HYDRODYNAMIC FORCES

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The bulk of the work presented was written during a sabbatical sponsored by the Volkswagen Foundation, Hannover, Germany

Photo on the binding:
Digitized and median filtered video image (laser light sheet flow visualization) of flow around a model structure. Photo by: Dr Bodo Ruck, Institute of Hydromechanics, University of Karlsruhe.

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HYDRAULIC STRUCTURES
DESIGN MANUAL

HYDRAULIC DESIGN CONSIDERATIONS

Preface

The present monograph of the IAHR Hydraulic Structures Design Manual has had an eventful history. After some preliminary discussions, Paul Kolkman from Delft Hydraulics consented in 1984 to take over the coordination of the work. An outline was prepared in the same year, and possible authors were proposed. Hydrodynamic forces on gates were to receive primary attention because of the lack of comprehensive information on that subject. Eduard Naudascher was to take over the chapter on high-head gates and parts of the chapter on low-head gates. By summer 1987, Kolkman, due to other commitments, had to step back from his commitment as coordinator. Possible replacements were discussed at the 1987 IAHR Congress at Lausanne. In order not to unduly delay publication, it was finally decided that Naudascher would write the entire monographs, and that he would ask experts in the field to review thoroughly the material and supplement it if indicated.

The result of this endeavour is the book at hand. The disadvantage of not drawing from the first-hand experiences of a number of authors may be counter-balanced by the advantage of homogeneity and consistent structuring, so important in rendering a book of practical use. An extensive review process was to insure that all information included is up-to-date and reliable and that it portrays the present state of the art.

Priority among the declared goals of the IAHR Manual was given to relevance to the civil-engineering designer rather than to completeness. Many more topics related to hydrodynamic forces could have been included, and it might be advisable to include some of these in a second edition. However, much of what is presented here can readily be transferred from one special case to another as well as from one field of application to another. Such general applicability, anyway, was the primary reason for selecting the form in which the force-inducing phenomena, the methods of prediction, and the data on hydrodynamic forces are presented in this book. The important lesson from recent failures of hydraulic structures, after all, is that the designer should train himself to identify those flow phenomena responsible for excessive loading of structures prior to their design, and that he should learn to handle the appropriate methods of prediction and the ways of generalizing data.

The bulk of the work presented, I completed during a sabbatical in 1987/88 sponsored by Volkswagen Foundation. The Sonderforschungsbereich 210 at the University of Karlsruhe, of which I am a member, granted the permission to bring out in its series of reports preprints of this monograph in March 1988 to solicit suggestions for improvement from experts in the field. I am greatly indebted to all colleagues and all my collaborators who have contributed ideas, criticism, and help in the preparation of the manuscript. Particular acknowledgement is due Professors M. Castro Delgado and D. Rockwell for reviewing certain sections, Professor B.C. Syamalarao for proof reading and other chores, and, above all, Professor J.S. McNown of the IAHR Editorial Committee for reviewing thoroughly the entire monographs and revising the English. All the drawings were prepared by Mrs I. Weber, and Dr R. Ermshaus helped with the photographs. I extend my cordial thanks to them as well as to Mrs C. Echte who typed the text. Her cheerful and devoted collaboration made it a joy to do this work. Last but by no means least, I wish to thank all official reviewers listed below for taking time off their busy schedules to read the material critically and suggest important improvements and additions.

