Manual for Curved Beam Model Piston Ring Design Tool (CBM-RDT)

(Console Version 1.0)

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Introduction

Curved Beam Model Ring Design Tool is an analytical tool that can be used in the design process of single-piece piston ring. It consists of 5 prime modules, each corresponding to a function summarized below:

- 1. Calculate geometric parameters of the ring cross section.
- 2. Calculate the ring free-shape, its final shape when subjected to a constant radial pressure (this final shape is called ovality) and the force distribution in circular bore. Knowing one of these distributions, this model determines the other two.
- 3. Calculate the ring-bore and ring-liner conformability: ring-bore and ring-groove interactions include asperity and lubrication forces along with gas, inertia and initial tangential load forces. Bore, groove upper and lower flanks distortions are also considered. Ring thermal expansion effect and radial temperature gradient moment are included in the model. Piston secondary motion and variation of oil viscosity on the liner with its temperature in addition to the existence of fuel spot are considered as well. A radial plot function is made separately to the computation one so that user can define the more convenient graphic parameters for the plot: magnification coefficient for bore distortion and ring-liner clearance, number of forces to represent and the maximum acceptable value to be represented for forces.
- 4. Conformability module for different ring gap locations defined uniformly along the bore circumferential direction. A radial plot animation function is made separately to the computation one. In addition to the graphic parameters mentioned in point 3, user can choose the number of frames per second for the video that will be created.
- 5. Calculate the ring static twist under FixOD or FixID constraint that is similar to practical measurement of static twist angle.

The first module is run always and is the first one to be executed. The other modules have independent inputs and outputs. They all require some of the outputs of the geometric parameters of the ring cross-section module as input. The following sections provide a description of these inputs and outputs.

The radial direction will be denoted by y and the axial one by z.

Module 1: Ring cross-section parameters calculation

Inputs

Ring cross-section can be defined:

- 1. By giving the points' coordinates:
 - a. By providing the number of points defining the cross section
 - b. Then providing the points' coordinates millimeters and in clockwise order with the outer-diameter (OD) on the left as shown in Figure 1. Each point will have an id.
 - c. Provide the id for the upper OD point (#6 in Figure 1), the upper ID (#7 in Figure 1), lower ID (#1 in Figure 1), lower OD (#2 in Figure 1), lower end point (#3 in Figure 1), minimum point (#4 in Figure 1), upper end point (#5 in Figure 1).
 - d. Linear coefficients for upper and lower edge factor (denoted by a_{21} and a_{22} respectively). Upper and lower edge factor are the linear coefficients in the parabolic shape parts of the running face: between lower end point (#3 in Figure 1) and minimum point (#4 in Figure 1) and between upper end point (#5 in Figure 1) and minimum point (#4 in Figure 1).

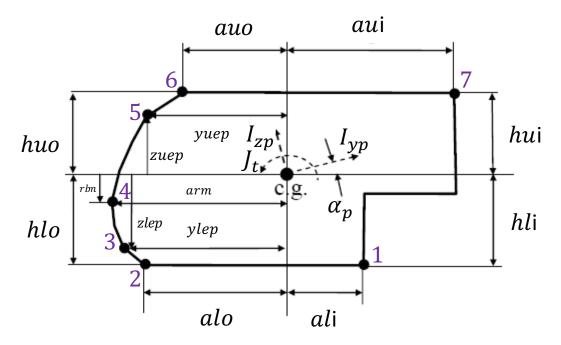


Figure 1

2. By providing the ring cross section parameters listed in the table below and shown in Figure 1.

Nomenclature	Variable	Comment	Unit
	designation		
Upper OD width	аио	Positive sign	mm
Upper OD height	huo	Positive sign	mm

Upper ID width	aui	Positive sign	mm
Upper ID height	hui	Positive sign	mm
Lower ID width	ali	Positive sign	mm
Lower ID height	hli	Positive sign	mm
Lower OD width	alo	Positive sign	mm
Lower OD height	hlo	Positive sign	mm
Lower end point width	ylep	Positive sign	mm
Lower end point axial location	zlep	Negative sign	mm
Minimum point width	arm	Positive sign	mm
Minimum point axial location	rbn	Positive sign if minimum point located above the gravity center point of the cross section and negative otherwise (negative sign in Figure 1)	mm
Upper end point width	уиер	Positive sign	mm
Upper end point axial location	zuep	Positive sign	mm
Linear coefficient for upper edge shape factor	a ₂₁		
Linear coefficient for lower edge shape factor	a_{11}		

Outputs

The outputs differ regarding the inputs provided.

1. If the inputs are defined using method 1, the outputs are the following:

Nomenclature	Variable designation	Comment	Unit
Center of mass radial coordinate	Ус	Can be positive or negative based on	mm
		the points'	

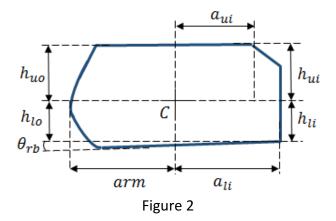
		coordinates	
Center of mass	7	provided Can be positive or	mm
axial coordinate	$Z_{\mathcal{C}}$	negative based on	IIIII
axiai coordinate		the points'	
		coordinates	
		provided	
Upper OD width	аио	Positive sign	mm
Upper OD height	huo	Positive sign	$\frac{mm}{mm}$
Upper ID width	aui	Positive sign	$\frac{mm}{mm}$
Upper ID height	hui	Positive sign	$\frac{mm}{mm}$
Lower ID width	ali		
	hli	Positive sign	mm
Lower ID height Lower OD width	alo	Positive sign	mm
		Positive sign	mm
Lower OD height	hlo	Positive sign	mm
Lower end point width	ylep	Positive sign	mm
Lower end point axial location	zlep	Negative sign	mm
Minimum point	arm	Positive sign	mm
width	arm	-	mm
Minimum point	rbn	Positive sign if	mm
axial location		minimum point	
		located above the	
		gravity center point	
		of the cross section	
		and negative	
		otherwise (negative	
		sign in Figure 1)	
Upper end point width	уиер	Positive sign	mm
Upper end point axial location	zuep	Positive sign	mm
Ring upper flank	$ heta_{rt}$	Positive sign.	deg
angle		Analogous to θ_{rb}	3
		shown in Figure 2.	
Ring lower flank	$ heta_{rb}$	Positive sign.	deg
angle	. ~	Shown in Figure 2.	-
Lower edge width	rb1	Positive sign. Axial	mm
		distance between	
		lower end point (#3	
		in Figure 1) and	

	Т	Τ	Т
		minimum point (#4	
		in Figure 1)	
Upper edge width	rb2	Positive sign. Axial	mm
		distance between	
		upper end point	
		(#5 in Figure 1) and	
		minimum point (#4	
		in Figure 1)	
Quadratic	a_{22}		mm
coefficient for			
upper edge shape			
factor			
Quadratic	a_{12}		mm
coefficient for			
lower edge shape			
factor			
Cross section area	Ac		mm^2
Moment of inertia	I_z		mm^4
in plane			
Moment of inertia	I_y		mm^4
out of plane	·		
Product of inertia	I_{yz}		mm^4
Principal moment	I_{zp}		mm^4
of inertia in plane	•		
Principal moment	I_{yp}		mm^4
of inertia out of			
plane			
Principal angle	α_p		deg
Polar moment of	I_p		mm^4
inertia			
Torsional factor	J_t		mm^4

2. If the inputs are defined using method 2, the outputs are the following:

Nomenclature	Variable	Comment	Unit
	designation		
Ring upper flank	$ heta_{rt}$	Positive sign.	deg
angle		Analogous to $ heta_{rb}$	
		shown in Figure 2.	
Ring lower flank	$ heta_{rb}$	Positive sign.	deg
angle		Shown in Figure 2.	
Lower edge width	rb1	Positive sign. Axial	mm
		distance between	

		lower end point (#3	
		in Figure 1) and	
		minimum point (#4	
		in Figure 1)	
Upper edge width	rb2	Positive sign. Axial	222.222
Opper eage wiath	102	distance between	mm
		upper end point	
		(#5 in Figure 1) and	
		minimum point (#4	
0 - 11	_	in Figure 1)	
Quadratic	a_{22}		mm
coefficient for			
upper edge shape			
factor			
Quadratic	a_{12}		mm
coefficient for			
lower edge shape			
factor	_		2
Cross section area	Ac		mm^2
Moment of inertia	I_z		mm^4
in plane			
Moment of inertia	$I_{\mathcal{Y}}$		mm^4
out of plane			
Product of inertia	I_{yz}		mm^4
Principal moment	I_{zp}		mm^4
of inertia in plane			
Principal moment	I_{yp}		mm^4
of inertia out of			
plane			
Principal angle	α_p		deg
Polar moment of	I_p		mm^4
inertia	P		
Torsional factor	J_t		mm^4



Module 2: Free-shape, ovality and force distribution in radial bore

This module consists of 3 sub-models each computing two of the three distributions from the third one. Inputs and outputs of each of these sub-modules are provided below.

