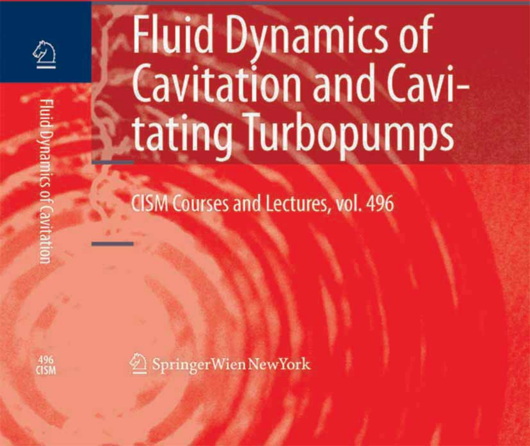
Luca d'Agostino
Maria Vittoria Salvetti
Editors

CISM
International Centre
for Mechanical Sciences

Fluid Dynamics of Cavitation and Cavitating Turbopumps



CISM Courses and Lectures, vol. 496

SpringerWienNewYork

d'Agostino · Salvetti *Eds.*

Fluid Dynamics of Cavitation

496
CISM

SpringerWienNewYork

CISM COURSES AND LECTURES

The series presents lecture notes, monographs, edited works and proceedings in the field of Mechanics, Engineering, Computer Science and Applied Mathematics.
Purpose of the series is to make known in the international scientific and technical community results obtained in some of the activities organized by CISM, the International Centre for Mechanical Sciences.

INTERNATIONAL CENTRE FOR MECHANICAL SCIENCES

COURSES AND LECTURES - No. 496

FLUID DYNAMICS OF CAVITATION AND CAVITATING TURBOPUMPS

EDITED BY

LUCA d'AGOSTINO
UNIVERSITY OF PISA, ITALY

MARIA VITTORIA SALVETTI
UNIVERSITY OF PISA, ITALY

SpringerWienNewYork

This volume contains 261 illustrations

Printed in Italy
SPIN 12182640

All contributions have been typeset by the authors.

ISBN 978-3-211-76668-2 SpringerWienNewYork

PREFACE

Cavitation is frequently encountered in hydraulic machinery, where it represents the major source of performance and life degradation and often provides the necessary excitation and compliance for triggering dangerous fluid dynamic instabilities. From the fundamental standpoint cavitation is a complex phenomenon, which poses formidable obstacles in terms of both physical and numerical modeling.

In July 2005 the Advanced School of the Centre International des Sciences Mecaniques (CISM), Udine, Italy, hosted a Course on the "Fluid Dynamics of Cavitation and Cavitating Turbopumps", held by some of the world leading experts in the field: Prof. C.E. Brennen, California Institute of Technology, Pasadena, California, USA, Prof. Y. Tsujimoto, Osaka University, Japan, Dr. J-P. Franc, LEGI, Grenoble, France, Prof. R. Saurel, Institut Universitaire de France and Polytech., Marseille, IUSTI, France, under the joint coordination by Prof. L. d'Agostino and M.V. Salvetti, Università di Pisa, Italy, who also contributed to the lectures.

The lectures of the speakers have been summarized here in a series of papers with the aim of providing a detailed introduction to the physics, fluid dynamics, modeling and numerical simulation of cavitation phenomena in engineering applications, with special emphasis on high performance turbopumps and their cavitation-induced instabilities. In particular, the first paper covers the more fundamental aspects of cavitation (nucleation, bubble dynamics, thermodynamic effects, cavitation erosion, stability of parallel bubbly flows) and the main kinds of cavitating flows (attached cavitation, cloud cavitation, supercavitation, ventilated supercavities, vortex cavitation, shear cavitation). The second paper provides an overview of the hydrodynamics and cavitation phenomena in turbopumps. The third series of papers focuses on the instabilities of cavitating turbopumps (cavitation surge, rotating cavitation, higher order cavitation surge, rotordynamic whirl forces). Finally, the last two papers describe two different approaches for the numerical simulation of cavitating flows. It is hoped that access to the above contributions is useful to students, researchers, scholars and professionals interested in perfecting their knowledge and understanding of cavitating flow phenomena and research in a wide range of engineering applications.

