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Calculation of load capacity of spur and helical gears — Application to marine gears

Calcul de la capacité de charge des engrenages cylindriques à dentures droite et hélicoïdale — Application aux engrenages marins

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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

International Standard ISO 9083 was prepared by Technical Committee ISO/TC 60, *Gears*, Subcommittee SC 2, *Gear capacity calculation*.

Annexes A and B form a normative part of ISO 9083. Annexes C to E are for information only.

Introduction

Procedures for the calculation of the load capacity of general spur and helical gears with respect to pitting and bending strength appear in ISO 6336-1, ISO 6336-2, ISO 6336-3 and ISO 6336-5. This International Standard is derived from ISO 6336-1, ISO 6336-2 and ISO 6336-3 by the use of specific methods and assumptions considered to be applicable to marine gears. Its application requires the use of allowable stresses and material requirements that are to be found in ISO 6336-5.

Calculation of load capacity of spur and helical gears — Application to marine gears

1 Scope

The formulae specified in this International Standard are intended for the establishment of a uniformly acceptable method for calculating the pitting resistance and bending strength capacity for the endurance of the main-propulsion and auxiliary gears of ships, offshore vessels and drilling rigs, having straight or helical teeth and subject to the rules of classification societies.

The rating formulae in this International Standard are not applicable to other types of gear tooth deterioration, such as plastic yielding, micropitting, scuffing, case crushing, welding and wear, and are not applicable under vibratory conditions where there may be an unpredictable profile breakdown. The bending strength formulae are applicable to fractures at the tooth fillet, but are not applicable to fractures on the tooth working profile surfaces, failure of the gear rim, or failures of the gear blank through web and hub. This International Standard does not apply to teeth finished by forging or sintering. This standard is not applicable to gears having a poor contact pattern.

This International Standard provides a method by which different gear designs can be compared. It is not intended to assure the performance of assembled drive gear systems. It is not intended for use by the general engineering public. Instead, it is intended for use by the experienced gear designer who is capable of selecting reasonable values for the factors in these formulae based on knowledge of similar designs and awareness of the effects of the items discussed.

WARNING — The user is cautioned that the calculated results of this International Standard should be confirmed by experience.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 53:1998, *Cylindrical gears for general and heavy engineering — Standard basic rack tooth profile.*

ISO 54:1996, *Cylindrical gears for general engineering and for heavy engineering — Modules*.

ISO 701:1998, *International gear notation — Symbols for geometrical data*.

ISO 1122-1:1998, *Vocabulary of gear terms — Part 1: Definitions related to geometry*.

ISO 1328-1:1995, *Cylindrical gears — ISO system of accuracy — Part 1: Definitions and allowable values of deviations relevant to corresponding flanks of gear teeth*.

ISO 6336-1:1996, *Calculation of load capacity of spur and helical gears — Part 1: Basic principles, introduction and general influence factors*.

ISO 6336-2:1996, *Calculation of load capacity of spur and helical gears — Part 2: Calculation of surface durability (pitting)*.

ISO 6336-3:1996, *Calculation of load capacity of spur and helical gears — Part 3: Calculation of tooth bending strength*.

ISO 6336-5:1996, *Calculation of load capacity of spur and helical gears — Part 5: Strength and quality of material*.

ISO/TR 10495:1997, *Cylindrical gears — Calculation of service life under variable loads — Conditions for cylindrical gears according to ISO 6336.*

3 Terms, definitions and symbols

For the purposes of this International Standard, the terms and definitions given in ISO 1122-1 apply. For symbols, see Table 1.