Inputs of sub-model computing the free-shape and the ovality from the force distribution in radial bore

Nomenclature	Variable designation	Comment	Unit
Bore diameter	D_b		mm
Ring Young modulus	E_r		GPa
Gap size when ring is closed to circular bore	gap		mm
Gap size when ring is closed to ovality (under constant pressure)	gap2		mm
Force distribution in radial bore		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one contains the pressure times ring height (axial width).	deg & N/m

IsPovAvg		1 to consider the constant linear force in computing the ovality equal to the average of the force distribution in radial bore provided, 0 to provide its value (Pov) .	
Constant linear force to consider in computing the ovality (pressure times the ring height (axial width))	Pov	Positive sign. User needs to provide this value only when IsPovAvg=0.	N/m
Number of elements for the FEM	Nbe	Positive integer	
Number of points within one element	Npe	Positive integer	
Tolerance for Newton-Raphson algorithm convergence used to compute the ovality	Newton _{tol}	Positive sign. Suggested value: 10^{-6}	
Maximum number of Newton- Raphson algorithm iterations used to compute the ovality	It _{Max}	Positive integer. Suggested value: 100	
Magnifying coefficient for the radial plot of the ovality	k	Positive sign. Suggested values: in order of 10	

Inputs provided by the ring cross-section parameters calculation module.

Nomenclature	Variable	Comment	Unit
	designation		
Moment of inertia	I_z		mm^4
in plane			
Minimum point	arm		mm
width			

Outputs of sub-model computing the free-shape and the ovality from the force distribution in radial bore

Two text files are generated:

- fs_frompr.txt containing two columns: 1st column contains the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one the free-shape in usual representation in millimeters.
- rov_frompr.txt containing two columns: 1st column contains the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one the ovality in usual representation in millimeters.

Three plots are generated:

- Curve of the free-shape in usual representation in millimeters as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.
- Radial plot of the ovality (closed shape of the ring under the constant pressure).
- Curve of the ovality in usual representation in microns as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.

Inputs of sub-model computing the force distribution in radial bore and ovality from the free-shape

Nomenclature	Variable	Comment	Unit
	designation		
Bore diameter	D_b		mm
IsBDist		1 to take into account bore	
		distortion when computing the	
		force distribution in radial bore, 0	
		otherwise	
Highest order in	Norder	Non-zero positive integer. User	
the Fourier series		has to provide this value if	
for bore distortion.		IsBDist=1.	
Ampdata		1 to provide the amplitudes and	
		phases of bore distortion directly,	
		0 to provide dr distribution. User	
		has to provide this value if	
		IsBDist=1.	

Amplitudes for bore distortion	A_b	Positive values. Number of amplitudes to provide is equal to Norder (0 th , 2 nd ,,Norder th amplitudes). User has to provide this value if IsBDist=1 and	μт
		Ampdata=1.	
Phases for bore distortion	ϕ_b	Number of phases to provide is equal to <i>Norder</i> — 1 (2 nd ,3 rd ,,Norder th phases). User has to provide this value if IsBDist=1 and Ampdata=1.	rad
Bore distortion distribution dr		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the bore distortion dr in microns. User has to provide this value if IsBDist=1 and Ampdata=0.	deg & μm
Gap size when ring is closed to circular bore	gap		mm
Gap size when ring is closed to ovality (under constant pressure)	gap2		mm
Ring density	$ ho_r$		kg/m^3
Ring Young modulus	E_r		GPa
Ring Poisson ratio	$\overline{ u_r}$		
Ring thermal expansion coefficient	α_T		1/ <i>K</i>
Ring gap position	t_g	Ring gap position in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°)	deg
Ring temperature	T_r		Celsuis

Number of elements for the	Nbe	Positive integer	
FEM			
Number of points	Npe	Positive integer	
within one element			
Liner Young	E_l		GPa
modulus			
Liner Poisson ratio	$ u_l$		
Plateau ratio	PR		
Liner surface roughness standard deviation	σ_p		μm
Piston upper land reference diameter	Drldu		mm
Ring groove root diameter	Drg		mm
Piston lower land reference diameter	Drldl		mm
Ring groove inner axial height	hgi		mm
Ring groove upper flank angle	$ heta_{gt}$		rad
Ring groove lower flank angle	$ heta_{gb}$		rad
Ring groove upper flank surface roughness standard deviation	σ_{gt}		μт
Ring groove lower flank surface roughness standard deviation	σ_{gb}		μт
Groove Poisson ratio	$ u_g$		
Groove Young	E_g		GPa
modulus	8		
Radius increase at	$Exp_{land,u}$		μm
the upper land	,		
during engine			
operation			
Radius increase at	$Exp_{land,l}$		μm
the lower land			

during angina			
during engine			
operation	Easo		
Top ring groove radius increase	Exp_{gr}		μm
during engine			
operation			
z coefficient for the	Z	6.804 is the adopted value in the	
asperity ring/liner		simplified formulation	
and ring/groove			
contact interaction			
K coefficient for the	K	1.198e-4 is the adopted value in	
asperity ring/liner		the simplified formulation	
and ring/groove			
contact interaction			
A coefficient for	\boldsymbol{A}	4.4068e-5 is the adopted value in	
the asperity		the simplified formulation	
ring/liner and			
ring/groove contact			
interaction			
arOmega coefficient for	Ω	4 is the adopted value in the	
the asperity		simplified formulation	
ring/liner and			
ring/groove contact			
interaction			
Friction coefficient	fc_{dry}		
for the asperity	, a.y		
ring/liner and			
ring/groove contact			
interaction			
Constant	cfct	1 is the adopted value in the	
coefficient for the	-,	simplified formulation	
asperity ring/liner			
and ring/groove			
contact interaction			
IsGDist		1 to take into account groove	
.555.50		distortion when computing the	
		force distribution in radial bore, 0	
		otherwise	
Number of orders	$Norder_{u}$	Non-zero positive integer. User	
starting from the	noruciu	has to provide this value if	
2 nd one in the		IsGDist=1.	
Fourier series for		1335131-1.	
Tourier series for			

groove upper flank			
distortion			
Ampdatau		1 to provide the amplitudes and phases of groove upper flank distortion directly, 0 to provide dz distribution. User has to provide this value if IsBDist=1.	
Amplitudes for groove upper flank distortion	A_{gu}	Positive values. Number of amplitudes to provide is equal to $Norder_u$ (0 th , 2 nd ,, $Norder_u$ th amplitudes). User has to provide this value if IsGDist=1 and Ampdatau=1.	
Phases for groove upper flank distortion	ϕ_{gu}	Number of phases to provide is equal to $Norder_u - 1$ ($2^{nd}, 3^{rd},, Norder_u^{th}$ phases). User has to provide this value if IsBDist=1 and Ampdatau=1.	
Groove upper flank distortion distribution dz		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the groove upper flank distortion dz in microns. User has to provide this value if IsGDist=1 and Ampdatau=0.	deg & μm
Number of orders starting from the 2 nd one in the Fourier series for groove lower flank distortion	Norder _l	Non-zero positive integer. User has to provide this value if IsGDist=1.	
Ampdatal		1 to provide the amplitudes and phases of ring lower flank distortion directly, 0 to provide dz distribution. User has to provide this value if IsGDist=1.	
Amplitudes for groove lower flank distortion	A_{gl}	Positive values. Number of amplitudes to provide is equal to $Norder_l$ (0 th , 2 nd ,, $Norder_l$ th	

		amplitudes). User has to provide this value if IsGDist=1 and Ampdatal=1.	
Phases for groove lower flank distortion	ϕ_{gl}	Number of phases to provide is equal to $Norder_l-1$ (2^{nd} ,3 rd ,, $Norder_l^{th}$ phases). User has to provide this value if	
		IsGDist=1 and Ampdatal=1.	
Groove lower flank distortion distribution dz		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the groove lower flank distortion dz in microns. User has to provide this value if IsGDist=1	deg & μm
Groove thermal	±:1±	and Ampdatal=0.	a a d
	$tilt_{thu}$		rad
tilting – upper flank Groove thermal	$tilt_{thl}$		rad
tilting – lower flank	$\iota\iota\iota\iota_{thl}$		ruu
IsPovAvg		1 to consider the constant linear force in computing the ovality equal to the average of the force distribution in radial bore that will be computed, 0 to provide its value (<i>Pov</i>)	
Constant linear force to consider in computing the ovality (pressure times the ring height (axial width))	Pov	Positive sign. User needs to provide this value only when IsPovAvg=0.	N/m
IsFreeshape		1 to provide the free-shape coordinates and 0 to provide the free-shape curvature	
Free-shape distribution		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed	deg & mm