The coordinators wish to acknowledge the constant support of CISM's Advanced School in the organization of the Course, and would like to express their special gratitude to Ms. Paola Agnola for her kind assistance, to Professor Alfredo Soldati for his friendly encouragement and finally to Prof. C.E. Brennen, Prof.

Y. Tsujimoto, Dr. J-P. Franc and Prof. R. Saurel for their prompt collaboration and outstanding contributions to the Course and this publication.

Maria Vittora Salvetti and Luca d'Agostino

CONTENTS

The Rayleigh-Plesset equation: a simple and powerful tool to understand various aspects of cavitation.

Jean-Pierre FRANC

University of Grenoble, France

Abstract. This chapter is a general introduction to cavitation. Various features of cavitating flows are analyzed on the basis of the Rayleigh-Plesset equation. They concern not only the simple configuration of a single spherical bubble but also complex cavitating flows as those observed in cavitating turbopumps. Scaling rules, erosive potential, thermodynamic effect, supercavitation, traveling bubble cavitation, cavitation modeling are some of the topics addressed here. They are examined through this simple, basic equation which proves to be a quite useful tool for a first approach of real cavitation problems.

1 Introduction

Cavitation is the development of vapor structures in an originally liquid flow. Contrary to boiling, the phase change takes place at almost constant temperature and is due to a local drop in pressure generated by the flow itself.

The occurrence of low pressure regions in flows is a well-known phenomenon. For example, in the case of a Venturi, i.e. a converging duct followed by a diverging one, the velocity is maximum at the throat where the cross section is minimum. Then, according to Bernoulli equation, the pressure is minimum there and the risk of cavitation is maximum.

Another example is the flow around a foil at a given angle of attack which is representative of that around the blades of a hydraulic machine. From classical hydrodynamics, it is well-known that the foil is subject to a lift because of a lower pressure on the suction side in comparison to the pressure side. Hence, the suction side is expected to be the place where cavitation will first develop.

A final example is that of vortices which are very common structures in many flows. Because of the rotation and the associated centrifugal forces, the pressure in the core of such structures is lower than outside. Hence vortices are likely to cavitate in their core. There are actually many situations in which cavitating vortices can be observed as tip vortices or coherent vortical structures in turbulent flows like wakes or shear layers.

As known from basic thermodynamics, phase change from liquid to vapor occurs at the vapor pressure p_v which depends only upon the temperature. It is usually a good approximation to consider that the critical pressure for the onset of cavitation is the vapor pressure p_v, although some deviations discussed later may occur.

1.1 The cavitation number

The degree of development of cavitation is characterized by a non dimensional parameter, the cavitation number σ , defined by:

$$\sigma = \frac{p_{ref} - p_v}{\frac{1}{2}\rho V^2} \tag{1.1}$$

In this expression, p_{ref} is a reference pressure taken at a given point in the liquid flow and V is a characteristic flow velocity. Both parameters need to be precisely specified for each practical situation. As an example, in the case of a cavitating flow past a single foil in a hydrodynamic tunnel (see e.g. Figure 3), the reference pressure and velocity are usually chosen as the pressure and velocity in the undisturbed liquid flow, far from the foil.

A non cavitating flow corresponds to large values of the cavitation number. This is easy to understand since large values of the cavitation number usually correspond to large values of the reference pressure. Then, it can be expected that the pressure will be everywhere above the vapor pressure and the flow will remain free of cavitation. It is clear that the cavitation number has no influence on the fully wetted flow which will remain the same whatever the cavitation number may be, provided it is large enough for the flow to remain actually non cavitating. This number is a pertinent parameter only for cavitating flows for which it can be considered as a scaling parameter which measures the global extent of cavitation.

