Application of Local Linearization to Supercavitating Compressible Flows past a Wedge(超高速液流における対称くさび空どうへの局所線形化法の応用)

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論 文 内 容 要 旨

INTRODUCTION

Research on cavity flows uptil now is confined mostly into incompressible flow field. For the strong demand of the high performance of hydraulic machinery, particularly to attaining the speed increase of blade elements of rocket pumps in liquid, it has began to enter not only into subsonic but also to transonic and supersonic flows. Therefore the effects of compressibility on flow pattern and cavity characteristics of supercavitating hydrofoil elements need to be investigated in minute.

In order to attain this goal, the simplest and most versatile approximate method is one based on a uniform linearization of governing equations which stem from the pioneering work of Prandtl-Glauert. Although this linearized theory of comprssible cavity flows has been developed in recent applications, it cannot ascertain the local features peculier to a compressible perturbed flow field. Further the linearized theory yields infinite perturbed velocity and fluid forces at Mach number 1 and in general requires that the freestream Mach number be sufficiently removed from unity such that the flow is either purely subsonic or purely supersonic. If both subsonic and supersonic flows occur in the flow field, then no unified theory which can yield reliable results in transonic and supersonic cavity flows is presently available to fill up the needs.

Thus the problem of practical importance being considered in the thesis is that of finding the cavity flow characteristics, in particular the cavity length and drag which results when a two-dimensional wedge, symmetric with respect to flow direction, is immerged in a compressible liquid. The thesis is presented in eight chapters showing detail derivations and elaborate discussions for various flows. Two types of liquid of particular interest considered are: i) compressibls pure water based on Tait's equation of state and ii) water with air content i.e. bubbly water.

The main objectives of presenting this thesis are two f lds: 1) to give an approximation of a two-dimensional steady nonlinear potential equation for a supercavitating wedge in compressible pure water and bubbly water flows based on the concept of local linearization. And then 2) to examine the effects of compressibility and the local behavior of the perturbed flow field throughout the whole Mach number range with a better accuracy than the existing linearized theory. The chapter-wise discussions are as follows:

CHAPTER-WISE DISCUSSION

A two-dimensional steady nonlinear potential equation for both compressible pure water and bubbly water flows are derived. The details of these derivations and the clarifications of pressure waves in a supersonic liquid flow are given in chapters 2 and 3. Some notable features of normal and oblique shock waves, their comparative study and the basic differences between supersonic liquid and gas flows are shown. Also the close relations of cavity streamline to the flow turning by expansion waves are pointed out.

The range of freestream Mach numbers is defined for the subsonic, transonic and supersonic cavity flows from both local linearization and shock wave theory. Fig. 1 shows the range of subsonic cavity flows for both compressible pure water and bubbly water. It is found that the range of subsonic Mach number flows decreases with an increase of cavitation number and for a bubbly water

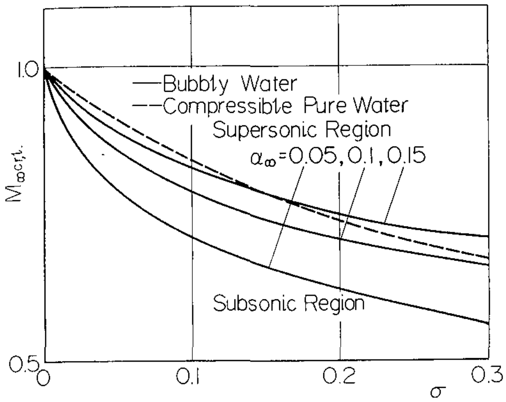

Fig. 1 Lower critical Mach number and its comparison.

