

© Copyright SEK Svensk Elstandard. Reproduction in any form without permission is prohibited.

## Vattenturbiner, magasineringspumpar och pumpturbiner – Hydrauliska egenskaper – Leveransprovning i modell

*Hydraulic turbines, storage pumps and pump-turbines –  
Model acceptance tests*

Som svensk standard gäller europastandarden EN IEC 60193:2019. Den svenska standarden innehåller den officiella engelska språkversionen av EN IEC 60193:2019.

### Nationellt förord

Europastandarden EN IEC 60193:2019

består av:

- **europastandardens ikraftsättningsdokument**, utarbetat inom CENELEC
- **IEC 60193, Third edition, 2019 - Hydraulic turbines, storage pumps and pump-turbines - Model acceptance tests**

utarbetad inom International Electrotechnical Commission, IEC.

Tidigare fastställd svensk standard SS-EN 60193, utgåva 1, 2000, gäller ej fr o m 2022-05-30.

---

ICS 27.140.00

---

Denna standard är fastställd av SEK Svensk Elstandard, som också kan lämna upplysningar om **sakinnehållet** i standarden.  
Postadress: Box 1284, 164 29 KISTA  
Telefon: 08 - 444 14 00.  
E-post: sek@elstandard.se. Internet: www.elstandard.se

---

### *Standarder underlättar utvecklingen och höjer elsäkerheten*

Det finns många fördelar med att ha gemensamma tekniska regler för bl a mätning, säkerhet och provning och för utförande, skötsel och dokumentation av elprodukter och elanläggningar.

Genom att utforma sådana standarder blir säkerhetsfordringar tydliga och utvecklingskostnaderna rimliga samtidigt som marknadens acceptans för produkten eller tjänsten ökar.

Många standarder inom elområdet beskriver tekniska lösningar och metoder som åstadkommer den elsäkerhet som föreskrivs av svenska myndigheter och av EU.

### *SEK är Sveriges röst i standardiseringsarbetet inom elområdet*

SEK Svensk Elstandard svarar för standardiseringen inom elområdet i Sverige och samordnar svensk medverkan i internationell och europeisk standardisering. SEK är en ideell organisation med frivilligt deltagande från svenska myndigheter, företag och organisationer som vill medverka till och påverka utformningen av tekniska regler inom elektrotekniken.

SEK samordnar svenska intressenters medverkan i SEKs tekniska kommittéer och stödjer svenska experters medverkan i internationella och europeiska projekt.

### *Stora delar av arbetet sker internationellt*

Utformningen av standarder sker i allt väsentligt i internationellt och europeiskt samarbete. SEK är svensk nationalkommitté av International Electrotechnical Commission (IEC) och Comité Européen de Normalisation Electrotechnique (CENELEC).

Standardiseringsarbetet inom SEK är organiserat i referensgrupper bestående av ett antal tekniska kommittéer som speglar hur arbetet inom IEC och CENELEC är organiserat.

Arbetet i de tekniska kommittéerna är öppet för alla svenska organisationer, företag, institutioner, myndigheter och statliga verk. Den årliga avgiften för deltagandet och intäkter från försäljning finansierar SEKs standardiseringsverksamhet och medlemsavgift till IEC och CENELEC.

### *Var med och påverka!*

Den som deltar i SEKs tekniska kommittéarbete har möjlighet att påverka framtida standarder och får tidig tillgång till information och dokumentation om utvecklingen inom sitt teknikområde. Arbetet och kontakterna med kollegor, kunder och konkurrenter kan gynnsamt påverka enskilda företags affärsutveckling och bidrar till deltagarnas egen kompetensutveckling.

Du som vill dra nytta av dessa möjligheter är välkommen att kontakta SEKs kansli för mer information.

### **SEK Svensk Elstandard**

Box 1284  
164 29 Kista  
Tel 08-444 14 00  
[www.elstandard.se](http://www.elstandard.se)

English Version

**Hydraulic turbines, storage pumps and pump-turbines - Model  
acceptance tests  
(IEC 60193:2019)**

Turbines hydrauliques, pompes d'accumulation et pompes-  
turbines - Essais de réception sur modèle  
(IEC 60193:2019)

Hydraulische Turbinen, Speicherpumpen und Pumpturbinen  
- Modellabnahmeprüfungen  
(IEC 60193:2019)

This European Standard was approved by CENELEC on 2019-05-30. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.



European Committee for Electrotechnical Standardization  
Comité Européen de Normalisation Electrotechnique  
Europäisches Komitee für Elektrotechnische Normung

**CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels**

## European foreword

The text of document 4/371/FDIS, future edition 3 of IEC 60193, prepared by IEC/TC 4 "Hydraulic turbines" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN IEC 60193.

The following dates are fixed:

- latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 2020-02-29
- latest date by which the national standards conflicting with the document have to be withdrawn (dow) 2022-05-30

This document supersedes EN 60193:1999.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC shall not be held responsible for identifying any or all such patent rights.

