博 士（工 学） チットラジャヤ ハリャディ グナワン

学 位 論 文 題 名

Dynamic Characteristics of Cylindrical Shells Partially Buried in Elastic Foundations

（部分的に分布する弾性基礎上の円筒シェルの動的特性）

学位論文内容の要旨

Cylindrical shells are extensively used in engineering fields in the form of structural components for storage tanks, pressure vessels, processing equipment, water ducts, subsea/ground pipelines, and in other applications. The strength, lightness, and spatial properties of the shells have been recognized as major advantages over other types of structures. On the other hand, the shells exhibit complex behaviors related to their characteristics in both the static and dynamic states. The problems are becoming more complex when considering the effects of foundations surrounding a shell and the interactions between fluid and shell. Pipelines conveying liquids are a real example of these problems. Failure of such structures during service imposes intolerable damage and costs on the surrounding environment and ecosystems. Therefore, an advanced analysis of the characteristics of cylindrical shells is needed to provide reliable information for the design of such structures. There are numerous studies of cylindrical shells that do not consider the presence of foundations. However, one problem that has not been fully investigated in the structural analysis is *how* a partially distributed elastic foundation affects the dynamic behavior of cylindrical shells. In practical applications, the shells are laid on a soil medium which may be considered as an elastic foundation. The problem seems as classical as beams on elastic foundations, but only a few literatures dealing with the problem is available. The main objectives of the present study may be summarized as follows: (1) to show the applicability of the semi-analytical finite element method to cylindrical shells partially buried in elastic foundations; (2) to give a better picture of the dynamic characteristics of the structures; (3) to determine details of the effect of the elastic foundation on the overall behavior of the cylindrical shell; and (4) to obtain general rules of the problem for use in the design of such structures.

The study investigates the dynamic characteristics of empty and fluid-loaded thin elastic circular cylindrical shells partially buried in elastic foundations by a semi-analytical finite element method. The shell is discretized into cylindrical finite elements. Two types of shape functions are considered: simple polynomial and analytical shape functions. Simple polynomial shape functions are commonly used in the classical finite element method. The analytical shape functions are derived from the governing equations of the empty shells disregarding terms corresponding to the elastic foundations. The foundations are represented by elastic springs distributed partially in the circumferential direction. Non-uniformities in the foundations in the circumferential direction are handled by a Fourier series and in the longitudinal direction by an element mesh strategy. The internal fluid is assumed to be incompressible, invicid, and the fluid motion is irrotational so that the flow can be described by a velocity potential which satisfies the Laplace equation. The hydrodynamic pressure acting on the shells is derived from the condition for dynamic coupling of the fluid-structure. In this study, the fluid domain in the sectional plane is treated analytically without discretization into finite elements.

The outline of the thesis is as follows:

Chapter 1 summarizes the general background of the study with emphasis on the importance of the analysis. It reviews previous work by other researchers. The overall approach including the general assumptions, methods, and objectives of the study are defined.
Chapter 2 develops the analytical model and basic formulation of cylindrical shells partially buried in elastic foundations. The chapter summarizes the derivation of the elemental matrices for the shell, foundation, and fluid. Simple polynomial and analytical shape functions used in the study are detailed in this chapter.
Chapter 3 describes the behavior of shells partially buried in elastic foundations and subjected to static loads namely gravity and internal liquid pressure loads. Convergence studies of the present method show that the accuracy of the solution depends on the total number of finite elements as well as on the total number of circumferential waves used to truncate the series. Different shell geometries give rise to different convergence behaviors. For relatively thin shells subjected to the gravity load, there are extreme values of the moments near the boundary between shell and foundation. The latter part of the chapter presents results for shells partially suspended on elastic foundations under an internal liquid pressure load.
Chapter 4 discusses the natural frequencies and modes of vibrations for empty shells on elastic foundations. Parametric studies on the distribution of natural frequencies for various shell geometries and foundation parameters are presented. As the spring stiffness increases, the natural frequencies increase differently for different shell geometries. In correlation to the free vibration analysis of empty shells, an energy analysis was conducted to provide better insights into the mechanics of the vibration. Based on the results, it was found that the dominant circumferential wave numbers band and shift to higher wave numbers as the radius-to-length ratio increases. A comparison of the solutions obtained by simple polynomial and by analytical shape functions is provided. The analytical shape functions show significant improvement in the convergence behavior and are therefore used in the analysis in the following chapters.
Chapter 5 deals with the interactive behavior of shell, foundations, and internal fluid. Generally, the natural frequencies of empty shells are lowered by the presence of the fluid. The natural frequencies of fluid-filled shells vary with the radius-to-length ratio in a manner similar to those of empty shells. For shells conveying fluid, the system experiences instabilities at certain high velocities, firstly due to divergence and secondly due to coupled-mode flutter after re-stabilization. The flow velocity corresponding to the first instability is the so-called critical velocity. The critical velocity of shells is increased by the existence of the elastic foundations.
Chapter 6 discusses the dynamic response of cylindrical shells on elastic foundations to localized impact loads. The effect of the foundation parameters is investigated in detail. Dynamic load factors for empty and fluid-filled shells are derived to provide detailed information for design purposes. Based on the results, it was found that the dynamic load factors both for empty and fluid-filled shells are quite similar in values.
Chapter 7 summarizes the results of the study and details the conclusions obtained by the present method. Important remarks regarding the behavior of the structure under consideration are also provided.

