Fundamentals of Cavitation

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by

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FOREWORD

This book treats cavitation, which is a unique phenomenon in the field of hydrodynamics, although it can occur in any hydraulic machinery such as pumps, propellers, artificial hearts, and so forth. Cavitation is generated not only in water, but also in any kind of fluid, such as liquid hydrogen. The generation of cavitation can cause severe damage in hydraulic machinery. Therefore, the prevention of cavitation is an important concern for designers of hydraulic machinery. On the contrary, there is great potential to utilize cavitation in various important applications, such as environmental protection.

There have been several books published on cavitation, including one by the same authors. This book differs from those previous ones, in that it is both more physical and more theoretical. Any theoretical explanation of the cavitation phenomenon is rather difficult, but the authors have succeeded in explaining it very well, and a reader can follow the equations easily. It is an advantage in reading this book to have some understanding of the physics of cavitation. Therefore, this book is not an introductory text, but a book for more advanced study.

However, this does not mean that this book is too difficult for a beginner, because it explains the cavitation phenomenon using many figures. Therefore, even a beginner on cavitation can read and can understand what cavitation is. If the student studies through this book (with patience), he or she can become an expert on the physics of cavitation.

In conclusion, this book is very comprehensive and instructive for advanced students, scientists, and engineers, who want to understand the true nature of cavitation.

The authors, Dr. Jean-Marie MICHEL and Dr. Jean-Pierre FRANC, are professors at the University of Grenoble, although Dr. MICHEL retired recently. They have much experience in the teaching and study of cavitation. Dr. MICHEL and Dr. FRANC have presented many important papers in internationally recognized academic journals such as the *Journal of Fluid Mechanics*, which are referenced in this book.

Dr. MICHEL and Dr. FRANC are the most suitable persons to write a book on cavitation such as this. I take great pleasure in being the first to congratulate them on their most recent contribution to this very unique and fascinating field.

March, 2003, Tokyo, Japan
Dr. Hiroharu KATO,
Professor Emeritus,
University of Tokyo

Preface

The present book is aimed at providing a comprehensive presentation of the phenomena involved in cavitation. It is focused on hydrodynamic cavitation, i.e. the kind of cavitation which occurs in flowing liquids, contrary to acoustic cavitation which is induced by an oscillating pressure field in a liquid almost at rest. Nevertheless, the principles which govern the hydrodynamic bubble and the acoustic bubble are basically the same.

Briefly, cavitation is the occurrence of vapor cavities inside a liquid. It is well known that in static conditions a liquid changes to vapor if its pressure is lowered below the so-called vapor pressure. In liquid flows, this phase change is generally due to local high velocities which induce low pressures. The liquid medium is then "broken" at one or several points and "voids" appear, whose shape depends strongly on the structure of the flow.

This book deals with all types of cavitation which develop in real liquid flows. This includes bubble cavitation (spherical bubbles in the simplest case), sheet cavitation, supercavitation and superventilation, cavitation in shear and vortex flows and some other patterns. It covers the field of cavitation inception as well as developed cavitation, which is encountered in advanced hydraulics at high speed.

It is intended for graduate students, research workers and engineers facing cavitation problems, particularly in the industrial fields of hydraulic machinery and marine propulsion. A special effort has been made to explain the physics of cavitation in connection with various phenomena such as surface tension, heat and mass transfer, viscosity and boundary layers, compressibility, nuclei content, turbulence, etc... In addition to the physical foundations of the phenomenon, various methods of investigation, either experimental or computational, are presented and discussed so that the reader can deal with original problems.

The book results from about 40 years of research carried out at Grenoble University in various fields of cavitation science, with the financial support of several firms and institutions, particularly the French Navy. Initially, two main influences converged to stimulate the creation by Pr. J. Dodu of the cavitation research group: the strong hydraulic experience of private Companies in Grenoble and the advice of renowned foreign scientists (M.S. Plesset, M.P. Tulin, B.R. Parkin, A.J. Acosta... and so many others) who delivered a detailed account of the *state of the art* to Pr. J. Dodu. Many of those initial scientific and industrial relationships have remained active over the years. Here we particularly wish to acknowledge the very fine contribution we received from Mr Y. Lecoffre, either in the design of experimental rigs or the initiation of new research programs. We must also remember the name of Pr. A. Rowe, whose acute insight into hydrodynamics and pioneering work on numerical modeling of cavitating flows are still present in our minds.