Karlsruhe, June 1989 Eduard Naudascher

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List of symbols

a	acceleration (Equation 2.24); gap width (Figure 3.5c)
A	area
$\mathcal{A}$	amplication factor
Ae	aeration parameter (Equations 2.100, 3.53)
b	width; tunnel width
B	width; gate width
c	wave celerity
c_a	celerity of pressure or acoustic wave (Equations 2.54, 2.97)
c_f	local resistance coefficient (Equations 2.8, 2.9, 3.34)
c_g	celerity of gravity wave (Equation 2.52)
C, C_1, C_2	local discharge coefficients (Equations 3.2, 3.5, 3.14)
C_o	coefficient for maximum discharge (Equation 3.8)
C_c	contraction coefficient (Figure 3.5a)
C_d	discharge coefficient for underflow (Equations 3.6, 4.10)
C_D, C_L	drag, lift coefficient (Equation 2.88)
$C_{D\mathrm{rms}}, C_{L\mathrm{rms}}$	root-mean-square drag, lift coefficient (Equation 2.32)
C_e	head-loss coefficient (Equation 3.3)
C_f	mean resistance coefficient (Equation 2.22)
C_F	force coefficient (Equations 2.89, 2.92)
C_h	piezometric-head coefficient (Equation 2.68)
C_m	inertia coefficient (Equation 2.29)
C_M	moment coefficient (Equation 4.35)
C_p	pressure coefficient (Equation 2.67)
C_{p+}, C_{p-}	coefficient of maximum positive, negative pressure deviation (Figure 2.15)
$C_{p'} = p'_{\mathrm{rms}}/(\rho V^2/2)$	coefficient of pressure fluctuations
C_{pb}	base-pressure coefficient (Equation 2.91)
C_q, C_{q*}	discharge coefficients for overflow (Equation 4.27)
C_x, C_y	force coefficients (Equations 4.33, 4.34)
d	thickness (diameter) of cylindrical body; gate thickness
D	diameter of pipe or jet

E	bulk modulus of elasticity
EFO	excitation due to fluid oscillator (Section 2.1.3)
EIE	extraneously induced excitation (Section 2.1.3)
f	frequency; Darcy-Weisbach resistance factor (Equations 3.12, 3.35)
f_o	vortex-shedding frequency
f_n	natural frequency of body oscillator
f_R	natural frequency of fluid oscillator
F	force (Equation 2.5)
F_D, F_L	drag, lift (Figure 2.1)
F_I	intertia force (Equation 2.27)
F_x, F_y	forces acting in x and y directions (Equation 4.4)
Fr	Froude number
g	acceleration of gravity
h	depth of flow (Figure 2.7); height of wall, step, or block; piezometric head; head of overflow (Figure 4.34)
$\tilde{h}$	wave amplitude
H	total head (Figures 3.2, 3.5; Equation 4.1; Figure 4.34)
ΔH	difference between headwater and tailwater level (Figure 3.2)
H_{ce}	head loss due to corner eddy (Figure 3.5)
H_e	entrance head loss (Figure 3.2, 3.5, Equation 3.3)
H_L	head loss
IIE	instability-induced excitation (Section 2.1.3)
κ	ratio of specific heats
k_s	average roughness height or equivalent sand roughness
Ka	cavitation number (Equations 2.98, 3.54)
l, L	lengths
L_p, L_v	correlation lengths (Figures 2.3, 2.4)
m	mass of body oscillator
M	moment
Ma	Mach number
MIE	movement-induced excitation (Section 2.1.3)
p	fluid pressure (Equation 3.10)
Δp	difference between air pressure below gate and atmospheric pressure (Figure 3.5b)
p'_{rms}	root-mean-square of pressure fluctuations (Equation 2.11)
p_v	vapor pressure
P	pressure force
q	discharge per unit width
Q	discharge or rate of flow
Q', Q''	discharge passing under and over gate, respectively
r	radius

R, R_*	radius; gas constant
R_p, R_v	correlation coefficients for pressure and velocity (Equations 2.12, 2.13)
Re	Reynolds number (Figure 2.6b)
$S(f)$	power spectral density (Equation 2.19)
S_o	channel slope
Sc	Scruton number (Equation 2.41b)
Sh	Strouhal number (Equation 2.31)
t	time
T	time; period ($T = 1/f$); absolute temperature (Equation 2.97)
Tu	turbulence level (Equation 2.4)
Un	unsteadiness parameter (Equations 2.102, 3.48)
v	velocity (Equation 2.1)
$v_* = \sqrt{\tau_o/\rho}$	shear velocity
V	average velocity
$\forall$	volume
V_j	jet velocity in vena contracta (Figure 3.5a)
$V_r = V/(f_n d)$	reduced velocity
w	width; weir height
W	probability density (Equation 2.15)
x, y, z	distance in x, y, z direction
$\dot{x} = dx/dt$	velocity
$\ddot{x} = d^2x/dt^2$	acceleration
y	distance; gate opening; depth of flow
y_n	normal depth
$\tilde{y}$	amplitude of body vibration in y direction
α	energy or Coriolis coefficient (Equations 3.10, 4.14)
β	momentum or Boussinesq coefficient (Equations 2.74, 4.14); damping coefficient; ratio ρ_{air}/ρ_w (Equation 2.97)
$\gamma = \rho g$	specific weight
Γ	vortex strength
δ	boundary-layer thickness (Figures 2.2a, b)
ε	factor ($\varepsilon < 1$); turbulence energy dissipation rate (Equation 2.23)
ζ	separation distance (Figure 2.2d); damping ratio ($\zeta = \beta/\beta_{cr}$)
η	relative amplitude ($\tilde{y}/d$); relative gate opening (Equation 3.7)
κ_B, κ_T	downpull coefficients (Equations 3.27, 3.28)
λ	wave length
μ	dynamic fluid viscosity
$\nu = \mu/\rho$	kinematic fluid viscosity
ξ	loss coefficient
ρ	fluid density

