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WAKE MODELING STUDIES

15 August 1971 through 31 July 1975

Final Report

July 1975

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Scientific Officer: Ralph D. Cooper, Program Director
Fluid Dynamics
Office of Naval Research

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INTRODUCTION

Contract N00014-72-C-0074 has consisted of two distinct investigations. The first, extending over the period 15 August 1971 to 30 June 1973, was an experimental and theoretical study of momentumless turbulent wakes (corresponding to self-propelled bodies). The experimental study involved measurements of the mean flowfield as well as measurements of the turbulent intensity and Reynolds stress within the wake of a propeller-driven model. This work was described in detail in a Final Report encompassing only this phase of the investigation, dated June 1973. The theoretical study involved the modeling of the growth and collapse of the turbulent wake behind a submarine in a stratfied ocean using simple phenomenological models. A separate Final Report describing this work in detail has been distributed, dated April 1973. Summaries of these two Final Reports will be included in the Report Summaries section.

The investigation which is the subject of the present report has as its objective the development of a computer code capable of computing the disturbance generated by a moving submerged body in a stratified ocean. Within this rather broad description, we limit our investigation to steady motion of the body (constant velocity and depth in an ocean whose properties vary in only the vertical direction) under neutral roll and pitch trim. A number of effects which may prove to be significant are not considered in this study, including that of roll trim associated with propeller torque, pitch trim associated with body and control surface lift forces, and the dispersive effects of ambient turbulence, currents and topography in the ocean. Within the framework of this idealized physical picture, the emphasis of this study is on optimizing the speed, simplicity and versatility of the code to make it suitable for engineering studies involving large numbers of individual calculations.

CODE DESCRIPTION

The code which has been developed has been documented in great detail in a series of technical reports which are summarized in a later section. A very brief description will be given here.

In keeping with the requirement for a fast and simple calculation, the disturbance is divided into two components; the potential disturbance (that which would result if the medium were not stratified) and the remaining portion of the disturbance which, sufficiently far from the body, becomes predominantly wave-like in nature. This second part of the disturbance is approximated by a description based on an eigenfunction expansion of the linearized equations of motion in the Fourier-transformed plane. This mathematical approach results in obtaining only the wave-like contribution of this component of the disturbance, which is then added to the potential solution to obtain the total disturbance. This approximation is quite good far from the body and come under question only in the near field, and only when the body velocity is so small that buoyancy effects are important where the potential disturbance dominates.

For both components of the disturbance, it is assumed that the sources of disturbance (the body and its turbulent wake) can be represented in terms of equivalent distributions of sources and sinks. These are presented in detail for a body represented by a point source-sink pair (a Rankine body in an unstratified flow) with a superstructure represented by a line source-sink pair. Turbulent wake collapse as a source of disturbance is represented by a distributed density source which introduces the out-of-equilibrium density distribution induced by turbulent mixing at an axial station representing the point at which buoyancy effects begin to dominate over mixing.

Two methods of evaluating the wave-like disturbance are presented. The solution is presented analytically in the form of a one-dimensional Fourier inversion integral. The integral can be evaluated numerically by using a Fast Fourier Transform algorithm or, alternatively, a stationary phase approximation can be used to analytically evaluate the integral. When the disturbance in the horizontal plane (the surface, for instance) is required, extending from the body to an axial station which is not too far downstream, the FFT is an extremely efficient algorithm. The disturbance at a single point, along a single line, or in the vertical plane is more efficiently calculated using the stationary phase approximation, and calculations very far downstream of the body can only be obtained in this way.

The eigenfunction expansion approach used in obtaining the wave-like disturbance requires the knowledge of the dispersion relation of the internal waves in the stratified ocean. To avoid any unnecessary loss of generality, the vertical density structure of the ocean is not restricted in form but is, rather, specified in tabular form. An efficient algorithm for obtaining the dispersion relation of an ocean described in such a general fashion has been developed and is an integral part of the code.

Documentation which has been separately distributed includes a three volume technical description of the analysis on which the code is based, plus a user's manual which describes the operation of the code and contains sample problems and code listings.