## Endorsement notice

The text of the International Standard IEC 60193:2019 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60041:1991	NOTE	Harmonized as EN 60041:1994
IEC 60609-1:2004	NOTE	Harmonized as EN 60609-1:2005 (not modified)
IEC 60609-2:1997	NOTE	Harmonized as EN 60609-2:1999 (not modified)
IEC 60994:1991	NOTE	Harmonized as EN 60994:1992 (not modified)
ISO 4006:1991	NOTE	Harmonized as EN 24006:1993 (not modified)
ISO 4373:2008	NOTE	Harmonized as EN ISO 4373:2008 (not modified)
ISO 5167-1:2003	NOTE	Harmonized as EN ISO 5167-1:2003 (not modified)
ISO 20456:2017	NOTE	Harmonized as EN ISO 20456 (not modified) <sup>1</sup>

---

<sup>1</sup> Under preparation. Stage at the time of publication: prEN ISO 20456.

## Annex ZA (normative)

### Normative references to international publications with their corresponding European publications

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: [www.cenelec.eu](http://www.cenelec.eu).

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 62097	2009	Hydraulic machines, radial and axial - Performance conversion method from model to prototype	EN 62097	2009
ISO 2186	2007	Fluid flow in closed conduits - Connections for pressure signal transmissions between primary and secondary elements	-	-
ISO 2533	1975	Standard Atmosphere	-	-
ISO 4185	-	Measurement of liquid flow in closed conduits - Weighing method	- EN 24185	1993
-	-		+ AC	1993
ISO 4287	1997	Geometrical Product Specifications (GPS) - Surface texture: Profile method - Terms, definitions and surface texture parameters	EN ISO 4287	1998
ISO 8316	-	Measurement of liquid flow in closed conduits - Method by collection of the liquid in a volumetric tank	- EN ISO 8316	1995

## CONTENTS

FOREWORD.....	13
1 Scope.....	15
2 Normative references .....	17
3 Terms, definitions, symbols and units .....	18
3.1 General.....	18
3.2 General terminology.....	18
3.3 Units .....	20
3.4 Definition of terms, symbols and units.....	20
3.4.1 List of terms and definitions by topic.....	20
3.4.2 Subscripts and symbols .....	21
3.4.3 Geometric terms .....	23
3.4.4 Physical quantities and properties .....	25
3.4.5 Discharge, velocity and speed terms .....	26
3.4.6 Pressure terms .....	27
3.4.7 Specific energy terms .....	27
3.4.8 Height and head terms .....	30
3.4.9 Power and torque terms.....	32
3.4.10 Efficiency terms .....	34
3.4.11 General terms relating to fluctuating quantities .....	35
3.4.12 Fluid dynamics and scaling terms <sup>a)</sup> .....	37
3.4.13 Dimensionless terms .....	38
3.4.14 Terms relating to additional performance data .....	39
4 Nature and extent of guarantees related to hydraulic performance .....	40
4.1 General.....	40
4.1.1 Design data and coordination .....	40
4.1.2 Definition of the hydraulic performance guarantees .....	40
4.1.3 Guarantees of correlated quantities .....	41
4.1.4 Form of guarantees .....	41
4.2 Main hydraulic performance guarantees verifiable by model test.....	41
4.2.1 Guaranteed quantities for any machine.....	41
4.2.2 Specific application.....	42
4.3 Guarantees not verifiable by model test .....	43
4.3.1 Guarantees on cavitation erosion .....	43
4.3.2 Guarantees on maximum momentary overspeed and maximum momentary pressure rise .....	44
4.3.3 Guarantees covering noise and vibration .....	44
4.4 Additional performance data .....	44
5 Execution of tests .....	45
5.1 Requirements of test installation and model.....	45
5.1.1 Choice of laboratory .....	45
5.1.2 Test installation .....	45
5.1.3 Model requirements .....	46
5.2 Dimensional check of model and prototype .....	49
5.2.1 General .....	49
5.2.2 Explanation of terms used for model and prototype.....	49
5.2.3 Purpose of dimensional checks.....	49
5.2.4 General rules.....	50