		T	
		frame with respect to the ring and	
		the second one contains the free-	
		shape coordinates in usual	
		representation in millimeters.	
		User has to provide this value if	
		IsFreeshape=1.	,
Free-shape		Text file with the first column	deg & 1/m
curvature		containing the circumferential	
distribution		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the ring and	
		the second one contains the free-	
		shape curvature coordinates in	
		usual representation in 1/m. User	
		has to provide this value if	
		IsFreeshape=0.	
Tolerance for	$Newton_{tol}$	Positive sign. Suggested value:	
Newton-Raphson		10^{-6}	
algorithm			
convergence used			
to compute the			
force distribution			
Maximum number	It _{Max}	Positive integer. Suggested value:	
of Newton-		100	
Raphson algorithm			
iterations used to			
compute the force			
distribution			
Tolerance for	$Newton_{tol2}$	Positive sign. Suggested value:	
Newton-Raphson		10^{-6}	
algorithm			
convergence used			
to compute the			
ovality			
Maximum number	It_{Max2}	Positive integer. Suggested value:	
of Newton-	PIWAL	100	
Raphson algorithm			
iterations used to			
compute the			
ovality			
Magnifying	k	Positive sign.	
coefficient for the	••	Suggested values: in order of 10	
Joennalent for the		1 2499cated falaca, ill older of 10	l

radial plot of the		
ovality		

Inputs provided by the ring cross-section parameters calculation module.

Nomenclature	Variable designation	Comment	Unit
Upper OD width	аио	Positive sign	mm
Upper OD height	huo	Positive sign	mm
Upper ID width	aui	Positive sign	mm
Upper ID height	hui	Positive sign	mm
Lower ID width	ali	Positive sign	mm
Lower ID height	hli	Positive sign	mm
Lower OD width	alo	Positive sign	mm
Lower OD height	hlo	Positive sign	mm
Ring upper flank angle	$ heta_{rt}$	Positive sign. Analogous to $ heta_{rb}$ shown in Figure 2.	deg
Ring lower flank angle	$ heta_{rb}$	Positive sign. Shown in Figure 2.	deg
Lower edge width	rb1	Positive sign. Axial distance between lower end point (#3 in Figure 1) and minimum point (#4 in Figure 1)	mm
Upper edge width	rb2	Positive sign. Axial distance between upper end point (#5 in Figure 1) and minimum point (#4 in Figure 1)	mm
Minimum point axial location	rbn	Positive sign if minimum point located above the gravity center point of the cross section and negative otherwise (negative sign in Figure 1)	mm
Quadratic coefficient for upper edge shape factor	a_{22}		mm
Quadratic coefficient for lower edge shape factor	a_{12}		mm
Linear coefficient for upper edge shape factor	a_{21}		

Linear coefficient	a_{11}		
for lower edge			
shape factor			
Minimum point	arm	Positive sign	mm
width			
Cross section area	Ac		mm^2
Principal moment	I_{zp}		mm^4
of inertia in plane	•		
Principal moment	I_{yp}		mm^4
of inertia out of	,		
plane			
Moment of inertia	I_z		mm^4
in plane			
Principal angle	α_p		deg
Polar moment of	I_p		mm^4
inertia	•		
Torsional factor	J_t		mm^4

Outputs of sub-model computing the force distribution in radial bore and ovality from the free-shape

Two text files are generated:

- rforce_fromfs.txt containing two columns: 1st column contains the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one the radial linear force in N/m.
- rov_fromfs.txt containing two columns: 1st column contains the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one the ovality in usual representation in millimeters.

Three plots are generated:

- Curve of the radial linear force in N/m as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.
- Radial plot of the ovality (closed shape of the ring under the constant pressure).
- Curve of the ovality in usual representation in microns as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.

The code also displays the tangential load determined from the force distribution computed.

Inputs of sub-model computing the force distribution in radial bore and freeshape from the ovality

Nomenclature	Variable designation	Comment	Unit
Bore diameter	D_b		mm
Ring Young modulus	E_r		GPa
Gap size when ring is closed to circular bore	gap		mm
Gap size when ring is closed to ovality (under constant pressure)	gap2		mm
Number of elements for the FEM	Nbe	Positive integer	
Number of points within one element	Npe	Positive integer	
Ovality distribution		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one contains the ovality radial coordinates in usual representation in microns.	deg & μm
Constant linear force to consider in computing the ovality (pressure times the ring height (axial width)) ISBDist	Pov	1 to take into account bore distortion when computing the force distribution in radial bore, 0	N/m
Highest order in the Fourier series for bore distortion.	Norder	otherwise Non-zero positive integer. User has to provide this value if IsBDist=1.	
Ampdata		1 to provide the amplitudes and phases of bore distortion directly, 0 to provide dr distribution. User	

		has to provide this value if	
		IsBDist=1.	
Amplitudes for bore distortion	A_b	Positive values. Number of amplitudes to provide is equal to Norder (0 th , 2 nd ,,Norder th amplitudes). User has to provide this value if IsBDist=1 and	μт
Phases for bore distortion	ϕ_b	Ampdata=1. Number of phases to provide is equal to Norder - 1 (2 nd ,3 rd ,,Norder th phases). User has to provide this value if IsBDist=1 and Ampdata=1.	rad
Bore distortion distribution dr		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the bore distortion dr in microns. User has to provide this value if IsBDist=1 and Ampdata=0.	deg & μm
Ring density	$ ho_r$	·	kg/m³
Ring Poisson ratio	v_r		07
Ring thermal expansion coefficient	α_T		1/K
Ring gap position	t_g	Ring gap position in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°)	deg
Ring temperature	T_r		Celsuis
Liner Young modulus	E_l		GPa
Liner Poisson ratio	$ u_l$		
Plateau ratio	PR		
Liner surface roughness standard deviation	σ_p		μm
Piston upper land reference diameter	Drldu		mm

Ring groove root diameter	Drg		mm
Piston lower land reference diameter	Drldl		mm
Ring groove inner axial height	hgi		mm
Ring groove upper flank angle	$ heta_{gt}$		rad
Ring groove lower flank angle	$ heta_{gb}$		rad
Ring groove upper flank surface roughness standard deviation	σ_{gt}		μт
Ring groove lower flank surface roughness standard deviation	σ_{gb}		μт
Groove Poisson ratio	$ u_g$		
Groove Young modulus	E_g		GPa
Radius increase at the upper land during engine operation	$Exp_{land,u}$		μт
Radius increase at the lower land during engine operation	$Exp_{land,l}$		μт
Top ring groove radius increase during engine operation	Exp_{gr}		μт
z coefficient for the asperity ring/liner and ring/groove contact interaction	Z	6.804 is the adopted value in the simplified formulation	
K coefficient for the asperity ring/liner and ring/groove contact interaction	K	1.198e-4 is the adopted value in the simplified formulation	

A coefficient for the asperity ring/liner and ring/groove contact interaction	A	4.4068e-5 is the adopted value in the simplified formulation	
Ω coefficient for the asperity ring/liner and ring/groove contact interaction	Ω	4 is the adopted value in the simplified formulation	
Friction coefficient for the asperity ring/liner and ring/groove contact interaction	fc_{dry}		
Constant coefficient for the asperity ring/liner and ring/groove contact interaction	cfct	1 is the adopted value in the simplified formulation	
IsGDist		1 to take into account groove distortion when computing the force distribution in radial bore, 0 otherwise	
Number of orders starting from the 2 nd one in the Fourier series for groove upper flank distortion	$Norder_u$	Non-zero positive integer. User has to provide this value if IsGDist=1.	
Ampdatau		1 to provide the amplitudes and phases of groove upper flank distortion directly, 0 to provide dz distribution. User has to provide this value if IsBDist=1.	
Amplitudes for groove upper flank distortion	A_{gu}	Positive values. Number of amplitudes to provide is equal to $Norder_u$ (0 th , 2 nd ,, $Norder_u$ th amplitudes). User has to provide this value if IsGDist=1 and Ampdatau=1.	