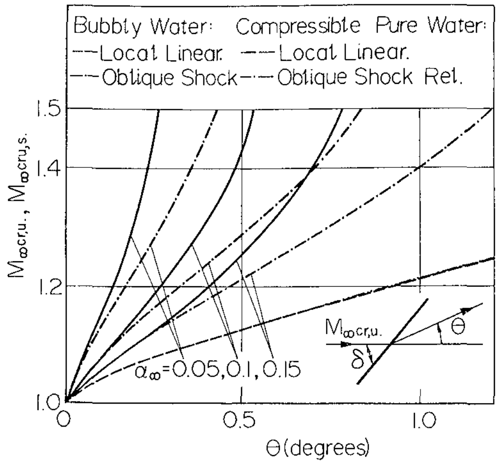

Fig. 2 Upper critical Mach number from local linearization and oblique shock relation and its comparison.

it further decreases with the decrease of air volume ratio. The range of transonic and supersonic Mach number flows with wedge half apex angle θ is shown in Fig. 2. The range of transonic flows in a bubbly water is greater than that of compressible pure water and substantially differs with a decrease of air volume ratio. This signifies that the local flow behind a detached or attached shock in bubbly water remains subsonic even at a high supersonic Mach number than that of compressible pure water due to a serious effect of air contents.

The solution and its derivation for a subsonic pure water flow are given in chapters 4 and 5. The governing equation of elliptic type for velocity potential is solved and then a simple correspondency between subsonic and incompressible pure water flows are shown. Hence, one can find with a better accuracy than the uniform linearization the data for a subsonic pure water flow by correcting the corresponding one in an incompressible flow.

An analysis for wall correction on cavity characteristics in a subsonic pure water flow through channel is given and discussed in chapter 5. For a small cavitation number, a better accuracy than the uniform linearization is shown through numerical examples. Fig. 3 shows the corresponding wall hight in an incompressible flow in comparison with that of uniform linearization. In uniform linearization the corresponding wall hight in an incompressible flow is independent of cavitation number whereas in local linearization it depends on cavitation number whereas showing the local features of the compressible perturbed flow.

The model- wise variation of cavity drag is shown in Fig. 4. In a closed and a semiclosed model the cavity drag decreases while in an open one it increases with the decrease of channel hight. This is mainly due to a model-wise variation of cavity length which with the decreases of channel hight increases sharply in a closed and a semiclosed model than an open one. Thc wall effect on cavity drag and length is shown in Fig. 5 in comparison with that of uniform linearization. The wall effect on cavity drag decreases while on cavity length it increases with an increase of Mach number. Also the chocking Mach

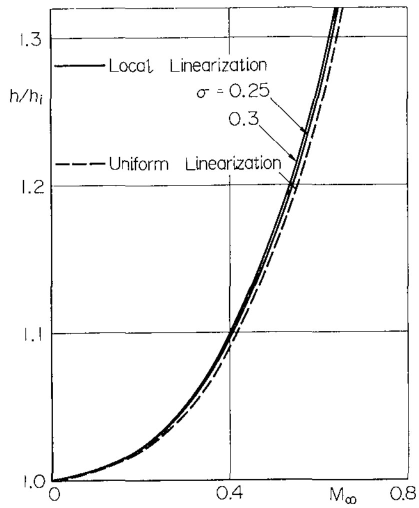

Fig. 3 Correspondence between two-dimensional subsonic and incompressible channel cavity flowsffor channel hight.

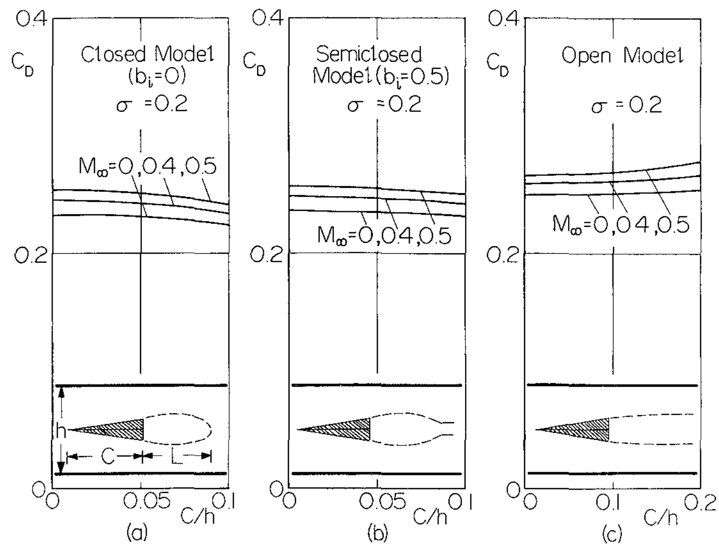

Fig. 4 Cavity drag of a supercavitating wedge at subsonic speeds through channel and its model-wise variation.