5.2.5	Procedure.....	51
5.2.6	Application for different types of machines.....	52
5.2.7	Methods .....	52
5.2.8	Accuracy of measurements.....	61
5.2.9	Dimensions of model and prototype to be checked .....	62
5.2.10	Permissible maximum deviations in geometrical similarity between prototype and model for turbines, pumps and pump-turbines .....	66
5.2.11	Surface waviness and roughness.....	71
5.3	Hydraulic similitude.....	74
5.3.1	Theoretical basic requirements and similitude numbers .....	74
5.3.2	Conditions for hydraulic similitude as used in this document.....	74
5.3.3	Similitude requirements for various types of model tests.....	75
5.3.4	Reynolds similitude.....	76
5.3.5	Froude similitude .....	77
5.3.6	Other similitude conditions.....	80
5.4	Test conditions .....	81
5.4.1	Determination of test conditions.....	81
5.4.2	Minimum values for model size and test conditions to be fulfilled.....	82
5.4.3	Stability and fluctuations during measurements .....	83
5.4.4	Adjustment of the operating point .....	83
5.5	Test procedures.....	83
5.5.1	Organization of tests.....	83
5.5.2	Inspections and calibrations .....	86
5.5.3	Execution of tests .....	88
5.5.4	Faults and repetition of tests .....	93
5.5.5	Final test report .....	94
5.6	Introduction to the methods of measurement.....	95
5.6.1	General .....	95
5.6.2	Measurements related to the main hydraulic performance guarantees .....	95
5.6.3	Measurements related to additional data .....	97
5.6.4	Acquisition and processing of data .....	97
5.7	Physical properties .....	97
5.7.1	General .....	97
5.7.2	Acceleration due to gravity .....	97
5.7.3	Physical properties of water.....	98
5.7.4	Physical conditions of atmosphere.....	104
5.7.5	Density of mercury.....	104
6	Main hydraulic performances: methods of measurement and results.....	105
6.1	Data acquisition and data processing.....	105
6.1.1	Overview .....	105
6.1.2	General requirements .....	105
6.1.3	Data acquisition.....	105
6.1.4	Component requirements.....	107
6.1.5	Check of the data acquisition system.....	110
6.2	Discharge measurement .....	112
6.2.1	General .....	112
6.2.2	Choice of the method of measurement.....	112
6.2.3	Accuracy of measurement .....	113
6.2.4	Primary methods .....	114

6.2.5	Secondary methods .....	115
6.3	Pressure measurement .....	118
6.3.1	General .....	118
6.3.2	Choice of pressure-measuring section .....	119
6.3.3	Pressure taps and connecting lines .....	119
6.3.4	Apparatus for pressure measurement .....	121
6.3.5	Calibration of pressure measurement apparatus .....	128
6.3.6	Vacuum measurements .....	129
6.3.7	Uncertainty in pressure measurements .....	129
6.4	Free water level measurement (see also ISO 4373) .....	129
6.4.1	General .....	129
6.4.2	Choice of water level measuring sections .....	130
6.4.3	Number of measuring points in a measuring section .....	130
6.4.4	Measuring methods .....	130
6.4.5	Uncertainty in free water level measurement .....	131
6.5	Determination of $E$ and $NPSE$ .....	132
6.5.1	General .....	132
6.5.2	Determination of the specific hydraulic energy $E$ .....	133
6.5.3	Simplified formulae for $E$ .....	135
6.5.4	Determination of the net positive suction-specific energy $NPSE$ .....	142
6.6	Shaft torque measurement.....	144
6.6.1	General .....	144
6.6.2	Methods of torque measurement.....	144
6.6.3	Methods of absorbing/generating power .....	145
6.6.4	Layout of arrangement.....	145
6.6.5	Checking of system .....	150
6.6.6	Calibration.....	150
6.6.7	Uncertainty in torque measurement (at a confidence level of 95 %) .....	151
6.7	Rotational speed measurement.....	152
6.7.1	General .....	152
6.7.2	Methods of speed measurement .....	152
6.7.3	Checking .....	152
6.7.4	Uncertainty of measurement.....	152
6.8	Computation and presentation of test results .....	153
6.8.1	General .....	153
6.8.2	Power, discharge and efficiency in the guarantee range .....	158
6.8.3	Computation of steady-state runaway speed and discharge.....	171
6.9	Error analysis .....	176
6.9.1	Definitions .....	176
6.9.2	Determination of uncertainties in model tests.....	178
6.10	Comparison with guarantees.....	182
6.10.1	General .....	182
6.10.2	Interpolation curve and total uncertainty bandwidth .....	183
6.10.3	Power, discharge and/or specific hydraulic energy and efficiency in the guarantee range .....	184
6.10.4	Runaway speed and discharge .....	188
6.10.5	Cavitation guarantees.....	189
7	Additional performance data – Methods of measurement and results.....	191
7.1	Introduction to additional data measurement.....	191



7.1.1	General .....	191
7.1.2	Test conditions and test procedures .....	192
7.1.3	Uncertainty in measurements .....	192
7.1.4	Model to prototype conversion .....	192
7.2	Fluctuating quantities .....	193
7.2.1	Data acquisition and processing for measurement of fluctuating quantities .....	193
7.2.2	Pressure fluctuations .....	197
7.2.3	Shaft torque fluctuations .....	213
7.3	Axial and radial thrust .....	214
7.3.1	General .....	214
7.3.2	Hydraulic axial thrust .....	215
7.3.3	Radial thrust .....	223
7.4	Hydraulic loads on control components .....	226
7.4.1	General .....	226
7.4.2	Guide vane torque .....	227
7.4.3	Runner blade torque .....	233
7.4.4	Pelton needle force and deflector torque .....	237
7.5	Testing in an extended operating range .....	241
7.5.1	General .....	241
7.5.2	Four quadrants .....	241
7.5.3	Operating modes (see Figure 116) .....	243
7.5.4	Scope of tests .....	244
7.5.5	Methods of testing in the extended operating range .....	246
7.6	Differential pressure measurement in view of prototype index test .....	248
7.6.1	General .....	248
7.6.2	Purpose of test .....	249
7.6.3	Execution of test .....	249
7.6.4	Analysis of test results .....	249
7.6.5	Transposition to prototype conditions .....	250
7.6.6	Uncertainty .....	250
Annex A (informative) Dimensionless terms .....		251
Annex B (normative) Physical properties, data .....		253
Annex C (informative) Summarized test and calculation procedure .....		261
C.1	General .....	261
C.2	Agreements to be reached prior to testing .....	261
C.3	Model, test facility and instrumentation .....	262
C.3.1	Model manufacture and dimensional checks .....	262
C.3.2	Test facility instrumentation and data acquisition system .....	262
C.4	Tests and calculation of the model values .....	262
C.4.1	Test types .....	262
C.4.2	Measurement of the main quantities during the test .....	263
C.4.3	Uncertainty of the measured quantities .....	263
C.4.4	Calculation of the quantities related to the main hydraulic performance .....	263
C.4.5	Calculation of the dimensionless factors or coefficients and of the Thoma number .....	263
C.4.6	Determination of $\delta_{\text{ref}}$ for the transposition of efficiency .....	264
C.4.7	Calculation of efficiency and power coefficients referred to $Re_M^*$ .....	264