Phases for groove upper flank distortion Groove upper flank	ϕ_{gu}	Number of phases to provide is equal to $Norder_u - 1$ ($2^{nd}, 3^{rd},, Norder_u^{th}$ phases). User has to provide this value if IsBDist=1 and Ampdatau=1.	deg & μm
distortion distribution dz		containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the groove upper flank distortion dz in microns. User has to provide this value if IsGDist=1 and Ampdatau=0.	иед & µт
Number of orders starting from the 2 nd one in the Fourier series for groove lower flank distortion	$Norder_l$	Non-zero positive integer. User has to provide this value if IsGDist=1.	
Ampdatal		1 to provide the amplitudes and phases of ring lower flank distortion directly, 0 to provide dz distribution. User has to provide this value if IsGDist=1.	
Amplitudes for groove lower flank distortion	A_{gl}	Positive values. Number of amplitudes to provide is equal to $Norder_l$ (0 th , 2 nd ,, $Norder_l$ th amplitudes). User has to provide this value if IsGDist=1 and Ampdatal=1.	
Phases for groove lower flank distortion	ϕ_{gl}	Number of phases to provide is equal to $Norder_l - 1$ ($2^{nd}, 3^{rd},, Norder_l^{th}$ phases). User has to provide this value if IsGDist=1 and Ampdatal=1.	
Groove lower flank distortion distribution dz		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder	deg & μm

		from thrust side (0°) to thrust side (360°) and the second one contains the groove lower flank distortion dz in microns. User has to provide this value if IsGDist=1 and Ampdatal=0.	
Groove thermal	tilt _{thu}		rad
tilting – upper flank			
Groove thermal	$tilt_{thl}$		rad
tilting – lower flank			
Tolerance for	Newton _{tol}	Positive sign. Suggested value:	
Newton-Raphson		10^{-6}	
algorithm			
convergence used			
to compute the			
force distribution			
Maximum number	It_{Max}	Positive integer. Suggested value:	
of Newton-		100	
Raphson algorithm			
iterations used to			
compute the force			
distribution			

Inputs provided by the ring cross-section parameters calculation module.

Nomenclature	Variable	Comment	Unit
	designation		
Upper OD width	аио	Positive sign	mm
Upper OD height	huo	Positive sign	mm
Upper ID width	aui	Positive sign	mm
Upper ID height	hui	Positive sign	mm
Lower ID width	ali	Positive sign	mm
Lower ID height	hli	Positive sign	mm
Lower OD width	alo	Positive sign	mm
Lower OD height	hlo	Positive sign	mm
Ring upper flank	$ heta_{rt}$	Positive sign. Analogous to $ heta_{rb}$	deg
angle		shown in Figure 2.	
Ring lower flank	$ heta_{rb}$	Positive sign. Shown in Figure 2.	deg
angle			
Lower edge width	rb1	Positive sign. Axial distance	mm
		between lower end point (#3 in	
		Figure 1) and minimum point (#4	
		in Figure 1)	

Upper edge width	rb2	Positive sign. Axial distance between upper end point (#5 in Figure 1) and minimum point (#4 in Figure 1)	mm
Minimum point axial location	rbn	Positive sign if minimum point located above the gravity center point of the cross section and negative otherwise (negative sign in Figure 1)	mm
Quadratic coefficient for upper edge shape factor	a_{22}		mm
Quadratic coefficient for lower edge shape factor	a_{12}		mm
Linear coefficient for upper edge shape factor	a_{21}		
Linear coefficient for lower edge shape factor	a_{11}		
Minimum point width	arm	Positive sign	mm
Cross section area	Ac		mm^2
Principal moment of inertia in plane	I_{zp}		mm^4
Principal moment of inertia out of plane	I_{yp}		mm^4
Moment of inertia in plane	I_z		mm^4
Principal angle	α_p		deg
Polar moment of inertia	I_p		mm^4
Torsional factor	J_t		mm^4

Outputs of sub-model computing the force distribution in radial bore and free-shape from the ovality

Two text files are generated:

- rforce_fromov.txt containing two columns: 1st column contains the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one the radial linear force in N/m.
- fs_fromov.txt containing two columns: 1st column contains the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one the free-shape in usual representation in millimeters.

Three plots are generated:

- Curve of the free-shape in usual representation in millimeters as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.
- Curve of the radial linear force in N/m as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.

The code also displays the tangential load determined from the force distribution computed.

Module 3: Calculate the ring-bore and ring-liner conformability for specific ring gap location

This module consists of 2 sub-models. The first one performs the computation related to the conformability study for one specific ring gap position. The second one uses the result of the first sub-model to generate the radial plots. Inputs and outputs of each of these sub-modules are provided below.

Inputs of sub-model performing the computation related to the conformability study for one specific ring gap location

Nomenclature	Variable	Comment	Unit
	designation		
IsBDist		1 to take into account bore	
		distortion when computing the	
		force distribution in radial bore, 0	
		otherwise	
IsPTilt		1 to take into account piston	
		dynamic tilt, 0 otherwise	
IsGDist		1 to take into account groove	
		distortion when computing the	
		force distribution in radial bore, 0	
		otherwise	

IsFreeshape		1 to provide the free-shape coordinates or curvature and 0 to provide the radial pressure distribution for the circular bore	
Bore diameter	D_b		mm
Gap size when ring is closed to circular bore	gap		mm
Ring Young modulus	E_r		GPa
Ring density	ρ_r		kg/m^3
Ring Poisson ratio	ν_r		
Ring thermal expansion coefficient	α_T		1/ <i>K</i>
Ring gap position	t_g	Ring gap position in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°)	deg
Ring temperature	T_r		Celsuis
Ring temperature increase from ID to OD distribution		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one contains the radial ring temperature increase from ID to OD in Celsius.	deg & Celsius
Number of elements for the FEM	Nbe	Positive integer	
Number of points within one element for contact and lubrication force calculation	Npe	Positive integer	
Number of points within one element for gas force calculation	Nge	Positive integer	

	7. 7	T	1
Highest order in	Norder	Non-zero positive integer. User	
the Fourier series		has to provide this value if	
for bore distortion.		IsBDist=1.	
Ampdata		1 to provide the amplitudes and	
		phases of bore distortion directly,	
		0 to provide dr distribution. User	
		has to provide this value if	
		IsBDist=1.	
Amplitudes for	A_b	Positive values. Number of	μm
bore distortion	В	amplitudes to provide is equal to	,
		Norder (0 th , 2 nd ,,Norder th	
		amplitudes). User has to provide	
		this value if IsBDist=1 and	
		Ampdata=1.	
Phases for bore	ф	Number of phases to provide is	rad
distortion	ϕ_b	equal to Norder – 1 (ruu
distortion			
		2 nd ,3 rd ,,Norder th phases). User	
		has to provide this value if	
		IsBDist=1 and Ampdata=1.	, ,
Bore distortion		Text file with the first column	deg & μm
distribution dr		containing the circumferential	
		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the bore distortion dr in	
		microns. User has to provide this	
		value if IsBDist=1 and Ampdata=0.	
Piston tilt angle	eta_p	User has to provide this value if	deg
	•	IsPTilt=1.	
Piston offset	off	Positive sign.	mm
zk coefficient for oil	zk		
viscosity			
calculation			
Temp1 variable for	$Temp_1$		Celsius
oil viscosity	_		
calculation			
Temp2 variable for	$Temp_2$		Celsius
oil viscosity	. 2		
calculation			
Oil density	$ ho_{oil}$		kg/m^3
2 5.51.5.67	r บน		

hlratio coefficient	hlratio		
for oil viscosity calculation			
Beta1 coefficient	eta_1		
for oil viscosity	<i>r</i> 1		
calculation			
Beta2 coefficient	eta_2		
for oil viscosity	· -		
calculation			
Viscosity of oil		Text file with the first column	deg & Pa.s
located within the		containing the circumferential	
groove		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the viscosity of oil	
		located within the groove in Pa.s.	
Liner Young	E_l		GPa
modulus			
Liner Poisson ratio	$ u_l$		
Plateau ratio	PR		
Liner surface	σ_p		μm
roughness			
standard deviation			
Piston upper land	Drldu		mm
reference diameter			
Ring groove root	Drg		mm
diameter	D 111		
Piston lower land	Drldl		mm
reference diameter	7 .		
Ring groove inner	hgi		mm
axial height	0		
Ring groove upper	$ heta_{gt}$		rad
flank angle	0		mad
Ring groove lower flank angle	$ heta_{gb}$		rad
Ring groove upper	σ		um
flank surface	σ_{gt}		μm
roughness			
standard deviation			
Ring groove lower	σ_{qb}		μт
flank surface	€gp		perio
Harri Sarrace		1	

roughness			
standard deviation			
Groove Poisson	$ u_{g}$		
ratio	· <i>y</i>		
Groove Young	E_g		GPa
modulus	L_g		ar u
Radius increase at	$Exp_{land,u}$		μm
the upper land	L'APland,u		μπ
during engine			
operation	E		
Radius increase at	$Exp_{land,l}$		μm
the lower land			
during engine			
operation -			
Top ring groove	Exp_{gr}		μm
radius increase			
during engine			
operation			
z coefficient for the	Z	6.804 is the adopted value in the	
asperity ring/liner		simplified formulation	
and ring/groove			
contact interaction			
K coefficient for	K	1.198e-4 is the adopted value in	
the asperity		the simplified formulation	
ring/liner and			
ring/groove			
contact interaction			
A coefficient for	\boldsymbol{A}	4.4068e-5 is the adopted value in	
the asperity		the simplified formulation	
ring/liner and			
ring/groove			
contact interaction			
arOmega coefficient for	Ω	4 is the adopted value in the	
the asperity		simplified formulation	
ring/liner and			
ring/groove			
contact interaction			
Friction coefficient	fc_{dry}		
for the asperity	- ,		
ring/liner and			
ring/groove			
contact interaction			