σ	standard deviation (Figure 2.3)
$\tau_o = \mu/(dv/dy)_{y=0}$	boundary-shear intensity
$\omega = 2\pi f$	circular frequency
ω_T	speed of rotation

Contents

CHAPTER 1

Introduction

Among the many forces to which hydraulic structures are exposed, only the forces induced by flow incident or past the structure will be treated in this monograph. The inclusion of such related subjects as forces due to waves or forces due to earthquakes or explosions would have required a separate monograph. The same is true for forces due to fluid-transients such as water hammer. As books are available on these subjects, they were excluded from the present monograph series. A similar restriction was necessary also regarding the types of hydraulic structures. Since the IAHR Hydraulic Structures Design Manual aims at giving information primarily to the civil-engineering designer, such mechanical-engineering structures as hydraulic machinery and equipment are covered only in passing.

Hydrodynamic forces are commonly subdivided into a time-averaged mean part and a fluctuating part. Fluctuating forces can be induced by a variety of basically different excitation mechanisms. As it is impossible to treat these thoroughly without due regard to the structural vibrations which they may induce, and since the vibration or structural response is important to the designer anyhow, a detailed treatment of the subject is left to the IAHR Monograph on flow-induced vibrations. In the following, the designer is merely shown how to assess an engineering system to insure that a possible source for load fluctuation is not overlooked. For this purpose, a survey is given mainly on the following excitation mechanisms (Section 2.2): (1) extraneous excitation due to turbulent flow, two-phase flow, and oscillating flow; (2) excitation due to flow instabilities; (3) self-excitation due to structural movements; and (4) excitation due to resonating fluid oscillators.

Regarding the mean forces, even the modern methods of prediction require supporting data from laboratory experiments or model tests, and these are prone to 'scale effects'. Although such effects may have little consequence for preliminary hydraulic considerations, they can well be essential in the final stage of design. Data on mean hydrodynamic forces are therefore presented so as to yield guidance with respect to the following major influencing factors or scale effects: (1) geometry and viscosity; (2) confining boundaries and roughness; (3)

approach-flow conditions including turbulence; (4) gravity, surface tension, and compressibility; (5) cavitation and aeration; (6) unsteadiness and structural vibration.

Special attention is given to hydrodynamic forces on high-head and low-head gates (Chapters 3 and 4). Again, however, the subject is presented in terms of the basic processes producing these forces (i.e. underflow, overflow, and simultaneous underflow and overflow) rather than in terms of the types of hydraulic structures affected. Although the latter would have been more convenient for the design engineer, the former offers the advantage of wider and deeper coverage as it leads naturally to generalizations and the transfer of information from one field of application to another.

The material presented in each section is amply illustrated with practical examples. These illustrations include the following hydraulic structures:

- Spillways and flip buckets (Figures 2.11, 2.12, 2.13, 2.56, 2.68, 2.70);
- Stilling basins (Figures 2.21, 2.22, 2.23, 2.92);
- Piers and submerged bridges (Figures 2.41, 2.60, 2.61, 2.82, 2.91, 2.93);
- Pipelines and pipe bends (Figures 2.28, 2.64, 2.78);
- Hydraulic machines (Figure 2.10);
- Valves (Figures 2.66, 2.67, 2.99, 2.100, 2.101);
- High-head leaf gates (Figures 3.33, 3.34, 3.38, 3.44, 3.53, 3.56);
- Low-head leaf gates (Figures 2.24, 3.34, 4.49, 4.57, 4.63, 4.69, 4.72, 4.75);
- Cylinder gates (Figures 3.1a, 3.57);
- Tainter gates (Figures 2.25, 2.26, 2.27, 4.70, 4.78);
- Flap and drum gates (Figures 4.46, 4.48, 4.56);
- Miter gates (Figures 2.57, 2.58).