The book is made of rather short chapters, each designed to correspond to one or two lectures. It is the result of our teaching program given over many years including a number of seminars. The lists of references (at the end of each chapter) are limited to major contributions, while the very abundant literature devoted to cavitation can be found from the quoted review papers.

After an introductory chapter, classic results relative to liquid breakdown are recalled in *chapter 2*. It is shown that a liquid can actually sustain absolute pressures smaller than the vapor pressure (and even tensions) without cavitating. This leads to the idea of nuclei (i.e. points of weakness in the liquid continuum) which is a fundamental concept in cavitation. The physics of the microbubble as a nucleus is presented in detail with a special emphasis on stability. *Chapter 2* ends with the definition of the quality of a liquid sample in terms of nuclei content, a key concept for the prediction of cavitation patterns in real liquid flows.

Chapters 3 to *5* are concerned with the isolated bubble. In *chapter 3*, basic results on the dynamics of the spherical bubble are presented and the famous RAYLEIGH-PLESSET equation is derived. Throughout the book, this fundamental equation is used to throw light on essential questions, such as scale effects. The evolution of a bubble in a non-symmetrical environment will result in deviations from sphericity which are discussed in *chapter 4*, together with the problem of the path of a bubble within a liquid flow. The effects of liquid compressibility and thermal diffusion are presented in *chapter 5*.

Chapters 6 to *9* address sheet cavitation, which appears on blades of propellers, foils of boats, or behind axisymmetric bodies such as torpedoes. *Chapters 6* and *9* are devoted to the neighbouring problems of supercavitation and superventilation respectively. A special effort has been made to present the analytical approach derived by our colleagues from Russia and Ukraine on the basis of the so-called "*Logvinovich independence principle of cavity expansion*" in the case of axisymmetric cavities. We are especially grateful to Pr. V.V. SEREBRYAKOV, Pr. Y.N. SAVCHENKO and their colleagues from the Kiev University. Through them, we became aware of the very significant research which was carried out in those countries over the years. One example (*chapter 9*) is the theoretical modeling of ventilated cavity pulsations by Pr. E.V. PARISHEV of Moscow University.

Partial sheet cavitation is addressed in *chapter 7* with special attention given to cloud cavitation, re-entrant jets and more generally to cavitation instabilities. Because of their practical importance, those subjects have been studied in a number of laboratories in the recent past, in Europe, Japan and the USA. We would like to thank especially Pr. Y. TSUJIMOTO (Osaka University) for numerous and fruitful discussions on cavitation instabilities. The interaction between traveling bubbles and attached sheet cavities is addressed in *chapter 8*. It is shown that the boundary layer on the wall together with the water nuclei content strongly influence the type of cavitation that can occur. Basic principles for the prediction of cavitation patterns on hydrofoils or pump blades are proposed.

Chapters 10 and *11* are devoted to vortex cavitation, tip vortex cavitation and shear cavitation respectively. Several results presented in *chapter 10* were obtained in the framework of a joined program supported by the French Navy. We are particularly grateful to Pr. D.H. FRUMAN who directed that research program, and to the colleagues of the associated laboratories : Bassin d'Essais des Carènes (Val de Reuil, France), École Navale (Brest, France), Institut de Machines Hydrauliques (Lausanne, Switzerland). The difficult subject of shear cavitation is approached in *chapter 11*, with a special emphasis on the physical analysis derived by Pr. R.E.A. ARNDT (University of Minnesota).

The main effects of cavitation on hydraulic equipments are also examined in this book. An overview on cavitation erosion is given in *chapter 12*, whereas the reader will find information on cavitation noise in several chapters.

We are very indebted to H. KATO (formerly Professor at the Tokyo University), Pr. K.V. ROZHDESTVENSKY (Saint Petersburg State Marine Technical University) and Pr. B. STOFFEL (Darmstadt University of Technology) who kindly accepted to review our manuscripts and made precious comments and suggestions. We are also grateful to our colleague Pr. F. MCCLUSKEY who accepted the difficult charge of correcting the English and spent a considerable time improving our manuscript, far beyond matters of pure form.