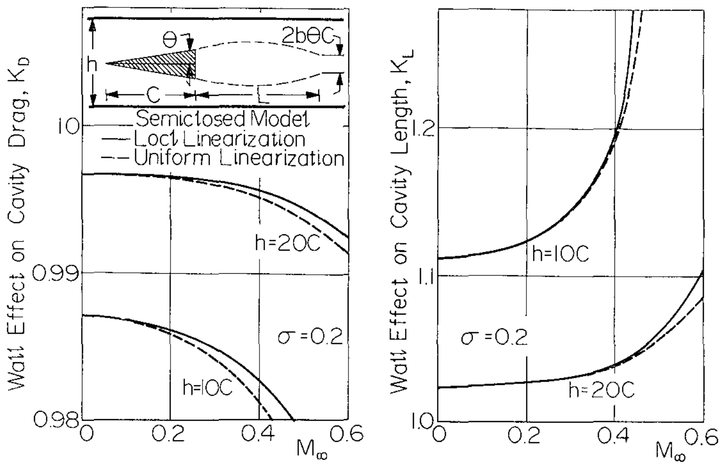

Fig. 5 Comparison of wall effect on cavity drag and length with that of uniform linearization.

number, the cavity drag and the contraction on the jet at chocking condition are determined. This is shown in Fig. 6. For a given cavitation number the chocking Mach number decreases while the chocking cavity drag increases with the decrease of channel wall hight.

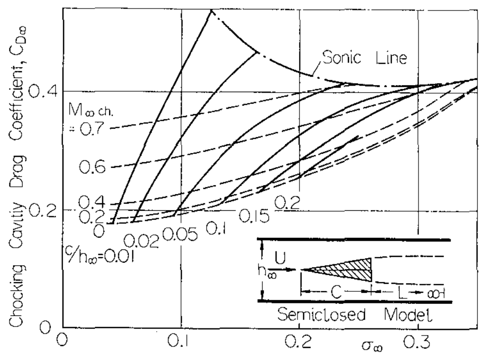

Fig. 6 Chocking cavity drag versus chocking cavitation and Mach numbers: semiclosed model, wedge of apex angle fifteen degrees.

Chapter 6 is concerned with transonic and supersonic supercavitating flows. The method of approximations are based on solving the nonlinear potential equation for compressible pure water flows given in chapter 2 by using the standard form of Green's theorem along with the concept of local linearization. In a transonic flow the result of cavity drag is in a closed analytical form. In a supersonic one the result is compared with the results of uniform linearization by Ackeret and exact theory, the later theory being derived from oblique shock relations given in chapter 2. The variation of cavity length with freestream Mach number is shown in Fig. 7. In transonic supercavitating flows the cavity length decreases very fast with an increase of freestream Mach number while in supersonic ones it decreases but slowly. Fig. 8 shows the variation of cavity drag with freestream Mach and cavitation numbers. It is seen

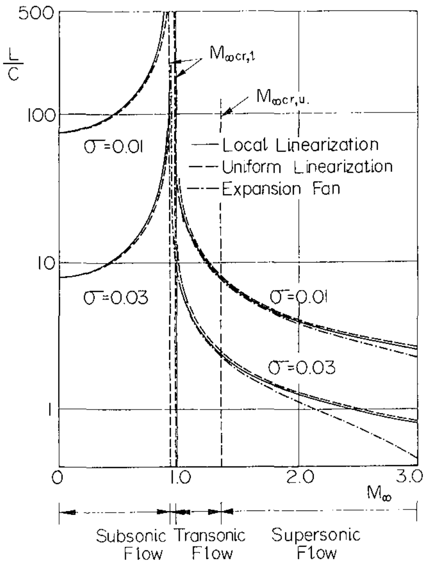

Fig. 7 Cavity length versus cavitation and freestream Mach numbers.