Constant coefficient for the asperity ring/liner and ring/groove contact interaction	cfct	1 is the adopted value in the simplified formulation	
IsGDist		1 to take into account groove distortion when computing the force distribution in radial bore, 0 otherwise	
Number of orders starting from the 2 nd one in the Fourier series for groove upper flank distortion	$Norder_u$	Non-zero positive integer. User has to provide this value if IsGDist=1.	
Ampdatau		1 to provide the amplitudes and phases of groove upper flank distortion directly, 0 to provide dz distribution. User has to provide this value if IsBDist=1.	
Amplitudes for groove upper flank distortion	A_{gu}	Positive values. Number of amplitudes to provide is equal to $Norder_u$ (0 th , 2 nd ,, $Norder_u$ th amplitudes). User has to provide this value if IsGDist=1 and Ampdatau=1.	
Phases for groove upper flank distortion	ϕ_{gu}	Number of phases to provide is equal to $Norder_u - 1$ (2^{nd} ,3 rd ,, $Norder_u^{th}$ phases). User has to provide this value if IsBDist=1 and Ampdatau=1.	
Groove upper flank distortion distribution dz		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the groove upper flank distortion dz in microns. User has to provide this value if IsGDist=1 and Ampdatau=0.	deg & μm

Number of orders starting from the 2 nd one in the Fourier series for groove lower flank distortion	Norder _l	Non-zero positive integer. User has to provide this value if IsGDist=1.	
Ampdatal		1 to provide the amplitudes and phases of ring lower flank distortion directly, 0 to provide dz distribution. User has to provide this value if IsGDist=1.	
Amplitudes for groove lower flank distortion	A_{gl}	Positive values. Number of amplitudes to provide is equal to $Norder_l$ (0 th , 2 nd ,, $Norder_l$ th amplitudes). User has to provide this value if IsGDist=1 and Ampdatal=1.	
Phases for groove lower flank distortion	ϕ_{gl}	Number of phases to provide is equal to $Norder_l-1$ ($2^{\rm nd}$, $3^{\rm rd}$,, $Norder_l^{\rm th}$ phases). User has to provide this value if IsGDist=1 and Ampdatal=1.	
Groove lower flank distortion distribution dz		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the groove lower flank distortion dz in microns. User has to provide this value if IsGDist=1 and Ampdatal=0.	deg & μm
Groove thermal tilting – upper flank	tilt _{thu}		rad
Groove thermal tilting – lower flank	tilt _{thl}		rad
Minimum oil film thickness to consider for liner lubrication	minoil	Suggested value: half the liner surface standard deviation $(\sigma_p/2)$	μт
Lubrication cases threshold	oilthreshold	Ratio between oil film thickness on liner by liner surface roughness	

groove lower region distribution containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side				
Fully flooded lubrication cases. Suggested value: 10 Viscosity factor for fuel spots Factor by which the oil viscosity should be divided in regions where we have fuel spots. Suggested value: 100 Gas pressure in groove upper region distribution Pu			standard deviation to consider as	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			threshold between partially and	
Viscosity factor for fuel spots Gas pressure in groove upper region distribution Gas pressure in groove inner region containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the gas pressure in groove inner region in Bar. Text file with the first column containing the circumferential direction angles in degrees defined with respect to the cylinder from thrust side (360°) and the second one contains the gas pressure in groove inner region in Bar. Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the fixed frame with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust sid			fully flooded lubrication cases.	
fuel spots should be divided in regions where we have fuel spots. Suggested value: 100 Gas pressure in groove upper region distribution Gas pressure in groove upper region distribution Gas pressure in groove upper region distribution Gas pressure in groove upper region in Bar. Gas pressure in groove inner region distribution Gas pressure in groove inner region distribution Gas pressure in groove inner region containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the gas pressure in groove inner region in Bar. Gas pressure in groove inner region in Bar. Gas pressure in groove inner region in Bar. Text file with the first column contains the gas pressure in groove inner region in Bar. Text file with the first column contains the gas pressure in groove inner region in Bar. Text file with the first column contains the gas pressure in groove inner region in Bar. Text file with the first column contains the gas pressure in groove inner region in Bar. Text file with the first column contains the gas pressure in groove inner region in Bar. Text file with the first column containing the circumferential direction angles in degrees defined with respect to the cylinder from thrust side (0°) to thrust side			Suggested value: 10	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	·	oilviscosityfactor	Factor by which the oil viscosity	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	fuel spots		should be divided in regions	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			where we have fuel spots.	
$\begin{array}{c} \text{groove upper} \\ \text{region distribution} \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\$			Suggested value: 100	
region distribution $ \begin{array}{c} \text{direction angles in degrees} \\ \text{defined with respect to the fixed} \\ \text{frame with respect to the cylinder} \\ \text{from thrust side (0°) to thrust side} \\ \text{(360°) and the second one} \\ \text{contains the gas pressure in} \\ \text{groove upper region in Bar.} \\ \hline \text{Gas pressure in} \\ \text{groove inner region} \\ \text{distribution} \\ \hline \\ \text{distribution} \\ \hline \\ \\ \text{Gas pressure in} \\ \text{groove inner region} \\ \text{distribution} \\ \hline \\ \text{distribution} \\ \hline \\ \text{down thrust side (0°) to thrust side} \\ \text{distribution} \\ \hline \\ \text{distribution} \\ \hline \\ \text{down thrust side (0°) to thrust side} \\ \text{distribution} \\ \hline \\ $	Gas pressure in	P_u	Text file with the first column	deg & Bar
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	groove upper		containing the circumferential	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	region distribution		direction angles in degrees	
			defined with respect to the fixed	
			frame with respect to the cylinder	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			from thrust side (0°) to thrust side	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			(360°) and the second one	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			contains the gas pressure in	
groove inner region distribution $ \begin{array}{c} \text{containing the circumferential} \\ \text{direction angles in degrees} \\ \text{defined with respect to the fixed} \\ \text{frame with respect to the cylinder} \\ \text{from thrust side } \\ \text{(360°) and the second one} \\ \text{contains the gas pressure in} \\ \text{groove inner region in Bar.} \\ \hline \text{Gas pressure in} \\ \text{groove lower} \\ \text{region distribution} \\ \hline \end{array} \begin{array}{c} P_d \\ \text{Text file with the first column} \\ \text{containing the circumferential} \\ \text{direction angles in degrees} \\ \text{defined with respect to the fixed} \\ \text{frame with respect to the cylinder} \\ \text{from thrust side (0°) to thrust side} \\ \hline \end{array} $			groove upper region in Bar.	
distribution direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the gas pressure in groove inner region in Bar. Gas pressure in groove lower region distribution P_d Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side	Gas pressure in	P_i	Text file with the first column	deg & Bar
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	groove inner region		containing the circumferential	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	distribution		direction angles in degrees	
			defined with respect to the fixed	
			frame with respect to the cylinder	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			from thrust side (0°) to thrust side	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			(360°) and the second one	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			contains the gas pressure in	
groove lower region distribution direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side			groove inner region in Bar.	
region distribution direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side	Gas pressure in	P_d	Text file with the first column	deg & Bar
defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side	groove lower		containing the circumferential	
frame with respect to the cylinder from thrust side (0°) to thrust side	region distribution		direction angles in degrees	
from thrust side (0°) to thrust side			defined with respect to the fixed	
			frame with respect to the cylinder	
(360°) and the second one			from thrust side (0°) to thrust side	
(500) and the second one			(360°) and the second one	
contains the gas pressure in			contains the gas pressure in	
groove lower region in Bar.			groove lower region in Bar.	
Piston speed V_p The axial axis is positively pointing $m. s^{-1}$	Piston speed	V_p	The axial axis is positively pointing	$m. s^{-1}$
upwards.			upwards.	
Piston acceleration A_p The axis is positively pointing $m. s^{-2}$	Piston acceleration	A_p	The axis is positively pointing	$m. s^{-2}$
upwards			upwards	
Oil film thickness $hrls$ Text file with the first column $deg \& \mu m$	Oil film thickness	hrls	Text file with the first column	deg & μm
left on liner into containing the circumferential	left on liner into		containing the circumferential	
the ring direction angles in degrees	the ring		direction angles in degrees	
distribution defined with respect to the fixed	distribution		defined with respect to the fixed	