Thanks also to our colleagues in the Grenoble Cavitation research group (J.C. JAY, M. MARCHADIER, M. RIONDET and J.F. VERDYS) whose technical competence allowed us to obtain a significant number of the experimental results presented in this book.

Our editors, Kluwer and Grenoble Sciences, deserve special acknowledgements. We are particularly grateful to Pr René MOREAU, Scientific Editor of the series *Fluid mechanics and its applications* and to the local team of Grenoble Sciences : Pr Jean BORNAREL (Grenoble University) who supported this project since its very beginning, Nicole SAUVAL who ensured the administrative work, Sylvie BORDAGE, Julie RIDARD and Thierry MORTURIER for their constant and exceptional care in the production of the manuscript.

Finally, we would like to thank once more our colleague and friend Hiro KATO whose scientific road crossed our own one so many times and who accepted to write the foreword for this book.

J.P. FRANC & J.M. MICHEL
November, 2003

LIST OF SYMBOLS

> *Numbers in square brackets refer to the corresponding chapters.*

a	Constant in the VAN DER WAALS state law [1]		ML^5T^{-2}
	Thermal diffusivity [2, 7]	m^2/s	L^2T^{-1}
	Viscous core radius [11]	m	L
$\mathbf{a_n}$	Amplitude of spherical harmonics [3]	m	L
b	Constant in the VAN DER WAALS state law [1]	m^3	L^3
B	STEPANOV factor [5, 7]		
c	Chord length [6, 7]	m	L
	Speed of sound [5, 7]	m/s	LT^{-1}
$\mathbf{c_v}$, $\mathbf{c_p}$	Heat capacities at constant volume (resp. constant pressure) [2, 5]	J/kg/°K	$L^2T^{-2}\theta^{-1}$
$\mathbf{C_s}$	Concentration of a gas dissoved in a liquid [2]	kg/m^3	ML^{-3}
$\mathbf{C_p}$	Pressure coefficient [1, 10, 11]		
$\mathbf{C_D}$	Drag coefficient [4, 6]		
$\mathbf{C_L}$	Lift coefficient [4, 6]		
$\mathbf{C_Q}$	Flowrate coefficient [5, 7, 9]		
D	Coefficient of mass diffusion [2]	m^2/s	L^2T^{-1}
	Diameter [6, 9]	m	L
	Drag force [6]	N	LMT^{-2}
e	Cavity thickness [6, 7]	m	L
$\mathbf{e_{ij}}$	Deformation rate [11]	s^{-1}	T^{-1}
f	Frequency [3, 7, 9]	s^{-1}	T^{-1}
Fr	FROUDE number [6, 9]		
h	Enthalpy [5]	J/kg	L^2T^{-2}
	Heat convective transfer coefficient [7]	$W/m^2/°K$	$MT^{-3}\theta^{-1}$
H	HENRY constant [2]	s^{-1}/m^2	
k	Polytropic exponent [5]		
l, dl	Curvilinear distance, length element	m	L
ℓ	Cavity length [6, 7, 9]	m	L