Table 1 — Symbols and abbreviations used in this International Standard

Symbol	Description or term	Unit
a	centre distance [a]	mm
b	facewidth	mm
b_{B}	facewidth of an individual helix of a double helical gear	mm
c_{γ}	mean value of mesh stiffness per unit facewidth	N/(mm·µm)
c'	maximum tooth stiffness of one pair of teeth per unit facewidth (single stiffness)	N/(mm·µm)
$d_{1,2}$	reference diameter of pinion, wheel	mm
$d_{\mathrm{a}1,2}$	tip diameter of pinion, wheel	mm
$d_{\mathrm{b}1,2}$	base diameter of pinion, wheel	mm
$d_{\mathrm{f}1,2}$	root diameter of pinion, wheel	mm
d_{sh}	shaft nominal diameter for bending	mm
d_{shi}	internal diameter of hollow shaft	mm
$d_{\mathrm{w}1,2}$	working pitch diameter of pinion, wheel	mm
$d_{\mathrm{Na}1,2}$	diameter of a circle defining the outer extremities of the usable flanks of tip chamfered/rounded gear teeth	mm
$f_{\mathrm{H}\beta}$	tooth alignment deviation (not including helix form deviation)	µm
f_{ma}	mesh misalignment due to manufacturing deviations	µm
f_{pb}	transverse base pitch deviation (the values of f_{pt} may be used for calculation in accordance with ISO 6336-1, using tolerances complying with ISO 1328-1)	µm
f_{sh}	helix deviation due to elastic deflections	µm
g_{α}	length of path of contact	mm
h	tooth depth	mm
h_{aP}	addendum of basic rack of cylindrical gears	mm
h_{fP}	dedendum of basic rack of cylindrical gears	mm
h_{Fe}	bending moment arm for load application at the outer point of single pair tooth contact	mm
l	bearing span	mm
m^{*}	relative individual gear mass per unit facewidth referenced to line of action	kg/mm
m_{n}	normal module	mm
m_{red}	reduced gear pair mass per unit facewidth referenced to the line of action	kg/mm
m_{t}	transverse module	mm
$n_{1,2}$	rotation speed of pinion, of wheel	min^{-1}
n_{E}	resonance speed	min^{-1}
p_{bn}	normal base pitch	mm

Table 1 — (*Continued*)

Symbol	Description or term	Unit
p_{bt}	transverse base pitch	mm
pr	protuberance of the tool	mm
q	finishing stock allowance of tooth flank	mm
q_s	notch parameter $s_{Fn} / 2\rho_F$	—
s	tooth thickness	mm
s_{Fn}	tooth-root chord at the critical section	mm
s_R	rim thickness	mm
u	gear ratio [a] $\lvert u \rvert = \lvert z_2/z_1 \rvert \geqslant 1$	—
v	tangential speed (without subscript: at reference circle ≈ tangential speed at pitch circle)	m/s
v_p	velocity parameter	—
$x_{1,2}$	profile shift coefficient of pinion, wheel	—
y_α	running-in allowance for a gear pair	µm
y_β	running-in allowance (equivalent misalignment)	µm
z_n	virtual number of teeth of a helical gear	—
$z_{1,2}$	number of teeth of pinion, of wheel [a]	—
A	auxiliary value for the determination of f_{sh}	mm·µm/N
B	total facewidth of a double helical gear including the gap	mm
C_a	tip relief	µm
C_B	basic rack factor (same rack for pinion and wheel)	—
C_R	gear blank factor	—
E	modulus of elasticity, Young's modulus	N/mm^2
F_m	the mean transverse load at the reference cylinder (= $F_t\, K_A K_v$)	N
F_t	(nominal) transverse tangential load at reference cylinder	N
F_{tH}	the determinant transverse load at the reference cylinder (= $F_t\, K_A\, K_v\, K_{H\beta}$)	N
F_β	total helix deviation	µm
$F_{\beta x}$	initial equivalent misalignment (before running-in)	µm
$F_{\beta y}$	initial equivalent misalignment (after running-in)	µm
K_v	dynamic factor	—
K_A	application factor	—
$K_{F\alpha}$	transverse load factor (root stress)	—

Table 1 — (*Continued*)

Symbol	Description or term	Unit
$K_{F\beta}$	face load factor (root stress)	—
$K_{H\alpha}$	transverse load factor (contact stress)	—
$K_{H\beta}$	face load factor (contact stress)	—
K_{γ}	mesh load factor (takes into account the uneven distribution of the load between meshes for multiple transmission paths)	—
$M_{1,2}$	auxiliary values for the determination of $Z_{B,D}$	—
N_L	number of cycles	—
N_S	resonance ratio in the main resonance range	—
P	transmitted power	kW
Ra	arithmetic mean roughness value (as specified in ISO 4287)	µm
Rz	mean peak-to-valley roughness (as specified in ISO 4287)	µm
S_F	factor of safety from tooth breakage	—
$S_{F\,min}$	minimum safety factor (tooth breakage)	—
S_H	factor of safety from pitting	—
$S_{H\,min}$	minimum safety factor (pitting)	—
$T_{1,2}$	pinion torque, wheel torque; (nominal)	Nm
Y_F	tooth form factor	—
$Y_{R\,rel\,T}$	relative surface factor	—
Y_S	stress correction factor	—
Y_X	size factor (tooth-root)	—
Y_{β}	helix angle factor (tooth-root)	—
$Y_{\delta\,rel\,T}$	relative notch sensitivity factor	—
Z_v	speed factor	—
$Z_{B,D}$	single pair tooth contact factors for the pinion, for the wheel	—
Z_E	elasticity factor	$\sqrt{N/mm^2}$
Z_H	zone factor	—
Z_L	lubricant factor	—
Z_R	roughness factor affecting surface durability	—
Z_W	work-hardening factor	—
Z_X	size factor (pitting)	—
Z_{β}	helix angle factor (pitting)	—
Z_{ϵ}	contact ratio factor (pitting)	—

