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

Jin S. Chung*
Department of Engineering, Colorado School of Mines, Golden, Colorado, USA

Bao-rong Cheng**
Tsinghua University, Beijing, China

H.-P. Huttelmaier
Department of Engineering, Colorado School of Mines, Golden, Colorado, USA

ABSTRACT

Three-dimensional (3-D), nonlinear, coupled, axial, bending and torsional responses of an 18,000-ft pipe system are studied with the new nonlinear finite element method (FEM) code presented in Part I with an example of the recovery of manganese nodules in the Pacific Ocean. For this Part II, the pipe top is pinned to a ship in waves, and its bottom end is attached with equipment (e.g., buffer) and is free and independent of the self-propelled seafloor nodule miner. The pipe system is subject to a vertically varying, current flow when establishing the static equilibrium configuration. For dynamic analysis, the pipe top is excited by periodic large-amplitude horizontal, as well as vertical, motions, the internal slurry flow, and the external hydrodynamic forces. For torsional coupling, a consistent mass-matrix formulation is used. The external torsional moments induce biaxial bending deflection and vibration in response to a unidirectional ocean current and cause a large pipe twist. The axial-to-torsion and axial-to-bending couplings are found to be strong. Response periods to large-amplitude excitations vary from the top to bottom of the pipe. The upward internal slurry flow reduces the axial stress and increases the horizontal displacements. Numerical stability of the solution is sensitive to the specific sequence of load steps, large flow-induced torsional moment, excitation frequencies, and excessive axial excitation amplitudes. The present response characteristics are quite different in many aspects from those examples in Part I with both ends of the pipe restrained.

INTRODUCTION

In the '70s and '80s (Chung, 1985; Chung and Tsurusaki, 1994), some international consortia of private corporations conducted extensive research and developed manganese nodule recovery technologies and mining systems for test operations in the 10,000-18,000-ft ocean floor. One of the more advanced technologies are reviewed in Chung and Tsurusaki (1994). The importance of axial stress as a design parameter was first pointed out by Chung and Whitney (1981a), for which only an uncoupled axial stress was investigated for an 18,000-ft vertical pipe. The study pointed out the necessity to use the coupled cases for pipe design.

One of the most crucial technological problems for the slow, continuously moving ship and seafloor mining system is to develop and simulate the coupled dynamic responses and control of a pipe system, which connects the seafloor to the ship. It requires a nonlinear coupled axial-bending-torsion dynamic analysis (Chung, 1980-1981). Among many possible problems, dynamic axial stresses have been found to be a very critical design parameter for such a deep-ocean pipe (Chung and Whitney, 1981b). Since then, research on axial vibrations and corresponding stresses has been carried out by numerous investigators for the development of marine risers and a long pipe with uncoupled cases (Aso, 1991).

Recently, Chung and Whitney (1994) reported the torsional moments caused by the relative ship-current flow asymmetric to the pipe and cables and by the buffer at the pipe-bottom level. A deep-ocean mining pipe may be equipped with power cables for underwater equipment, such as a buffer at the pipe-bottom end, compressed-air pipe for air-lift, and pump power cables. However, little evidence has been found for the solution of the above coupled dynamic problems, especially including the flow-induced torsional moment and fluid-structure interactions. While implicit time integration and a finite element model (FEM) without the torsional moments (Chung, Whitney and Loden, 1980, 1981; Chung and Felippa, 1981b) were regarded (Huang, 1991) as one of the most advanced models, they also had a drawback: The possibility of causing numerical instability beyond a critical pipe velocity. Moreover, details of this proprietary technology have not yet been made available to the literature.

In order to evaluate mining system concepts and their improvement, a FEM computer code simulating nonlinear axial-bending-torsional pipe behavior is developed and validated for both static and dynamic solutions, as presented in Part I (Chung, Cheng and Huttelmaier, 1994). Equations of the hydrodynamic forces and the finite element modeling are not repeated here and should be referred to Part I.

PIPE MODEL AND COUPLED RESPONSES

The manganese nodule recovery pipe system in a 10,000-18,000-ft-deep ocean (Chung, Whitney and Loden, 1980) is used for the present analysis (Table 1). The pipe top is pinned with no rotation allowed about the pipe axis ($\theta z = 0$), while its bottom end

* ISOPE Member.
** Currently a visiting scholar at Colorado School of Mines, Golden, Colorado, USA
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, large deflection, large amplitude, axial, bending and torsional vibrations, biaxial vibrations, resonance, deep-ocean mining, 18,000 ft.