C.4.8	Correction of the model-measured values taking into account the influence of cavitation .....	264
C.5	Calculation of prototype quantities .....	264
C.6	Plotting of model or prototype results .....	264
C.7	Comparison with the guarantees .....	265
C.8	Final protocol .....	265
C.9	Final test report .....	265
Annex D (normative)	The scale effect on hydraulic efficiency for reaction machines .....	266
D.1	Basic statements and assumptions .....	266
D.2	Efficiency transposition formulae .....	266
D.2.1	Derivation of the general formula for efficiency transposition .....	266
D.2.2	Amount of relative scalable losses in the range of guaranteed efficiencies .....	267
D.2.3	Determination of the effect of scaling on the efficiency of the model .....	269
D.2.4	Determination of the formula for the transposition of efficiency from model to prototype .....	271
Annex E (informative)	Comparison of the hydraulic efficiency transposition methods of IEC 60193 and IEC 62097 for reaction machines .....	273
E.1	IEC 60193 transposition method .....	273
E.1.1	Applications .....	273
E.1.2	Limitations .....	273
E.2	IEC 62097 transposition method .....	274
E.2.1	Applications .....	274
E.2.2	Limitations .....	274
Annex F (normative)	Computation of the prototype runaway characteristics taking into account friction and windage losses of the unit .....	275
Annex G (informative)	Example of determination of the best smooth curve: method of separate segments .....	276
G.1	General .....	276
G.2	Principle of the method .....	276
G.3	Choice of the minimum width of the intervals .....	278
G.4	Determination of the intervals .....	278
Annex H (informative)	Examples of analysis of sources of error and uncertainty evaluation .....	279
H.1	General .....	279
H.2	Example of analysis of sources of error and of uncertainty evaluation in the measurement of a physical quantity .....	279
H.2.1	General .....	279
H.2.2	Errors arising during calibration .....	280
H.2.3	Errors arising during the tests .....	281
H.3	Example of calculation of uncertainty due to systematic errors in the determination of the specific hydraulic energy, mechanical runner/impeller power and hydraulic efficiency .....	281
H.3.1	General .....	281
H.3.2	Discharge .....	282
H.3.3	Pressure .....	282
H.3.4	Specific hydraulic energy .....	282
H.3.5	Power .....	283
H.3.6	Hydraulic efficiency .....	283
H.4	Example of calculation of uncertainty due to systematic errors in the determination of the net positive suction specific energy .....	284

H.4.1	General .....	284
H.4.2	Discharge .....	284
H.4.3	Pressure .....	284
H.4.4	Net positive suction specific energy .....	284
Annex I (normative)	The scale effect on hydraulic efficiency for Pelton turbines .....	286
I.1	General.....	286
I.2	Similarity considerations .....	286
I.3	Transposition formula .....	288
Annex J (normative)	Analysis of random errors for a test at constant operating conditions .....	289
J.1	General.....	289
J.2	Standard deviation .....	289
J.3	Confidence levels .....	290
J.4	Student's <i>t</i> distribution .....	290
J.5	Maximum permissible value of uncertainty due to random errors.....	291
J.6	Example of calculation .....	292
Annex K (normative)	Calculation of plant Thoma number $\sigma_{pl}$ .....	293
K.1	Definition of $\sigma_{pl}$ , <i>NPSE</i> and <i>NPSH</i> .....	293
K.2	Data needed to calculate $\sigma_{plc}$ .....	294
Annex L (informative)	Flux diagram of specific hydraulic energy, flow and power .....	296
Annex M (informative)	Synchronous and asynchronous components of pressure signals .....	299
Annex N (informative)	Natural frequency of the hydraulic system .....	301
Annex O (informative)	Calculation of axial force components .....	302
O.1	General.....	302
O.2	Calculating the force acting on the runner crown ( $F_2$ ) .....	302
O.2.1	General .....	302
O.2.2	Pressure specific energy losses due to seal clearance .....	302
O.2.3	Pressure specific energy losses through the centrifugal zones between the stationary and rotating parts .....	304
O.2.4	Pressure specific energy losses in a pressure relief/equilibrium pipe .....	305
O.2.5	Additional specific energy losses .....	306
O.3	Calculating the force acting on the runner band ( $F_3$ ).....	307
Bibliography.....		308
Figure 1–	Schematic representation of a hydraulic machine.....	22
Figure 2 –	Guide vane opening and angle .....	22
Figure 3 –	Reference diameter and bucket width .....	24
Figure 4 –	Determination of $\sigma_0$ and $\sigma_1$ for typical cavitation curves.....	29
Figure 5 –	Reference level of machine .....	31
Figure 6 –	Flux diagram for power and discharge.....	33
Figure 7 –	Illustration of some definitions related to oscillating quantities.....	36
Figure 8 –	Procedure for dimensional checks, comparison of results "steel to steel" and application of tolerances for model and prototype .....	51
Figure 9 –	Example of spiral case and distributor dimensions to be checked.....	54
Figure 10 –	Example of draft tube dimensions to be checked .....	54