Table 1 — (*Continued*)

Symbol	Description or term	Unit
α_{n}	normal pressure angle	°
α_{t}	transverse pressure angle	°
α_{wt}	transverse pressure angle at the working pitch cylinder	°
α_{P0}	normal pressure angle of the basic rack for cylindrical gears	°
β	helix angle (without subscript — at the reference cylinder)	—
β_{b}	base helix angle	°
ϵ_{α}	transverse contact ratio	—
$\epsilon_{\alpha n}$	virtual contact ratio, transverse contact ratio of a virtual gear	—
ϵ_{β}	axial overlap ratio	—
ϵ_{γ}	total contact ratio ($\epsilon_{\gamma} = \epsilon_{\alpha} + \epsilon_{\beta}$)	—
κ_{β}	factor characterizing the equivalent misalignment after running-in	—
$\nu_{40,50}$	kinematic viscosity at 40 °C, 50 °C	—
ν_{f}	viscosity parameter	—
ρ_{fP}	root fillet radius of the basic rack for cylindrical gears	mm
ρ_{rel}	radius of relative curvature	mm
ρ_{C}	radius of relative curvature at the pitch surface	mm
ρ_{F}	tooth-root fillet radius at the critical section	mm
σ_{B}	tensile strength	N/mm^2
σ_{F}	tooth-root stress	N/mm^2
$\sigma_{F\,lim}$	nominal stress number (bending)	N/mm^2
σ_{FE}	allowable stress number (bending) = $\sigma_{F\,lim}\,Y_{ST}$	N/mm^2
σ_{FG}	tooth-root stress limit	N/mm^2
σ_{FP}	permissible tooth-root stress	N/mm^2
σ_{F0}	nominal tooth-root stress	N/mm^2
σ_{H}	calculated contact stress	N/mm^2
$\sigma_{H\,lim}$	allowable stress number (contact)	N/mm^2
σ_{HG}	modified allowable stress number = $\sigma_{HP}\,S_{H\,min}$	N/mm^2
σ_{HP}	permissible contact stress	N/mm^2
σ_{H0}	nominal contact stress	N/mm^2
$\omega_{1,2}$	angular velocity of pinion, or wheel	rad/s

[a] For external gear pairs a, u, z_1 and z_2 are positive; for internal gear pairs a, u and z_2 are negative with z_1 positive.

4 Application

4.1 Design, specific applications

4.1.1 General

Gear designers shall recognize that requirements for different applications vary considerably. Use of the procedures of this International Standard for specific applications demands a careful appraisal of all applicable considerations, in particular:

— the allowable stress of the material and the number of load repetitions;

— the consequences of any percentage of failure (failure rate);

— the appropriate factor of safety.

Design considerations to prevent fractures emanating from stress raisers in the tooth flank, tip chipping and failures of the gear blank through the web or hub should be analysed by general machine design methods.

Any variances according to the following shall be reported in the calculation statement.

a) If a more refined method of calculation is desired or if compliance with the restrictions in clause 4.1 is for any reason impractical, relevant factors may be evaluated according to the basic standard or another application standard.

b) Factors derived from reliable experience or test data may be used instead of individual factors according to this International Standard. Concerning this, the criteria for Method A in ISO 6336-1:1996, 4.1.8, are applicable.

In other respects, rating calculations shall be strictly in accordance with this International Standard if stresses, safety factors, etc. are to be classified as being in accordance with this International Standard.

This International Standard is applicable when the wheel blank, shaft/hub connections, shafts, bearings, housings, threaded connections, foundations and couplings conform to the requirements regarding accuracy, load capacity and stiffness forming the basis for the calculation of the load capacity of gears.

Although the method described in this International Standard is mainly intended for recalculation purposes, by means of iteration it can also be used to determine the load capacities of gears. The iteration is accomplished by selecting a load and calculating the corresponding safety factor against pitting, S_{H1}, for the pinion. If S_{H1} is greater than $S_{H\,min}$ the load is increased, if it is smaller than $S_{H\,min}$ the load is reduced. This is done until the load chosen corresponds to $S_{H1} = S_{H\,min}$. The same method is used for the wheel ($S_{H2} = S_{H\,min}$) and also for the safety factors against tooth breakage, $S_{F1} = S_{F2} = S_{F\,min}$.