The onset of cavitation generally appears for a critical value of the cavitation number known as the incipient cavitation number σ_i . Starting from the fully wetted flow, cavitation inception can be reached either by decreasing the reference pressure or increasing the flow velocity, both leading to a decrease in cavitation number. Any further decrease will lead to an additional development of cavitation. In the case of Figure 3 for instance, the cavity will grow and its length will increase with a decrease in cavitation number leading to a longer cavity comparable to the supercavity shown in Figure 5. If the reference pressure is now increased, it is generally observed that cavitation disappears for a critical cavitation number somewhat higher than σ_i . Incipient and desinent cavitation numbers are often different and an hysteresis effect is often observed.

1.2 Main types of cavitation

Looking at real cavitating flows as that in a cavitating turbopump (Figure 1) or around a propeller (Figure 2), it appears that the liquid vapor interfaces have generally complicated shapes. There is a wide variety of types of cavitation and basically we can identify the following ones:

- ✓ *attached cavities* as that shown in Figures 3 to 5. Cavitation appears here in the form of a cavity attached to the suction side of the foil. The type of cavitation shown in Figure 3 is known as partial cavitation since the cavity covers only partially the upper side. On the contrary, a supercavity as shown in Figure 5 fully covers the suction side and closes downstream the foil trailing edge.
- ✓ *traveling bubble cavitation* with more or less isolated bubbles according mainly to the nuclei density in the free stream (Figures 6 to 8).
- ✓ *cavitation clouds* which can take various forms. Figure 9 gives an example of two clouds shed by an unsteady partial cavity. This is an illustration of the partial cavitation instability

which is triggered by a re-entrant jet developing upward from the closure region of the cavity.

✓ *cavitating vortices* which can be more or less structured. They are observed in particular at the tip of three-dimensional foils (Figure 10) or in the turbulent wake of bluff bodies where they are less organized because of turbulence (Figure 11).

Secondary effects as interactions between bubbles or with solid walls, fission, coalescence, interface instabilities, re-entrant jet, turbulence… can dramatically complicate previous basic shapes of liquid / vapor interfaces at both large and small scales. The analysis of cavitation can then be particularly difficult because of the geometric complexity of the liquid / vapor interfaces.

1.3 Overview of chapter

Despite this complexity, many basic results can be rather easily derived from the Rayleigh-Plesset equation. This equation, presented in section 2, applies to an isolated spherical bubble which is assumed to remain spherical all along its life. It gives how its radius changes because of the change in pressure it might go through during its life. This is the case, for instance, of an initial microbubble or cavitation nucleus carried by a liquid flow which undergoes pressure changes as it goes along the blades of a hydraulic machine. It grows in low pressure regions, becomes a macroscopic cavitation bubble and finally collapses downstream where the pressure recovers.

Section 3 is devoted to the presentation of a few basic results on single bubbles. First equilibrium is considered and it is shown that the critical pressure for the explosive growth of a nucleus may be significantly smaller than vapor pressure because of surface tension. The two main stages in the typical evolution of a cavitation bubble, i.e. growth and collapse, are then addressed with emphasis on the collapse time, which is a characteristic time scale of great importance in cavitation. Finally, it is shown that a bubble in a liquid is an oscillator because of the elastic behavior of the non condensable gas generally enclosed; the period of oscillation, which is another characteristic time scale, is introduced.

Section 4 is devoted to the presentation of non dimensional forms of the Rayleigh-Plesset equation from which a few conclusions on cavitation scaling are deduced. A first form based on the introduction of characteristic times – pressure, viscous and surface tension times – allows the estimation of the relative importance of each of these phenomena on the dynamics of a single bubble. A second form appropriate to the case of a bubble traveling on the suction side of a blade allows the derivation of scaling laws for traveling bubble cavitation.

Section 5 addresses thermal effects in cavitation. An extended form of the Rayleigh-Plesset equation including thermal effects is derived. Once more it is made non dimensional in order to develop a practical criterion for the estimation of the so called thermodynamic effect in cavitation.

Section 6 is relative to supercavitation, a field in which the Rayleigh-Plesset equation is surprisingly applicable. According to the Logvinovich independence principle, the dynamics of any cross section of a supercavity is independent of the neighboring ones and can be modeled by a Rayleigh type equation. This section shows that the Rayleigh equation, originally derived for spherical bubbles, may also be useful for other cavities whose geometry is actually far from being spherical.