For a more detailed compilation of the hydraulic structures treated, the reader is referred to the subject index at the end of this book. Moreover, the IAHR Editorial Committee of this design manual intends to bring out another series of monographs in the near future which will serve the practising engineer as an application index. In this series, primary emphasis will be given to various kinds of hydraulic structures, and the reader will be aided in the selection of the relevant sections of the present manual to be consulted to insure hydraulically safe designs.

On all subjects of the design manual, including hydrodynamic forces, research is being performed so intensively and new practical experiences are accumulating so rapidly today that it is impossible to present material in a final form. All coleagues working in this field are therefore invited to report new findings from both research and practical experience to the IAHR Editorial Committee (c/o IAHR Secretariat, Delft Hydraulics, Delft, Netherlands), in order that these findings may be incorporated in the revised new editions which are planned to appear in five to ten year intervals.

Publication of the IAHR Hydraulic Structures Design Manual was undertaken with the intent to consolidate hydraulic-design information which is normally scattered among a vast number of journals and books. In spite of such consolidation, the manual will probably be regarded as too extensive. The inevitable, and unfortunate, course of events will be that only a very small part of the information will be extracted, simplified, and reduced to straight-forward 'design criteria'.

But the extent of the problem is far greater than this. In every one of the monographs of the present series, the authors are cautioning the reader that, despite the narrow definition of the monograph subjects, only a small selection of relevant information can be included, and even that information must be confined within the limits of the present state-of-the-art. Thus, even if a designer were to observe every item presented in the design manual, he could still not be sure that its structure would be completely safe from the hydraulic point of view. And, of course, Hydraulics is by no means the only thing that needs to be considered in the design! Where would we end up if monograph series were prepared for every other technical field involved in the design of hydraulic structures? Are engineers not overburdened with the know-how they need to acquire as matters stand? And then: not a single word has been mentioned about the environmental and social impacts of the engineer's work. How could we do justice to these important subjects? By means of the computer? I doubt it. If the computer fails to help in relatively simple hydraulic problems, as exemplified in this monograph, how should it ever be able to help us avoid the many unwanted side effects on the environment and on society?

The only possible conclusion appears to the author to be greater self-restraint and modesty in our technical aspirations ....

CHAPTER 2

Fluctuating and mean hydrodynamic forces

2.1 INTRODUCTORY REMARKS

2.1.1 *Fluctuating and mean components of flow and forces*

The hydrodynamic force on a structure immersed in a uniform flow, F, is commonly split into a component acting in the direction of the approach flow and two components acting perpendicular to it. The former is called the drag, F_D, and the one acting perpendicular to the axis of an elongated structure is called lift or side thrust, F_L. Figure 2.1 depicts an example of a cylindrical structure in a uniform cross flow for which the velocity, v, fluctuates due to turbulence. If the flow is steady in the mean ($\bar{v} = \text{const}$), one may write

$$v_x = \bar{v} + v'_x, \quad v_y = v'_y, \quad v_z = v'_z \tag{2.1}$$

In general, the bar over a symbol denotes the time mean of the respective quantity, i.e.

$$\bar{v} = \lim_{T\to\infty} \frac{1}{T}\int_o^T v(t)\,\mathrm{d}t \tag{2.2}$$

and the prime denotes its fluctuating part. For the turbulent flow shown in Figure 2.1, the velocity fluctuations have components in all directions. A convenient measure of the fluctuating components is the root-mean-square value

$$v'_{\mathrm{rms}} = \sqrt{\overline{v'^2}} = \lim_{T\to\infty} \left[\frac{1}{T}\int_o^T v'^2(t)\,\mathrm{d}t\right]^{1/2} \tag{2.3}$$

and the turbulence intensity is usually defined by the turbulence level

$$Tu = \frac{(v'_x)_{\mathrm{rms}}}{\bar{v}} \tag{2.4}$$