Figure 11 – Example of the dimensions to be checked on a bulb unit.....	55
Figure 12 – Example of the dimensions to be checked on the runner/impeller of a radial flow machine.....	56
Figure 13 – Runner/impeller of radial flow machine: examples of locations for blade profile measuring sections for templates or measuring points for CMM.....	57
Figure 14 – Runner/impeller of radial flow machine: check of outlet width and blade profiles by means of templates as illustrated on a Francis runner.....	57
Figure 15 – Runner/impeller of radial flow machine: check of inlet and outlet widths between blades (example of a pump-turbine runner).....	58
Figure 16 – Runner/impeller of axial flow machine: example of locations for blade profile measuring sections for templates or measuring points for CMM.....	58
Figure 17 – Runner/impeller of axial flow machine: definition of blade adjustment and of blade profile tolerances.....	58
Figure 18 – Pelton turbine: example of dimensions to be checked on the distributor and the housing of vertical and horizontal shaft machines.....	59
Figure 19 – Pelton turbine: example of dimensions to be checked on the buckets and nozzles.....	60
Figure 20 – Definition of waviness and surface roughness.....	72
Figure 21 – Low specific hydraulic energy turbine example of recommended maximum surface roughness values on the runner blades (pressure side and suction side).....	73
Figure 22 – Relation between the setting level $z_f$ of a Francis turbine and the cavitation reference level $z_c$ .....	78
Figure 23 – Dependence of $\sigma$ values on level $z$ for model and prototype.....	78
Figure 24 – Acceleration due to gravity $g$ ( $m \cdot s^{-2}$ ).....	98
Figure 25 – Density of distilled water $\rho_{wd}$ ( $kg \cdot m^{-3}$ ).....	101
Figure 26 – Time multiplexing data acquisition system.....	106
Figure 27 – Bus operated data acquisition system.....	107
Figure 28 – Time delay.....	108
Figure 29 – Typical low-pass filter attenuation characteristics.....	109
Figure 30 – Different measurement chains and their recommended checkpoints.....	111
Figure 31 – Examples of pressure taps.....	120
Figure 32 – Types of pressure manifolds: a) with separate connecting lines to manifold and b) with ring manifold.....	121
Figure 33 – Examples of experimental setup of liquid column manometers.....	123
Figure 34 – Dead weight manometer with compensation by pressure or force transducer (example of experimental set-up).....	126
Figure 35 – Pressure weighbeam (example of experimental set-up).....	127
Figure 36 – Stilling well.....	130
Figure 37 – Point and hook gauges.....	131
Figure 38 – Example showing main elevations, heights and reference levels of the test rig and model machine.....	134
Figure 39 – Determination of specific hydraulic energy through differential pressure measuring instrument.....	137
Figure 40 – Determination of specific hydraulic energy of the machine through separate measurement of gauge pressures.....	138
Figure 41 – Determination of specific hydraulic energy of the machine through separate measurement of pressures by water column manometers.....	139