Section 7 is devoted to an analysis of cavitation erosion using once more the Rayleigh equation. Firstly, it is shown that the spherical collapse of a bubble generates a pressure pulse of high amplitude that can largely exceed the yield strength of usual materials and hence cause damage. The flow aggressiveness of a single bubble and consequently of a whole cavitating flow is then analyzed with a special emphasis on the influence of velocity on erosive potential. The section closes with a few general remarks on the erosive potential of various cavitating flows, still based on a discussion of the Rayleigh equation.

In section 8, it is shown that the dynamics of other types of cavities, as ring bubbles, can be modeled by a Rayleigh-Plesset type equation, with some changes and additional terms which take into account the specificities of such cavitating structures, as vorticity.

The chapter ends with a brief presentation of a cavitation model based on the Rayleigh-Plesset equation and often used for simulation. The liquid is assumed to carry cavitation nuclei and the Rayleigh-Plesset equation, which models the evolution of individual bubbles in the cluster, is coupled to Navier-Stokes equations. Such a technique is appropriate to the modeling of complex real cavitating flows, as for instance cloud cavitation generated by a pulsating leading edge cavity.

Figure 1. Cavitating flow in the inducer of a rocket engine turbopump (Courtesy of SNECMA Moteurs and CNES)

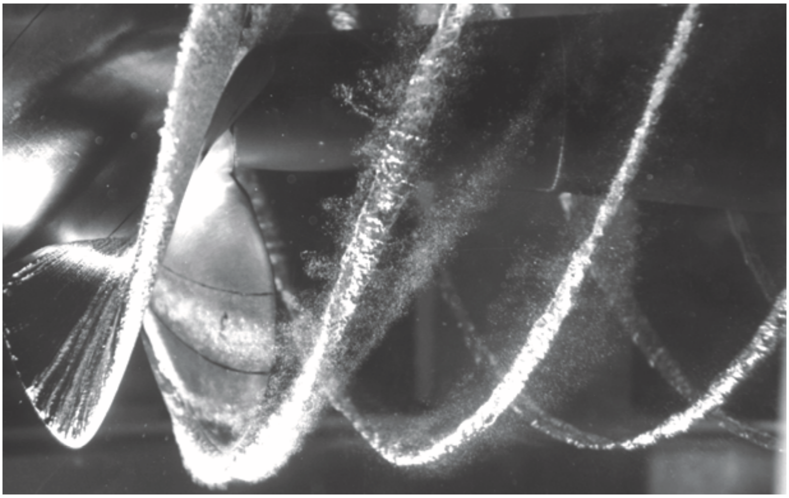


Figure 2. Cavitating flow in a marine propeller (Courtesy of DGA/BEC)

