improvement, a computer code simulating a nonlinear axial (z -) bending (x - and y -) torsional (θz -) pipe responses (Fig. 1) was developed

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Unit conversion: 1 m = 3.281 ft, 1 ft/s = 0.305 m/s.

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KEY WORDS: Coupled pipe dynamics, periodic excitation, linear, nonlinear, axial, bending and torsional vibrations, biaxial vibrations, resonance frequency, deep-ocean mining, 4,000 ft, seafloor equipment.