		 	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the oil film thickness left	
		on liner into the ring in microns.	
Oil film thickness	hot	Text file with the first column	deg & μm
on the upper		containing the circumferential	
groove flank		direction angles in degrees	
distribution		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the oil film thickness on	
		the upper groove flank in microns.	
Oil film thickness	hob	Text file with the first column	deg & μm
on the lower		containing the circumferential	
groove flank		direction angles in degrees	
distribution		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the oil film thickness on	
		the lower groove flank in microns.	
Liner temperature	$Temp_l$	Text file with the first column	deg &
distribution	• •	containing the circumferential	Celsius
		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the temperature liner in	
		Celsius. This temperature	
		distribution will be used to	
		compute oil viscosity.	
Fuel spots	isfuel	Text file with the first column	deg & Ø
distribution	,	containing the circumferential	<i>U</i> -
		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the fuel spots (1 for	
		existence of fuel, 0 for non-	
		existence).	
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	7.	6	
b coefficient for	b	Suggested value: 2.1	
fully flooded			
correlation			
c coefficient for	С	Suggested value: 0.102	
fully flooded			
correlation			
d coefficient for	d	Suggested value: -0.04	
fully flooded			
correlation			
e coefficient for	e	Suggested value: 0.90229	
fully flooded			
correlation			
Correlation	Ph	Suggested value: 398.56	Bar
pressure for			
deterministic			
partially flooded			
forces			
Correlation	K_{OCR}	Suggested value: 2.523	
exponent for	NOCR	Juggested value. 2.323	
deterministic			
partially flooded			
forces		Constant desired 15-2	D
Reference viscosity	μ_U	Suggested value: 1.5e-2	Pa.m
for deterministic			
partially flooded			
forces			
ap coefficient for	ар	Suggested value: 0.039342	
deterministic			
partially flooded			
forces			
cp1 coefficient for	cp_1	Suggested value: -2.965331	
exponent Kp in			
deterministic			
partially flooded			
forces			
cp2 coefficient for	cp_2	Suggested value: 1.499148	
exponent Kp in	-		
deterministic			
partially flooded			
forces			
F0 coefficient for	F_0	Suggested value: 0.098577	
deterministic	U		
acterminatio			1

partially flooded			
shear force			
cf1 coefficient for	cf_1	Suggested value: -0.383954	
exponent Kp in			
deterministic			
partially flooded			
forces			
cf2 coefficient for	cf_2	Suggested value: 0.138443	
exponent Kp in			
deterministic			
partially flooded			
forces			
Ring width to use	$r_{\!\scriptscriptstyle W}$		mm
for the			
deterministic			
hydrodynamic			
correlation			
IsFreeshaped		1 to provide the free-shape	
		coordinates and 0 to provide the	
		free-shape curvature. User has to	
		provide this value if	
		lsFreeshape=1.	
Free-shape		Text file with the first column	deg & mm
distribution		containing the circumferential	
		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the ring and	
		the second one contains the free-	
		shape coordinates in usual	
		representation in millimeters.	
		User has to provide this value if	
		IsFreeshape=1 and	
		IsFreeshaped=1.	
Free-shape		Text file with the first column	deg & 1/m
curvature		containing the circumferential	
distribution		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the ring and	
		the second one contains the free-	
		shape curvature coordinates in	
		usual representation in 1/m. User	
		has to provide this value if	

		IsFreeshape=1 and Isfreeshaped=0.	
Force distribution in radial bore		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one contains the pressure times ring height (axial width). User has to provide this value if IsFreeshape=0.	deg & N/m
Tolerance for Newton-Raphson algorithm convergence	$Newton_{tol}$	Positive sign. Suggested value: 10^{-6}	
Maximum number of Newton- Raphson algorithm iterations	It_{Max}	Positive integer. Suggested value: 100	

Inputs provided by the ring cross-section parameters calculation module.

Nomenclature	Variable	Comment	Unit
	designation		
Upper OD width	аио	Positive sign	mm
Upper OD height	huo	Positive sign	mm
Upper ID width	aui	Positive sign	mm
Upper ID height	hui	Positive sign	mm
Lower ID width	ali	Positive sign	mm
Lower ID height	hli	Positive sign	mm
Lower OD width	alo	Positive sign	mm
Lower OD height	hlo	Positive sign	mm
Ring upper flank	$ heta_{rt}$	Positive sign. Analogous to $ heta_{rb}$	deg
angle		shown in Figure 2.	
Ring lower flank	$ heta_{rb}$	Positive sign. Shown in Figure 2.	deg
angle			
Lower edge width	rb1	Positive sign. Axial distance	mm
		between lower end point (#3 in	
		Figure 1) and minimum point (#4	
		in Figure 1)	
Upper edge width	rb2	Positive sign. Axial distance	mm
		between upper end point (#5 in	

		Figure 1) and minimum point (#4 in Figure 1)	
Minimum point axial location	rbn	Positive sign if minimum point located above the gravity center point of the cross section and negative otherwise (negative sign in Figure 1)	mm
Quadratic coefficient for upper edge shape factor	a_{22}		mm
Quadratic coefficient for lower edge shape factor	a_{12}		mm
Linear coefficient for upper edge shape factor	a_{21}		
Linear coefficient for lower edge shape factor	a_{11}		
Minimum point width	arm	Positive sign	mm
Cross section area	Ac		mm^2
Principal moment of inertia in plane	I_{zp}		mm^4
Principal moment of inertia out of plane	I_{yp}		mm^4
Moment of inertia in plane	I_z		mm^4
Moment of inertia out of plane	$I_{\mathcal{Y}}$		mm^4
Principal angle	α_p		deg
Polar moment of inertia	I_p		mm^4
Torsional factor	J_t		mm^4

Outputs of sub-model performing the computation related to the conformability study for one specific ring gap location

One text file is generated res_conf_one_gap.txt. It contains 20 columns, specified below from the left to the right:

- Column 1: Circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring. This angles distribution will be used for the ring's coordinates and clearances results from column 2 to column 10.
- Column 2: Ring liner clearance in microns. Always non-negative.
- Column 3: Ring neutral axis lift in microns. The zero level is located at the middle of the groove inner region. The axial axis is positively pointing upwards.
- Column 4: Ring radial coordinate in microns. This is defined respect to the nominal radius defined by $R_r = \left(\frac{D_b}{2} arm\right)*(1 + \alpha_T(T_r 25))$. A positive radial coordinate means that the ring cross-section centroid is located outside the circle with a radius equal to the nominal one.
- Column 5: Ring twist angle in degrees. A positive ring twist angle means the ring cross section is rotated in the clockwise direction with the ring's outer-diameter (OD) on the left as shown in Figure 1 and Figure 2.
- Column 6: Minimum liner clearance point location with respect to the centroid in microns. A positive sign means that this point is located above the centroid axial level.
- Column 7: Upper OD point clearance with the groove in microns. Always non-negative.
- Column 8: Upper ID point clearance with the groove in microns. Always non-negative.
- Column 9: Lower OD point clearance with the groove in microns. Always non-negative.
- Column 10: Lower ID point clearance with the groove in microns. Always non-negative.
- Column 11: Circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring. This angles distribution will be used for forces, moments and stresses results from column 12 to column 20.
- Column 12: Radial force in N/m (force per unit circumferential length of the ring). A
 positive sign corresponds to a compression force.
- Column 13: Ring-liner radial force in N/m (force per unit circumferential length of the ring).
- Column 14: Axial force in N/m (force per unit circumferential length of the ring). The axial axis is positively pointing upwards.
- Column 15: Twist moment in N (moment per unit circumferential length of the ring). The
 angular orientation is positive in the clockwise direction with the ring's outer-diameter
 (OD) on the left as shown in Figure 1 and Figure 2.
- Column 16: Bending moment at the ring cross-section centroid in Nm.
- Column 17: Stress at upper OD point in MPa. A positive sign corresponds to extension.
- Column 18: Stress at upper ID point in MPa. A positive sign corresponds to extension.
- Column 19: Stress at lower OD point in MPa. A positive sign corresponds to extension.
- Column 20: Stress at lower ID point in MPa. A positive sign corresponds to extension.

Six plots are generated:

- The first one contains the curve of the ring-liner clearance and the ring radial coordinate as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring. Both are plotted in microns.
- The second plot gives the curve of the ring neutral axis lift and the minimum liner clearance point location with respect to the centroid as a function of the circumferential

- direction angles in degrees defined with respect to the fixed frame with respect to the ring. Both are given in microns. It also gives the ring twist angle in degrees as a function of the same circumferential direction angles in degrees.
- The third plot displays the 4 curves of lower/upper OD/ID clearances with the groove, all in microns and as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.
- The fourth plot contains the curve of the radial force, ring-liner radial force and axial one all in N/m as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring. It also gives the twist moment in N as a function of the same circumferential direction angles in degrees.
- The fifth plot gives the bending moment at the ring cross-section centroid in Nm as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.
- The sixth plot displays the 4 curves of stresses at lower/upper OD/ID points all in MPa as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.