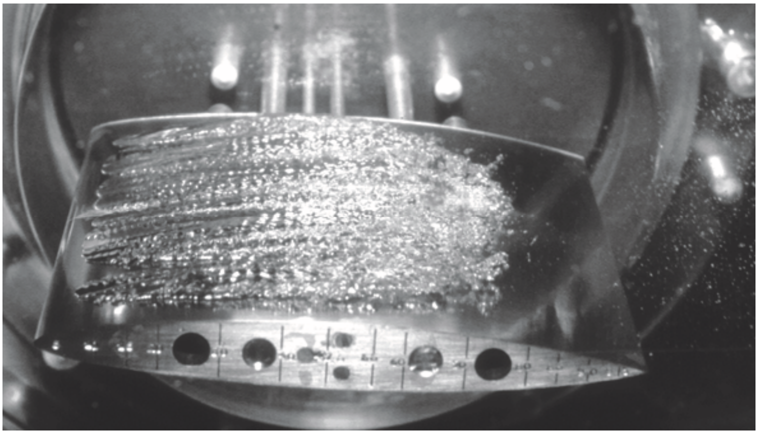


Figure 3. Partial cavity flow on a hydrofoil

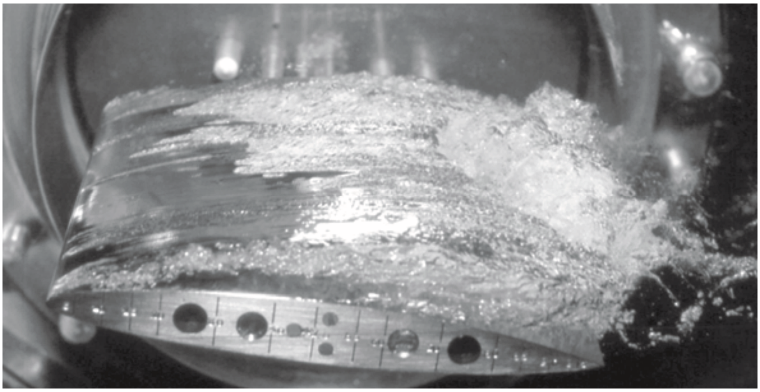


Figure 4. Unstable partial cavitation on a hydrofoil

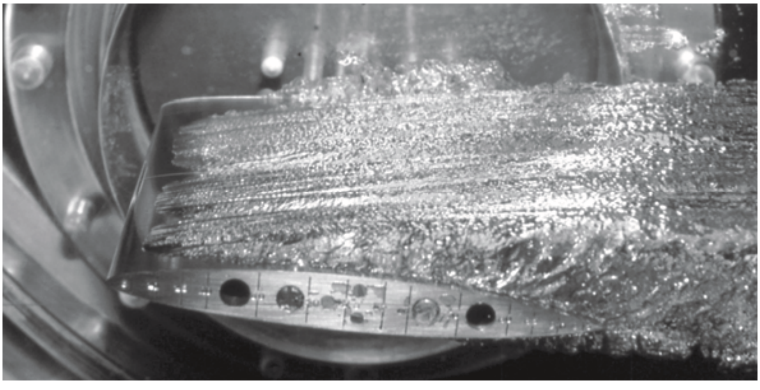


Figure 5. Supercavity flow around a hydrofoil in a cavitation tunnel

Figure 6. Two cavitation bubbles on the suction side of a hydrofoil

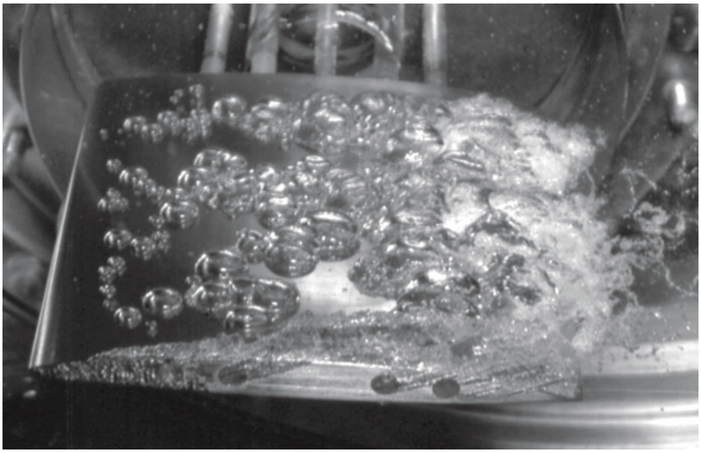


Figure 7. Traveling bubble cavitation at medium angle of attack

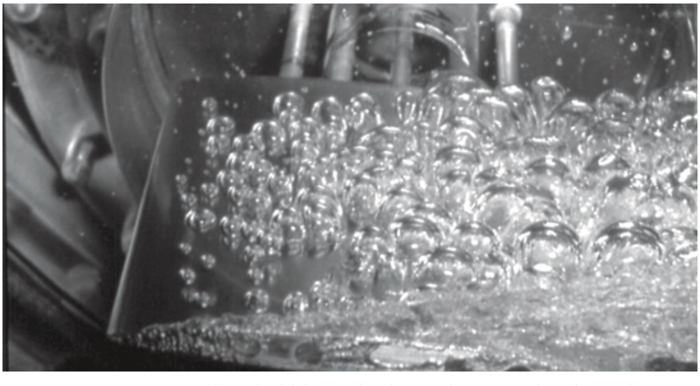


Figure 8. Traveling bubble cavitation at large angle of attack