L	Latent heat of vaporization	J/kg	L^2T^{-2}
	Lift force[6]	N	MLT^{-2}
$\dot{m}$	Mass flowrate through a unit surface area[1]	kg/m²/s	$ML^{-2}T^{-1}$
	Mass loss rate[12]	kg/s	MT^{-1}
M	Virtual mass of an immersed body[4]	kg	M
n(R)	Density distribution of nuclei size[2]	/cm³/ΔR	L^{-4}
N	Density concentration of nuclei[2]	/cm³	L^{-3}
p	Absolute pressure[1]	Pa	$ML^{-1}T^{-2}$
p_c	Cavity pressure[1, 6, 7, 9]	Pa	$ML^{-1}T^{-2}$
p_g	Partial gas pressure inside a cavity[1, 9]	Pa	$ML^{-1}T^{-2}$
p_r	Pressure at the reference point[1]	Pa	$ML^{-1}T^{-2}$
$p_v(T)$	Vapor pressure at temperature T[1]	Pa	$ML^{-1}T^{-2}$
q	Mass flowrate through a unit surface area[7]	kg/m²/s	$ML^{-2}C$
Q	Heat transfer[1]	J	ML^2T^{-2}
Q_m	Mass flowrate of air[9]	kg/s	MT^{-1}
r	Radial coordinate[3, 6, 9]	m	L
R	Spherical bubble radius[3]	m	L
	Radius of an axisymmetric cavity[6, 9]	m	L
$\dot{R}$	Bubble interface velocity[3]	m/s	LT^{-1}
Re	REYNOLDS number		
$\vec{R}_p$	Force exerted by the liquid on an immersed body[4]	N	MLT^{-2}
s	Curvilinear distance[3, 8]	m	L
S	Cavity cross-sectional area[6, 9]	m²	L^2
	STROUHAL number[7, 9, 11]		
	Surface tension of the liquid[2, 3]		
t	Time	s	T
t_{rr}	Radial stress[3]	Pa	$ML^{-1}T^{-2}$
T	Absolute temperature[1, 7]	°K	θ
	Period[3, 9]	s	T
u	Radial component of the velocity[3, 5]	m/s	LT^{-1}
V	Velocity[4]	m/s	LT^{-1}
$\mathcal{V}$	Bubble or cavity volume[5, 9]	m³	L^3

W	Relative velocity [4]	m/s	LT^{-1}
We	WEBER number [3]		
x, y, z	Cartesian coordinates [3, 6, 10]	m	L

> Greek characters

$\boldsymbol{\alpha}$	Angle of attack [6]		
$\boldsymbol{\alpha_\ell}$	Liquid thermal diffusivity [5]	m^2/s	L^2T^{-1}
$\boldsymbol{\delta}$	Boundary layer thickness [8]	m	L
$\boldsymbol{\Delta}$	Increment operator		
$\boldsymbol{\varepsilon}$	Small parameter		
	Strain [12]		
$\boldsymbol{\varphi}$	Non-dimensional frequency [9]		
	Velocity potential [4, 6]	m^2/s	L^2T^{-1}
$\boldsymbol{\gamma}$	Ratio of heat capacities ($\gamma = c_p/c_v$) [2, 3, 9]		
$\boldsymbol{\Gamma}$	Circulation [10, 11]	m^2/s	L^2T^{-1}
$\boldsymbol{\lambda}$	Thermal conductivity [2, 5]	W/m/°K	$MLT^{-3}\theta^{-1}$
	Wavelength [9, 11]	m	L
$\boldsymbol{\mu}$	Dynamic viscosity [3, 11]	kg/m/s	$ML^{-1}T^{-1}$
$\boldsymbol{\nu}$	Kinematic viscosity [3, 11]	m^2/s	L^2T^{-1}
$\boldsymbol{\rho}$	Density [1, 2, 3...]	kg/m^3	ML^{-3}
$\boldsymbol{\sigma}$	Normal stress [12]	Pa	$ML^{-1}T^{-2}$
$\boldsymbol{\sigma_v}$	Cavitation number [1]		
$\boldsymbol{\sigma_{vi}}, \boldsymbol{\sigma_{vd}}$	Incipient (resp. desinent) cavitation number [1, 2, 8, 10, 11]		
$\boldsymbol{\sigma_a}$	Relative pressure of air inside a ventilated cavity [9]		
$\boldsymbol{\sigma_c}$	Relative underpressure of a developed cavity [1, 6, 7, 9]		
$\boldsymbol{\Sigma}$	BRENNEN thermodynamic parameter [5]	$m/s^{3/2}$	$LT^{-3/2}$
$\boldsymbol{\tau}$	Characteristic time [2, 3, 6, 9]	s	T
	RAYLEIGH time for the bubble collapse [3]	s	T
$\boldsymbol{\omega}$	Rotation rate [11]	/s	T^{-1}
$\boldsymbol{\Omega}$	Vorticity [10, 11]	/s	T^{-1}

> Subscripts

c	Cavity
min	Minimum value
g	Gas
v	Vapor
ℓ	Liquid
0	Initial value. Mean value
r	Reference point