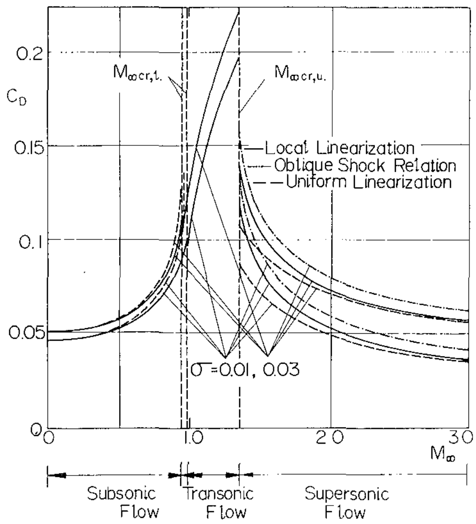

Fig. 8 Cavity drag versus cavitation and freestream Mach numbers.

that, for a particular cavitation number, the cavity drag grows sharply with an increase of freestream Mach numbers from high subsonic speed and reaches a maximum at $M_{\infty cr,u.}$ after which it decreases at first discontinuously at the $M_{\infty cr,u.}$ and then slowly and continuously as should be usual in purely supersonic flows. This increment in cavity drag is mainly due to formation of a local subsonic zone around the wedge formed by a detached shock wave ahead of the wedge nose at $1 < M_\infty < M_{\infty cr,u.}$ · With a gradual in freestream Mach number this detached shock wave turn weaker in strength and comes closer to the wedge nose, finally attaching itself to the wedge nose at $M_{\infty cr,u.}$and forming the whole flow field as purely supersonic ones. As a result the cavity drag ceases to increase with a further little increment in freestream Mach number at the upper critical.

A comparative study between compressible pure water flows and bubbly water flows past a steady two-dimensional supercavitating wedge is given in chapter 7. The clarifications of compressibility effects by local linearization which preserved the local features of air contents in the flow field with unified approach higher accuracy than the former linearized one are given. The variation of cavity length and drag with freestream Mach number in bubbly water flows are shown in Figs. 9 and 10. In purely subsonic flows the cavity drag is a little smaller while the cavity length is larger than that in compressible pure water. In transonic and purely low supersonic flows both cavity drag and length are less than those in compressible pure water and depend substantially on the air contents.

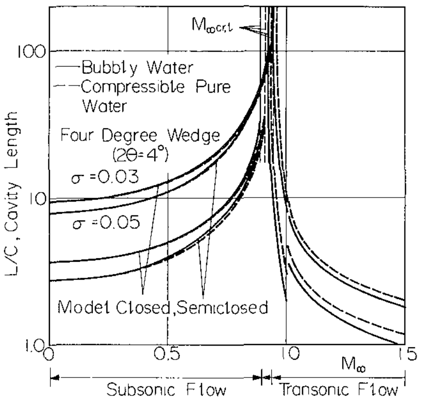

Fig.9 Camparisons between cavity length in bubbly and compressible pure water flows for various cavitation and freestream Mach numbers.

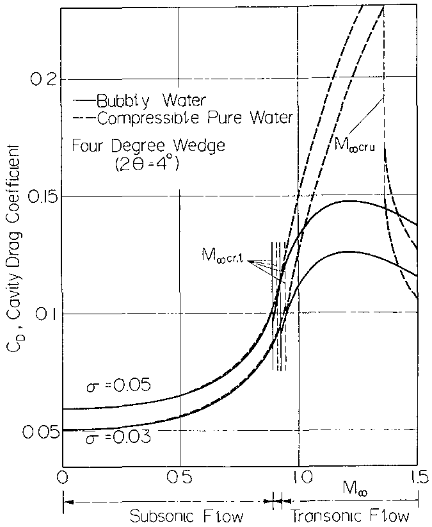

Fig.10 Comparisons between cavity drag in bubbly and compressible pure water flows for various Mach and cavitation numbers.

CONCLUDING REMARKS

The flow patterns over a two-dimensional supercavitating wedge at subsonic, transonic and supersonic speeds are clarified by a local linearization concept. The range of freestream Mach numbers is defined for the subsonic, transonic and supersonic liquid flows. The effect of compressibility and its local features on cavity characteristics are shown to be minute. Some notable features of pressure waves in supersonic liquid flows are clarified and also the close relations of cavity streamline to the flow turning by expansion waves are pointed out. The main results may be summarized as follows:

i) The correspondences between the steady two-dimensional supercavitating wedge in a subsonic and in an incompressible liquid flows are explained within the frame-work of local linearization technique. Hence, one can find with a better accuracy than the uniform linearization the data for a compressible liquid flow by correcting the corresponding one in an incompressible flow.