REPORT SUMMARIES

- Final Report - "An Experiment on the Wake of a Slender Propeller-Driven Body," R. L. Gran, TRW Report No. 20086-6006-RU-00, June 1973.

The momentumless wake of a slender propeller-driven model in a wind tunnel at a Reynolds number of 6.3×10^4 (based upon diameter) is examined using the hot-wire anemometer. Measurements of the mean flowfield including swirl are presented, as well as measurements of the turbulent intensity and Reynolds stress within the first 20 diameters behind the model. The data are compared with a previous experiment at a similar Reynolds number but which used a blunt body and a high-speed jet as a propulsion source. Significant differences are noted in the development of the two wakes which are caused by body bluntness and propeller-induced swirl. For example, the turbulent intensity is lower by a factor of two for the present data, and the wake width is somewhat narrower. The effects of swirl on the mean flowfield are important for $x/D \leq 6$, whereas farther downstream the swirl component primarily affects the turbulent energy balance. A theoretical model of the flow is also presented which describes the flow quite well, given the measured conditions at one location. The constants of the turbulence model are determined experimentally and compared with determinations made for other flowfields. The present values of these constants are comparable, although the strict universality of these constants is not conclusive.

- Final Report - "A Phenomenological Model for the Momentumless Turbulent Wake in a Stratified Medium," D.R.S. Ko, TRW Report No. 20086-6007-RU-00, April 1973.

The growth and collapse of the turbulent wake behind a submarine in a stratified ocean is studied analytically using simple phenomenological models. The present analysis closely follows the previous integral approach of Ko, based on the concept of local similarity and turbulent entrainment. A non-uniform entrainment rate, obtained by considering the three turbulent velocity components separately, marks the main difference to the previous approach. However, the present analysis is still limited to a wake without swirl and does not include the energy leakage through the internal wave field.

A series of parametric studies have been performed to study the effects of various operational conditions (such as stratification and speed) as well as the initial conditions on the wake flowfield.

The solutions were found to be sensitive to some initial conditions. The physical significance, the range of conceivable values, and the constraints of these initial conditions are discussed. The differences between a blunt body wake and a slender body wake are pointed out, based on these parametric studies.

A comparison with the experiment of Schooley and Stewart is presented. Again, an extremely high initial turbulent intensity and degree of mixing are needed in the calculation. In addition to the fact that the body is practically a blunt one, it seems to suggest that an excessive amount of energy (more than required to balance the body drag for maintaining a uniform speed) may have been imparted to the wake. A much different result is expected from the wake of a slender, submarine-like body.

- "Submarine Effects Engineering Code: 1. Dispersion Relation Calculation," Eric Baum and David Henryson, TRW Report No. 20086-6010-RU-00, Feb. 1974.

A numerical method of determining the dispersion relation for internal waves in a stratified medium with a general vertical density distribution is documented. The method is based on a finite difference approximation to the relevant homogeneous differential equation, reducing the problem to that of finding the eigenvalues of the resulting set of coupled algebraic equations.

- "Submarine Effects Engineering Code: 2. Disturbance Calculation: Far-Field," Eric Baum, TRW Report No. 20086-6011-RU-00, July 1974.

An analytical description of the inviscid wave-like disturbance generated by a submerged moving body in a generally stratified medium is presented. The analysis is based on an eigenfunction expansion of the linearized equations of motion in the Fourier-transform plane. The inversion integrals are evaluated using stationary phase approximations, valid in the far field.

- "Submarine Effects Engineering Code: 3. Disturbance Calculation: Near-Field," Eric Baum, TRW Report No. 20086-6012-RU-00, October 1974.

This volume describes the inversion of the Fourier transform of the disturbance using the Fast-Fourier-Transform algorithm. The non-wake-like near-field (potential) disturbance is also evaluated.

- "Submarine Effects Engineering Code: 4. Operating Instructions," David Henryson, TRW Report No. 20086-6013-RU-00, July 1975.

Operating instructions, sample calculations, and listings of the code described in volumes 1 through 3 are presented in this volume.

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This report summarizes work performed in the development of a code for predicting the disturbance generated by a submerged moving body in a generally stratified medium. Details of this work have been documented separately.

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