Finally, it is concluded that the present formulation is useful for analyzing cylindrical shells partially buried in elastic foundations. Non-uniformities in the foundation in the circumferential and longitudinal directions are simple to deal with while at the same time the method preserves the simplicity of the finite element method in applying boundary conditions. The present study provides fundamental information on the dynamic characteristics of cylindrical shells partially buried in elastic foundations.

学位論文審査の要旨

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（部分的に分布する弾性基礎上の円筒シェルの動的特性）

石油、ガスなどのライフライン施設に用いられる管路の動的挙動の解明は、しばしば地盤—流体—構造相関問題としての取り扱いを要求される。しかし、これまでの取り扱いのほとんどは、地中にある管路を対象にし、梁理論に基づくものである。

本論文は、今後用途の拡大が予想される地盤上に敷設される管路を取り上げ、その動的挙動をより正確に把握するために管路を円筒シェル理論で記述し、上述の相関問題の定式化を行い、1) 高効率・高精度な解析手法の提示及び 2) これらの構造物を設計する上で、必須の工学的課題である自由振動特性と動的応答特性の把握を目的にしている。

第 1 章では、本研究で考察する部分的に分布する弾性基礎上の円筒シェル (以下、「構造物」と称する) に関する既往の研究成果 (計算方法、動的特性) を概観し、本研究のこの研究分野における重要性を位置づけるとともに、研究の目的と意義を明らかにしている。

第 2 章では、第 3 章から第 5 章で用いられる解析モデルと有限要素法に基づく各種の要素マトリックスについて一括述べている。すなわち、円筒シェルの剛性・質量マトリックス、弾性基礎の地盤剛性マトリックス、流体の付加質量マトリックス及び流体速度に依存する付加減衰・付加剛性マトリックスの導出を、形状関数に多項式を採用する場合と空中にある円筒シェルの常微分方程式の余解を採用する場合について行っている。

第 3 章では、「構造物」の動的挙動を理解する上に必要不可欠となる静的解析を自重とシェル内部に液体が存在する場合について行っている。

第 4 章では、解析手法の特性と「構造物」の動的挙動を解明する上で有益な情報を与える自由振動特性について、液体のない場合を対象にして述べている。まず、解析手法については、変位関数にシェルの微分方程式の与解を用いれば比較的少ない自由度で高精度の解が得られ、R/h(R=シェルの半径、h=厚さ) の値が大きい「薄いシェル」では要素分割数が、R/h の値が小さい「厚いシェル」では地盤ばねの円周方向フーリエ級数の展開項級が支配的な離散化因子であることを明らかにしている。次に、自由振動特性については、半径方向地盤ばね定数 (kw) に対する弾性基礎と円筒シェルの相対剛性比の変化は、「厚いシェル」では地盤ばねの円周方向分布角度の増加と伴に線形

分布に近づき、一方「薄いシェル」ではkwの小さい範囲で増加し、それ以後はほほ一定となるという特徴を見出している。

第5章では、液体の「構造物」の自由振動特性に与える影響を検討している。自由振動特性を特徴付ける流体と円筒シェルの等価質量比の地盤ばね定数(kw)に対する変化は、「薄いシェル」と「厚いシェル」では大きく異なり、「厚いシェル」の場合において、kwの値の増加と伴に単調に減少することを明らかにした。さらに、流速は固有振動数に大きな影響を与え、流速の増加と伴に固有振動数は減少すること、ダイバージェンス型不安定となる限界流速(固有振動数が零になるときの流速)の値はR/hの値が大きい程また地盤ばね定数(kw)の値が小さい程小さくなることを明らかにしている。

第6章では、外力として、分布矩形パルス力が作用する「構造物」の応答解析を行い、変位・応力に関する基本的特性を調べている。すなわち、パルス載荷時間と構造物の基本固有周期の比に対する変位・応力の応答倍率は、流体の有無に関係なく、「薄いシェル」及び「厚いシェル」とも、ほぼ同じ値を示すという特徴的な特性を見出している。

第7章では、本研究で得られた成果を総括している。

これを要するに、著者は、部分的に分布する弾性基礎上にあり、内部に液体を有する円筒シェルの動的問題に対して、効率的な解析手法を提示し、その離散化条件を示すと伴に、自由振動特性・動的応答特性について設計上有益な知見を得たものであり、構造力学及び構造動力学の発展に貢献するところ大なるものがある。よって著者は、北海道大学博士(工学)の学位を授与される資格あるものと認める。