4.1.2 Gear data

This International Standard is applicable within the following constraints.

a) Types of gear:

— external and internal, involute spur, helical and double helical gears;

— for double helical gears, it is assumed that the total tangential load is evenly distributed between the two helices; if this is not the case (e.g. due to externally applied axial forces), this shall be taken into account; the two helices are treated as two single helical gears in parallel;

— planetary and other gear trains with multiple transmission paths.

b) Range of the transverse contact ratios of actual spur and helical gear pairs:

— $1{,}2 < \epsilon_\alpha < 2{,}5$ (affects c', c_γ, K_V, $K_{H\beta}$, $K_{F\beta}$, $K_{H\alpha}$ and $K_{F\alpha}$).

c) Range of helix angles:

— β less than or equal to 30° (affects c', c_γ, K_V and $K_{H\beta}$).

d) Basic racks:

— no restriction[1)].

4.1.3 Wheel blank, wheel rim

This International Standard is applicable when s_R, the thickness of the wheel rim under the tooth roots of internal and external gears, is > 3,5 m_n.

4.1.4 Materials

These include steels (affects Z_E, $\sigma_{H\,lim}$, σ_{FE}, K_V, $K_{H\beta}$ and $K_{F\beta}$). For materials and their abbreviations used in this International Standard, see Table 2. For other materials, see ISO 6336-1, ISO 6336-2, ISO 6336-3 and ISO 6336-5

Table 2 — Materials

Material	Abbreviation
Steel ($\sigma_B < 800$ N/mm²)	St
Through-hardening steel, alloy or carbon, through-hardened ($\sigma_B \geqslant 800$ N/mm²)	V
Case-hardened steel, case hardened	Eh
Steel, flame or induction hardened	IF
Nitriding steel, nitrided	NT (nitr.)
Through-hardening and case-hardening steel, nitrided	NV (nitr.)
Through-hardening and case-hardening steel, nitrocarburized	NV (nitrocarb.)

4.1.5 Lubrication

The calculation procedures are valid for gears that are spray or oil-bath lubricated using a lubricant approved by the manufacturer/designer of the gears. This validity is further subject to the condition that, at all times of operation, an adequate quantity of approved lubricant is available to the gear mesh. Provision for cooling shall ensure that temperatures assumed for purposes of calculations are not exceeded (affects lubricant film formation i.e. factors Z_L, Z_V and Z_R).

Provided that sufficient lubricant is available to the mesh, grease lubrication of slow speed auxiliaries is not excluded.

1) For all practical purposes, it may be assumed that the proportions of the basic rack of the tools are equal to those of the basic rack of the gear.

4.2 Safety factors

It is necessary to distinguish between the safety factor relative to pitting, S_H, and the safety factor relative to tooth breakage, S_F.

For a given application, adequate gear load capacity is demonstrated by the computed values of S_H and S_F being equal to or greater than the values $S_{H\,min}$ and $S_{F\,min}$, respectively.

Choice of the value of a safety factor should be based on the degree of confidence in the reliability of the available data and the consequences of possible failures.

Important factors to be considered are:

a) the allowable stress numbers used in the calculation are valid for a given probability of failure (the material values in ISO 6336-5:1996 are valid for 1 % probability of damage);

b) the specified quality and the effectiveness of quality control at all stages of manufacture;

c) the accuracy of specification of the service duty and external conditions;

d) tooth breakage is often considered to be a greater hazard than pitting.

Therefore, the chosen value for $S_{F\,min}$ should to be greater than the value chosen for $S_{H\,min}$. For calculation of actual safety factor see 6.1.5 (S_H, pitting) and 7.1.4 (S_F, tooth breakage).

It is recommended that the minimum values of the safety factors should be agreed upon between the purchaser, the manufacturer and the classification authority.

4.3 Input data

The following data shall be available for the calculations:

a) gear data:

a, z_1, z_2, m_n, d_1, d_2, d_{a1}, d_{a2}, b, x_1, x_2, α_n, β, ϵ_α, ϵ_β (see ISO 53:1998, ISO 54:1996);

b) cutter basic rack tooth profile:

h_{a0}, ρ_{a0} (see ISO 53:1998);

c) design and manufacturing data:

C_{a1}, C_{a2}, f_{pb}, $S_{H\,min}$, $S_{F\,min}$, Ra_1, Ra_2, Rz_1, Rz_2;

materials, material hardness and heat treatment details, gear accuracy grades, bearing span l, positions of gears relative to bearings, dimensions of pinion shaft d_{sh} and, when applicable, helix modification (crowning, end relief);

d) power data:

P or T or F_t, n_1, v_1, details of driving and driven machines.

Requisite geometrical data can be calculated according to national standards.