Figure 42 – Pelton turbines with vertical axis: determination of specific hydraulic energy of the machine .....	140
Figure 43 – Pelton turbines with horizontal axis: determination of specific hydraulic energy of the machine .....	141
Figure 44 – Low-head machines: determination of specific hydraulic energy of the machine using free water levels .....	142
Figure 45 – Determination of net positive suction energy <i>NPSE</i> and net positive suction head <i>NPSH</i> .....	143
Figure 46 – Balance arrangement .....	146
Figure 47 – Balance arrangement with gear .....	147
Figure 48 – Balance arrangement with two separate frames .....	147
Figure 49 – Arrangement with machine bearings and seals not in balance .....	147
Figure 50 – Arrangement with lower bearing and seal not in balance .....	148
Figure 51 – Arrangement with intermediate bearing and seal not in balance .....	148
Figure 52 – Arrangement using a torquemeter .....	148
Figure 53 – Arrangement using a torquemeter with machine bearings and seals in balance.....	149
Figure 54 – Arrangement using a torquemeter with machine bearings and seals not in balance.....	149
Figure 55 – Choosing the appropriate transposition method.....	153
Figure 56 – Single-regulated (Francis) model turbine: performance hill diagram (discharge factor versus speed factor) .....	155
Figure 57 – Single-regulated (Francis) model turbine: performance hill diagram (energy coefficient versus discharge coefficient).....	155
Figure 58 – Double-regulated (Kaplan) model turbine: performance hill diagram .....	156
Figure 59 – Single-regulated (radial) model pump: performance diagram.....	156
Figure 60 – Double-regulated model pump: performance diagram.....	157
Figure 61 – Pelton model turbine: performance hill diagram (example for a six-nozzle machine).....	157
Figure 62 – Single-regulated (radial) model pump-turbine: general four-quadrant diagram .....	158
Figure 63 – Reaction machines: procedure for calculating test results in view of comparison with guarantees .....	159
Figure 64 – Single-regulated turbine: three-dimensional surface of hydraulic efficiency and curves of performance at $E_{nD}$ constant.....	161
Figure 65 – Single-regulated pump: performance curves.....	162
Figure 66 – Double-regulated turbine: performance curves at $E_{nD}$ constant .....	163
Figure 67 – Double-regulated pump: performance curves at $E_{nD}$ constant.....	164
Figure 68 – Non-regulated turbine: performance curves.....	165
Figure 69 – Non-regulated pump: performance curves .....	166
Figure 70 – Efficiency curve correction in order to take into account cavitation influence (e.g. tubular machines at overload operation) .....	167
Figure 71 – Francis model turbine: cavitation curves.....	167
Figure 72 – Model pump: cavitation curves .....	167
Figure 73 – Francis model turbine cavitation curves: examples of limits for application of transposition formula .....	169
Figure 74 – Runaway curves for a single-regulated turbine (Francis) .....	172

Figure 75 – Runaway curves for a single-regulated turbine (six-nozzle Pelton) .....	172
Figure 76 – Runaway speed determined by extrapolation: example for a single-regulated turbine (Francis).....	172
Figure 77 – Influence of Thoma number on runaway speed and discharge of a single-regulated turbine (Francis).....	173
Figure 78 – Influence of the Thoma number on runaway speed and discharge of a double-regulated turbine (Kaplan).....	174
Figure 79 – Influence of the Thoma number on the off-cam runaway curves of a double-regulated turbine (Kaplan).....	174
Figure 80 – Example of calibration curve .....	178
Figure 81 – Single-regulated machine.....	184
Figure 82 – Double-regulated machine .....	184
Figure 83 – Single-regulated turbine: comparison between guarantees and measurements .....	185
Figure 84 – Non-regulated turbine: comparison between guarantees and measurements .....	186
Figure 85 – Non-regulated pump: comparison between guarantees and measurements.....	187
Figure 86 – Francis turbine runaway speed and discharge curves: comparison between guarantees and measurements .....	189
Figure 87 – Model turbine cavitation curve and comparison with the guarantee on the influence of the cavitation on the efficiency.....	190
Figure 88 – Typical data acquisition system.....	194
Figure 89 – Frequency response of analogue anti-aliasing filter .....	195
Figure 90 – Suggested locations of transducers.....	200
Figure 91 – Pump diagram with exploration paths .....	202
Figure 92 – Turbine hill-chart with exploration paths .....	203
Figure 93 – Normal pump mode operation of an $n_{QE} = 0,102$ pump-turbine model .....	205
Figure 94 – Zero discharge operation (10 % guide vane opening) of an $n_{QE} = 0,102$ pump-turbine model .....	205
Figure 95 – Part load operation of an $n_{QE} = 0,321$ Francis turbine model: $Q_{nD}/Q_{nDopt} = 0,719$ .....	206
Figure 96 – Higher part load operation of an $n_{QE} = 0,226$ Francis turbine model: $Q_{nD}/Q_{nDopt} = 0,764$ .....	207
Figure 97 – Full load operation of an $n_{QE} = 0,173$ Francis turbine model: $Q_{nD}/Q_{nDopt} = 1,218$ .....	208
Figure 98 – Example of waterfall diagram of pressure fluctuations in the draft tube of a Francis turbine, transducer $p_1$ .....	209
Figure 99 – Example of summarized diagram of pressure fluctuations in the draft tube of a Francis turbine, transducer $p_2$ .....	210
Figure 100 – Interaction of the external system with sources of pressure fluctuations from the hydraulic machine.....	211
Figure 101 – Definition of coordinate system .....	214
Figure 102 – Individual elements of axial force acting on a radial machine.....	216
Figure 103 – Typical testing arrangement for axial thrust measurement.....	218
Figure 104 – Typical calibration arrangement for axial thrust measurement .....	219