ii) The dependence of compressibility correction to cavity drag on flow models is shown to be minute. For a small cavitation number the present theory yields less effect of compressibility on cavity drag than the former uniformly linearized one. Also comparisons of the proposed theoretical results with experimental ones appear to indicate the appropriateness of the semiclosed mndel in a subsonic cavity flow.

iii) The method of analysis of a subsonic channel cavity flow in liquid past a wedge is proposed. This gives with a better accuracy than the uniform linearization the necessary wall correction on cavity characteristics of a supercavitating wedge by correcting the corresponding one in an unbounded flow. Also the chocking Mach number, drag and the contraction on the jet at chocking condition which depend on flow models are determined.

iV) In a transonic supercavitating flow the cavity drag is expressed in a simple closed analytical form and in a purely low supersonic one the present theory gives results much more precise than the uniform linearization does. In general, the cavity drag in a transonic supercavitating flow increases while the length decreases sharply with an increase in cavitation and freestream Mach numbers. In a purely supersonic one both cavity drag and length decrease with an increase of freestream Mach number.

V) A comparative study for compressibility effect on cavity characteristics between pure water and bubbly water flows past a supercavitating wedge at subsonic, transonic and supersonic speeds is made. The analysis preserved the local features of air contents in the flow with a better accuracy than the uniform linearization does. In essence, the cavity drag in a subsonic bubbly water flow is a little smaller while the cavity length is larger than that in a compressible pure water. In transonic and supersonic flows both cavity drag and length are shown to be less than those in a compressible pure water and depend substantially with air contents.

審　査　結　果　の　要　旨

超高速液流機械においては，羽根への相対流入マッハ数が増加しており，キャビテーション（以下，空どうと書く）発生下における液体圧縮性の動的効果全般に関する知見が要請されている。一般に，圧縮性は流れのじょう乱を大きくし，局所性を強めるので，既存の線形解法では，精度よい捕そくを期待できない。また，液体に特有な有限振巾の圧力波動についても，未解決の点が多い。本研究は，流れを支配する基礎式の型が変っても，マッハ数の全領域に亘って，一貫した適用が可能で，かつ高精度が期待できる局所線形解法の展開により，対称くさび空どう特性における圧縮性効果と圧力波動との関連について，理論的研究を行ったもので，全文八章より成る。

第一章は，緒論である。

第二章では，純水における基礎式および衝撃波，膨張波の前後諸量間の関係を示し，特に，空どう流線上および斜め衝撃波背後で臨界状態に達した時の一様流マッハ数を，それぞれ下部および上部臨界マッハ数と定義して，基礎式の解析域との関連を明確にしている。

第三章では，微小気泡を均一に含む水流の基礎式および衝撃波，膨張波について考察し，純水との著しい相違点を強調している。

第四章では，下部臨界マッハ数以下の亜音速空どう特性の局所線形解法を展開している。非圧縮空どうとの対応関係，空どう模形への圧縮性効果，プラントル・グロアート解との関係などの所論は，示唆に富んでいる。

第五章では，平行流路内の亜音速水流における空どう特性の局所線形解法により，チョーキング・マッハ数と下部臨界マッハ数および流路高さとの関係を明らかにし，さらに，空どう特性に及ぼす上下壁影響への圧縮性効果について，有用な資料を提供している。

第六章では，下部および上部臨界マッハ数の中間領域にある遷音速空どうについて，局所線形解法により，それぞれの領域における空どう特性を明らかにしている。さらに，膨張波による空どう長さ，斜め衝撃波による空どう長さ，斜め衝撃波による空どう抗力およびアッケレー解との比較から，本解法の精度を位置づけている。

第七章では，微小気泡を含む水流のマッハ数全領域に亘る空どう特性と空気体積比の関係および純水との相違について論じている。

第八章は，結論である。

以上要するに，本論文は局所線形解法をマッハ数の全領域に適用して，対称くさび空どう特性における圧縮性効果および圧力波動との関連について，広範囲に亘る理論的研究を行ったもので，得られた成果は，流体工学ならびに機械工学に寄与する所が少くない。

よって，本論文は工学博士の学位論文として合格と認める。