The code also displays the tangential load determined from the force distribution computed.

Inputs of sub-model performing the radial plots related to the conformability study for one specific ring gap location

Inputs that need to be provided by the user.

Nomenclature	Variable designation	Comment	Unit
Magnification coefficient for radial plot of bore distortion and ring liner clearance	mag1	Positive sign. Suggested value: 3000	
Number of radial forces to represent	numforce	Positive integer. Suggested value: 200	
Maximum acceptable value for forces to be represented	fstop	Positive sign.	N/m

This code also uses bore distortion, FEM related, ring gap size, ring-liner clearance, radial force and ring-liner force inputs and outputs of the sub-model performing the computation related to the conformability study for one specific ring gap location.

Outputs of sub-model performing the radial plots related to the conformability study for one specific ring gap location

Two plots are generated:

- The first one contains radial plot of the bore and the ring with the specified magnification coefficient. It also contains scaled lines showing the ring-liner forces based on the number of forces to be represented and the maximum acceptable value specified. It also displays separate message(s) if the bore or/and the ring is(are) misrepresented because of the magnification coefficient. It also shows the ring gap location within the bore fixed reference from thrust to thrust side and shows a message in case the force is truncated somewhere based on the maximum acceptable value for force to be represented that has been chosen.
- The second one contains radial plot of the bore and the ring with the specified magnification coefficient. It also contains scaled lines showing the radial forces based on the number of forces to be represented and the maximum acceptable value specified. It also displays separate message(s) if the bore or/and the ring is(are) misrepresented because of the magnification coefficient. It also shows the ring gap location within the bore fixed reference from thrust to thrust side and shows a message in case the force is truncated somewhere based on the maximum acceptable value for force to be represented that has been chosen.

Module 4: Calculate the ring-bore and ring-liner conformability for different ring gap locations

This module consists of 2 sub-models. The first one performs the computation related to the conformability study for different ring gap positions. The second one uses the result of the first sub-model to generate the radial plots. Inputs and outputs of each of these sub-modules are provided below.

Inputs of sub-model performing the computation related to the conformability study for different ring gap locations

Inputs that need to be provided by the user.

Nomenclature	Variable	Comment	Unit
	designation		
IsBDist		1 to take into account bore	
		distortion when computing the	
		force distribution in radial bore, 0	
		otherwise	
IsPTilt		1 to take into account piston	
		dynamic tilt, 0 otherwise	

IsGDist		1 to take into account groove distortion when computing the force distribution in radial bore, 0 otherwise	
IsFreeshape		1 to provide the free-shape coordinates or curvature and 0 to provide the radial pressure distribution for the circular bore	
Bore diameter	D_b		mm
Gap size when ring is closed to circular bore	gap		mm
Ring Young modulus	E_r		GPa
Ring density	$ ho_r$		kg/m^3
Ring Poisson ratio	$\overline{ u_r}$		
Ring thermal expansion coefficient	$lpha_T$		1/ <i>K</i>
Ring temperature	T_r		Celsuis
Ring temperature increase from ID to OD distribution		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring and the second one contains the radial ring temperature increase from ID to OD in Celsius.	deg & Celsius
Number of elements for the FEM	Nbe	Positive integer	
Number of points within one element for contact and lubrication force calculation	Npe	Positive integer	
Number of points within one element for gas force calculation	Nge	Positive integer	
Highest order in the Fourier series for bore distortion.	Norder	Non-zero positive integer. User has to provide this value if IsBDist=1.	

Ampdata		1 to provide the amplitudes and	
		phases of bore distortion directly, 0 to provide dr distribution. User	
		has to provide this value if	
		IsBDist=1.	
A	1		
Amplitudes for	A_b	Positive values. Number of	μm
bore distortion		amplitudes to provide is equal to Norder (0 th , 2 nd ,,Norder th	
		amplitudes). User has to provide	
		this value if IsBDist=1 and	
		Ampdata=1.	
Phases for bore	ϕ_b	Number of phases to provide is	rad
distortion	Ψ D	equal to $Norder - 1$ (
GISCOT CIOTI		2 nd ,3 rd ,,Norder th phases). User	
		has to provide this value if	
		IsBDist=1 and Ampdata=1.	
Bore distortion		Text file with the first column	deg & μm
distribution dr		containing the circumferential	αυ σα μπι
distribution di		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the rixed	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the bore distortion dr in	
		microns. User has to provide this	
		value if IsBDist=1 and Ampdata=0.	
Distantilt angle	ρ		doa
Piston tilt angle	eta_p	User has to provide this value if IsPTilt=1.	deg
Piston offset	o f f		22222
	off	Positive sign.	mm
zk coefficient for oil	zk		
viscosity			
calculation	T		Calaina
Temp1 variable for	$Temp_1$		Celsius
oil viscosity			
calculation	m m		<i>C.</i> 1 :
Temp2 variable for	$Temp_2$		Celsius
oil viscosity			
calculation		-	1 / 2
Oil density	$ ho_{oil}$	1	kg/m³
hlratio coefficient	hlratio		
for oil viscosity			
calculation			

Beta1 coefficient	eta_1		
for oil viscosity	r ı		
calculation			
Beta2 coefficient	eta_2		
for oil viscosity	, 2		
calculation			
Viscosity of oil		Text file with the first column	deg & Pa.s
located within the		containing the circumferential	J
groove		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the viscosity of oil	
		located within the groove in Pa.s.	
Liner Young	E_l		GPa
modulus			
Liner Poisson ratio	ν_l		
Plateau ratio	PR		
Liner surface	σ_p		μm
roughness	•		
standard deviation			
Piston upper land	Drldu		mm
reference diameter			
Ring groove root	Drg		mm
diameter			
Piston lower land	Drldl		mm
reference diameter			
Ring groove inner	hgi		mm
axial height			
Ring groove upper	$ heta_{gt}$		rad
flank angle			
Ring groove lower	$ heta_{gb}$		rad
flank angle			
Ring groove upper	σ_{gt}		μm
flank surface	-		
roughness			
standard deviation			
Ring groove lower	σ_{gb}		μm
flank surface			
roughness			
standard deviation			

Groove Poisson	$ u_{g} $		
ratio	3		
Groove Young	E_g		GPa
modulus			
Radius increase at	$Exp_{land,u}$		μm
the upper land			
during engine			
operation			
Radius increase at	$Exp_{land,l}$		μm
the lower land			
during engine			
operation			
Top ring groove	Exp_{gr}		μm
radius increase			
during engine			
operation			
z coefficient for the	Z	6.804 is the adopted value in the	
asperity ring/liner		simplified formulation	
and ring/groove			
contact interaction			
K coefficient for	K	1.198e-4 is the adopted value in	
the asperity		the simplified formulation	
ring/liner and			
ring/groove			
contact interaction			
A coefficient for	A	4.4068e-5 is the adopted value in	
the asperity		the simplified formulation	
ring/liner and			
ring/groove			
contact interaction			
arOmega coefficient for	Ω	4 is the adopted value in the	
the asperity		simplified formulation	
ring/liner and			
ring/groove			
contact interaction			
Friction coefficient	fc_{dry}		
for the asperity			
ring/liner and			
ring/groove			
contact interaction			
Constant	cfct	1 is the adopted value in the	
coefficient for the		simplified formulation	
asperity ring/liner			

and ring/groove			
contact interaction			
IsGDist		1 to take into account groove distortion when computing the force distribution in radial bore, 0 otherwise	
Number of orders starting from the 2 nd one in the Fourier series for groove upper flank distortion	Norder _u	Non-zero positive integer. User has to provide this value if IsGDist=1.	
Ampdatau		1 to provide the amplitudes and phases of groove upper flank distortion directly, 0 to provide dz distribution. User has to provide this value if IsBDist=1.	
Amplitudes for groove upper flank distortion	A_{gu}	Positive values. Number of amplitudes to provide is equal to $Norder_u$ (0 th , 2 nd ,, $Norder_u$ th amplitudes). User has to provide this value if IsGDist=1 and Ampdatau=1.	
Phases for groove upper flank distortion	ϕ_{gu}	Number of phases to provide is equal to $Norder_u - 1$ ($2^{nd}, 3^{rd},, Norder_u^{th}$ phases). User has to provide this value if IsBDist=1 and Ampdatau=1.	
Groove upper flank distortion distribution dz		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the groove upper flank distortion dz in microns. User has to provide this value if IsGDist=1 and Ampdatau=0.	deg & μm
Number of orders starting from the 2 nd one in the Fourier series for	Norder _l	Non-zero positive integer. User has to provide this value if IsGDist=1.	