Figure 105 – Axial force factor versus discharge factor at different constant specific hydraulic energies in pump mode.....	221
Figure 106 – Axial force factor versus speed factor measured at different guide vane openings in the four quadrants of a pump-turbine .....	221
Figure 107 – Typical arrangements for radial thrust measurement (horizontal or vertical shaft) .....	224
Figure 108 – Design examples for torque measuring guide vanes.....	228
Figure 109 – Guide vane torque factor versus guide vane angle measured at different constant specific hydraulic energies in turbine mode.....	230
Figure 110 – Guide vane torque factor versus guide vane angle measured at different constant specific hydraulic energies in pump mode.....	231
Figure 111 – Guide vane torque factor versus speed factor measured at different constant guide vane angles in the four quadrants of a pump-turbine .....	231
Figure 112 – Example for runner blade torque measuring arrangement using telemetry.....	234
Figure 113 – Performance and hydraulic runner blade torque characteristics of an axial turbine measured at one constant runner blade angle $\beta$ and various constant guide vane angles $\alpha$ .....	236
Figure 114 – Pelton needle force factor as a function of relative needle stroke .....	240
Figure 115 – Example of four quadrants operation of a radial-type pump-turbine .....	242
Figure 116 – Chart illustrating the various operating modes.....	244
Figure 117 – S-shape characteristics in turbine brake mode .....	247
Figure 118 – Characteristic of a pump with positive slope range in a limited discharge range.....	247
Figure 119 – Example of graphical representation of index test data.....	250
Figure D.1 – Efficiency change in hydraulically similar operating conditions A and B having different $Re$ values .....	267
Figure D.2 – Variation of relative scalable losses.....	268
Figure D.3 – Transposition curve for model efficiency using best efficiency point.....	270
Figure D.4 – Efficiency increase from constant $Re_{M^*}$ to constant $Re_P$ .....	271
Figure D.5 – Efficiency increase from different $Re_M$ to constant $Re_P$ .....	272
Figure F.1 – Single-regulated turbine: determination of the maximum runaway speed of the prototype taking into account the friction and windage losses of the unit.....	275
Figure G.1 – Principle of the method of separate segments .....	277
Figure G.2 – Example of determination of intervals .....	277
Figure I.1 – Influence of Froude number .....	287
Figure I.2 – Influence of Weber number .....	288
Figure I.3 – Influence of Reynolds number.....	288
Figure K.1 – Definition for determination of net positive suction energy, $NPSE$ , and net positive suction head, $NPSH$ , of a prototype machine ( $E_{LS} \neq 0$ ).....	293
Figure L.1 – Turbine .....	296
Figure L.2 – Pump .....	297
Figure M.1 – a) Representation of asynchronous pressure pulsation and location of pressure transducers, and b) synchronous and c) asynchronous parts of the pressure signal.....	300
Figure O.1 – Crown seal clearance .....	304
Figure O.2 – Crown radius .....	305
Figure O.3 – Pressure relief pipe .....	306

Figure O.4 – Runner band seal .....	307
Table 1 – Permissible maximum deviations .....	68
Table 2 – Maximum recommended prototype surface roughness $Ra$ .....	73
Table 3 – Similitude numbers .....	74
Table 4 – Similitude requirements for various types of model tests .....	76
Table 5 – Minimum values for model size and test parameters .....	82
Table 6 – Coefficients of the Herbst and Roegenor formula .....	100
Table 7 – Minimum test specific hydraulic energy .....	102
Table 8 – Nomenclature for Figure 46 to Figure 54 .....	146
Table 9 – Variables defining the operating point of a machine .....	154
Table 10 – Summary of errors that determine total measurement uncertainty .....	179
Table 11 – Definition of individual force elements of axial thrust .....	217
Table 12 – Non-hydraulic forces influencing radial thrust measurement .....	225
Table 13 – Definition of quadrants and operating modes .....	242
Table B.1 – Acceleration due to gravity $g$ ( $m \cdot s^{-2}$ ) .....	253
Table B.2 – Density of distilled water $\rho_{Wd}$ ( $kg \cdot m^{-3}$ ) (1 of 2) .....	254
Table B.3 – Kinematic viscosity of distilled water $\nu$ ( $m^2 \cdot s^{-1}$ ) .....	256
Table B.4 – Vapour pressure of distilled water $p_{Va}$ (Pa) .....	257
Table B.5 – Density of dry air $\rho_a$ ( $kg \cdot m^{-3}$ ) .....	258
Table B.6 – Ambient pressure $p_{amb}$ (Pa) .....	259
Table B.7 – Density of mercury $\rho_{Hg}$ ( $kg \cdot m^{-3}$ ) .....	260
Table D.1 – $V_{ref}$ values .....	269
Table I.1 – Numerical data for surface tension $\sigma^*$ .....	287
Table J.1 – Confidence levels .....	290
Table J.2 – Values of Student's $t$ .....	291
Table J.3 – Computation of the estimated standard deviation and the uncertainty for eight observations .....	292
Table K.1 – Summary of calculated $\sigma_{plc}$ values and other relevant data .....	295



## INTERNATIONAL ELECTROTECHNICAL COMMISSION

**HYDRAULIC TURBINES, STORAGE PUMPS AND PUMP-TURBINES –  
MODEL ACCEPTANCE TESTS**

## FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 60193 has been prepared by IEC technical committee 4: Hydraulic turbines.

This third edition cancels and replaces the second edition published in 1999. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) update to methods/measuring tools currently used for checking dimensions on both model and prototype;
- b) update to requirements of accuracy in the dimensional check procedure as a result of new technology;

- c) merging of tables/sections with redundant information in dimension check in 5.2;
- d) update to methods of measuring discharge;
- e) update to pressure fluctuation methods and terminology;
- f) specification of measuring times for accurate pressure fluctuation analyses in the model;
- g) redefine definition for the transposition of pressure fluctuations to prototype;
- h) update to surface waviness requirements in prototype;
- i) redefining methods/references in clause on cavitation nuclei content (5.7.3.2.2);
- j) update to 7.3 and review of methods on radial thrust measurements;
- k) update to 7.4 (Hydraulic loads on control components);
- l) update and develop methodology in 7.5 for testing in the extended operating range;
- m) update to 7.6 concerning index testing;
- n) update to methods for measuring roughness;
- o) updates to references;
- p) updates to figures;
- q) revision of sigma definition;
- r) reference to new method of transposition in accordance with IEC 62097.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
4/371/FDIS	4/373/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

## HYDRAULIC TURBINES, STORAGE PUMPS AND PUMP-TURBINES – MODEL ACCEPTANCE TESTS

### 1 Scope

This document applies to laboratory models of any type of impulse or reaction hydraulic turbine, storage pump or pump-turbine.

This document applies to models of prototype machines either with unit power greater than 5 MW or with reference diameter greater than 3 m. Full application of the procedures herein prescribed is not generally justified for machines with smaller power and size. Nevertheless, this document may be used for such machines by agreement between the purchaser and the supplier.

In this document, the term "turbine" includes a pump-turbine operating as a turbine and the term "pump" includes a pump-turbine operating as a pump.

This document excludes all matters of purely commercial interest, except those inextricably bound up with the conduct of the tests.

This document is concerned with neither the structural details of the machines nor the mechanical properties of their components, so long as these do not affect model performance or the relationship between model and prototype performances.

This document covers the arrangements for model acceptance tests to be performed on hydraulic turbines, storage pumps and pump-turbines to determine if the main hydraulic performance contract guarantees (see 4.2) have been satisfied.

It contains the rules governing test conduct and prescribes measures to be taken if any phase of the tests is disputed.

The main objectives of this document are:

- to define the terms and quantities used;
- to specify methods of testing and of measuring the quantities involved, in order to ascertain the hydraulic performance of the model;
- to specify the methods of computation of results and of comparison with guarantees;
- to determine if the contract guarantees that fall within the scope of this document have been fulfilled;
- to define the extent, content and structure of the final report.

The guarantees can be given in one of the following ways:

- guarantees for prototype hydraulic performance, computed from model test results considering scale effects;
- guarantees for model hydraulic performance.

Moreover, additional performance data (see 4.4) can be needed for the design or the operation of the prototype of the hydraulic machine. Contrary to the requirements of Clauses 4 to 6 related to main hydraulic performance, the information of these additional data given in Clause 7 is considered only as recommendation or guidance to the user (see 7.1).

It is particularly recommended that model acceptance tests be performed if the expected field conditions for acceptance tests (see IEC 60041:1991) would not allow the verification of guarantees given for the prototype machine.

A transposition method taking into account the model and prototype wall surface roughness for the performance conversion on pump-turbines, Francis turbines, and axial machines is described in IEC 62097. This method requires model and prototype surface roughness data and takes into account the shift in  $\eta_{ED}$ ,  $Q_{ED}$  and  $P_{ED}$  factors for determining the transposition of efficiency between model and prototype. However, in the case of Francis machines with semi-spiral casing and axial machines, the transposition method has not been fully validated due to a lack of data. In addition, IEC 62097 does not apply to storage pumps, Pelton turbines, and Dériaz. Therefore, for these and otherwise specifically agreed upon cases where hydraulically smooth flow conditions are assumed on the model and the prototype, the transposition formula and procedure given in Annex D and Annex I can be applied. Applications and limitations of both this document and IEC 62097 transposition methods are discussed in Annex E.

The method for performance conversion from model to prototype needs to be clearly defined in the main hydraulic performance contract.

This document may also be applied to model tests for other purposes, i.e. comparative tests and research and development work.

If model acceptance tests have been performed, field tests can be limited to index tests (see IEC 60041:1991).

If a contradiction is found between this document and any other document, this document prevails.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62097:2009, *Hydraulic machines, radial and axial – Performance conversion method from model to prototype*

ISO 2186:2007, *Fluid flow in closed conduits – Connections for pressure signal transmissions between primary and secondary elements*

ISO 2533:1975, *Standard atmosphere*

ISO 4185:1980, *Measurement of liquid flow in closed conduits – Weighing method*

ISO 4287:1997, *Geometrical Product Specifications (GPS) – Surface texture: Profile method – terms, definitions and surface texture parameters*

ISO 8316:1987, *Measurement of liquid flow in closed conduits – Method by collection of the liquid in a volumetric tank*