groove lower flank			
distortion			
Ampdatal		1 to provide the amplitudes and phases of ring lower flank distortion directly, 0 to provide dz distribution. User has to provide this value if IsGDist=1.	
Amplitudes for groove lower flank distortion	A_{gl}	Positive values. Number of amplitudes to provide is equal to $Norder_l$ (0 th , 2 nd ,, $Norder_l$ th amplitudes). User has to provide this value if IsGDist=1 and Ampdatal=1.	
Phases for groove lower flank distortion	ϕ_{gl}	Number of phases to provide is equal to $Norder_l - 1$ ($2^{nd}, 3^{rd},, Norder_l^{th}$ phases). User has to provide this value if IsGDist=1 and Ampdatal=1.	
Groove lower flank distortion distribution dz		Text file with the first column containing the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the cylinder from thrust side (0°) to thrust side (360°) and the second one contains the groove lower flank distortion dz in microns. User has to provide this value if IsGDist=1 and Ampdatal=0.	deg & μm
Groove thermal tilting – upper flank	$tilt_{thu}$		rad
Groove thermal tilting – lower flank	$tilt_{thl}$		rad
Minimum oil film thickness to consider for liner lubrication	minoil	Suggested value: half the liner surface standard deviation $(\sigma_p/2)$	μт
Lubrication cases threshold	oilthreshold	Ratio between oil film thickness on liner by liner surface roughness standard deviation to consider as threshold between partially and fully flooded lubrication cases. Suggested value: 10	

	1		
Viscosity factor for fuel spots	oilviscosityfactor	Factor by which the oil viscosity should be divided in regions where we have fuel spots. Suggested value: 100	
Gas pressure in	P_u	Text file with the first column	deg & Bar
groove upper		containing the circumferential	
region distribution		direction angles in degrees	
		defined with respect to the fixed frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the gas pressure in	
Gas pressure in	P_i	groove upper region in Bar. Text file with the first column	deg & Bar
groove inner region	I i	containing the circumferential	ueg & bui
distribution		direction angles in degrees	
distribution		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the gas pressure in	
		groove inner region in Bar.	
Gas pressure in	P_d	Text file with the first column	deg & Bar
groove lower	1 a	containing the circumferential	acg & Bai
region distribution		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the gas pressure in	
		groove lower region in Bar.	
Piston speed	V_p	The axial axis is positively pointing	$m. s^{-1}$
,	P	upwards.	
Piston acceleration	A_p	The axis is positively pointing	$m. s^{-2}$
	P	upwards	
Oil film thickness	hrls	Text file with the first column	deg & μm
left on liner into		containing the circumferential	-
the ring		direction angles in degrees	
distribution		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	

		contains the oil film thickness left	
		on liner into the ring in microns.	
Oil film thickness	hot	Text file with the first column	deg & μm
on the upper	not	containing the circumferential	uey & μm
groove flank		direction angles in degrees	
distribution		defined with respect to the fixed	
distribution		frame with respect to the lixed	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the oil film thickness on	
		the upper groove flank in microns.	
Oil film thickness	hob	Text file with the first column	doa & um
on the lower	пов		deg & μm
groove flank		containing the circumferential direction angles in degrees	
distribution		defined with respect to the fixed	
distribution		frame with respect to the rixed	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the oil film thickness on	
		the lower groove flank in microns.	
Liner temperature	$Temp_l$	Text file with the first column	deg &
distribution	Τεπιρί	containing the circumferential	Celsius
distribution		direction angles in degrees	Ceisius
		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the temperature liner in	
		Celsius. This temperature	
		distribution will be used to	
		compute oil viscosity.	
Fuel spots	isfuel	Text file with the first column	deg & Ø
distribution	is juci	containing the circumferential	ucy & p
distribution		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the cylinder	
		from thrust side (0°) to thrust side	
		(360°) and the second one	
		contains the fuel spots (1 for	
		existence of fuel, 0 for non-	
		existence).	
		chistories).	

	•		1
b coefficient for	b	Suggested value: 2.1	
fully flooded			
correlation			
c coefficient for	С	Suggested value: 0.102	
fully flooded			
correlation			
d coefficient for	d	Suggested value: -0.04	
fully flooded			
correlation			
e coefficient for	е	Suggested value: 0.90229	
fully flooded			
correlation			
Correlation	Ph	Suggested value: 398.56	Bar
pressure for			
deterministic			
partially flooded			
forces			
Correlation	K_{OCR}	Suggested value: 2.523	
exponent for	NOCR	Suggested value. 2.323	
deterministic			
partially flooded			
forces		Constant of the August 1 For 2	D
Reference viscosity	μ_U	Suggested value: 1.5e-2	Pa.m
for deterministic			
partially flooded			
forces			
ap coefficient for	ар	Suggested value: 0.039342	
deterministic			
partially flooded			
forces			
cp1 coefficient for	cp_1	Suggested value: -2.965331	
exponent Kp in			
deterministic			
partially flooded			
forces			
cp2 coefficient for	cp_2	Suggested value: 1.499148	
exponent Kp in	-		
deterministic			
partially flooded			
forces			
F0 coefficient for	F_0	Suggested value: 0.098577	
deterministic	÷ U		
acterministic			

partially flooded			
shear force			
cf1 coefficient for	cf_1	Suggested value: -0.383954	
exponent Kp in			
deterministic			
partially flooded			
forces			
cf2 coefficient for	cf_2	Suggested value: 0.138443	
exponent Kp in			
deterministic			
partially flooded			
forces			
Ring width to use	r_w		mm
for the			
deterministic			
hydrodynamic			
correlation			
IsFreeshaped		1 to provide the free-shape	
		coordinates and 0 to provide the	
		free-shape curvature. User has to	
		provide this value if	
		lsFreeshape=1.	
Free-shape		Text file with the first column	deg & mm
distribution		containing the circumferential	
		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the ring and	
		the second one contains the free-	
		shape coordinates in usual	
		representation in millimeters.	
		User has to provide this value if	
		IsFreeshape=1 and	
		IsFreeshaped=1.	
Free-shape		Text file with the first column	deg & 1/m
curvature		containing the circumferential	
distribution		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the ring and	
		the second one contains the free-	
		shape curvature coordinates in	
		usual representation in 1/m. User	
		has to provide this value if	

		IsFreeshape=1 and	
		Isfreeshaped=0.	
Force distribution		Text file with the first column	deg & N/m
in radial bore		containing the circumferential	
		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the ring and	
		the second one contains the	
		pressure times ring height (axial	
		width). User has to provide this	
		value if IsFreeshape=0.	
Tolerance for	$Newton_{tol}$	Positive sign. Suggested value:	
Newton-Raphson		10^{-6}	
algorithm			
convergence			
Maximum number	It_{Max}	Positive integer. Suggested value:	
of Newton-		100	
Raphson algorithm			
iterations			
Number of ring gap	num_{Tg}	Positive integer	
positions equally	Ü		
spaced between 0			
and 359 degrees			
within bore fixed			
reference from			
thrust to thrust			
side to consider			

Inputs provided by the ring cross-section parameters calculation module.

Nomenclature	Variable designation	Comment	Unit
Upper OD width	аио	Positive sign	mm
Upper OD height	huo	Positive sign	mm
Upper ID width	aui	Positive sign	mm
Upper ID height	hui	Positive sign	mm
Lower ID width	ali	Positive sign	mm
Lower ID height	hli	Positive sign	mm
Lower OD width	alo	Positive sign	mm
Lower OD height	hlo	Positive sign	mm
Ring upper flank	θ_{rt}	Positive sign. Analogous to $ heta_{rb}$	deg
angle		shown in Figure 2.	

Ring lower flank angle	$ heta_{rb}$	Positive sign. Shown in Figure 2.	deg
Lower edge width	rb1	Positive sign. Axial distance between lower end point (#3 in Figure 1) and minimum point (#4 in Figure 1)	mm
Upper edge width	rb2	Positive sign. Axial distance between upper end point (#5 in Figure 1) and minimum point (#4 in Figure 1)	mm
Minimum point axial location	rbn	Positive sign if minimum point located above the gravity center point of the cross section and negative otherwise (negative sign in Figure 1)	mm
Quadratic coefficient for upper edge shape factor	a_{22}		mm
Quadratic coefficient for lower edge shape factor	a_{12}		mm
Linear coefficient for upper edge shape factor	a_{21}		
Linear coefficient for lower edge shape factor	a ₁₁		
Minimum point width	arm	Positive sign	mm
Cross section area	Ac		mm^2
Principal moment of inertia in plane	I_{zp}		mm^4
Principal moment of inertia out of plane	I_{yp}		mm^4
Moment of inertia in plane	I_z		mm^4
Moment of inertia out of plane	I_y		mm^4
Principal angle	α_p		deg

Polar moment of inertia	I_p	mm ⁴
Torsional factor	J_t	mm^4

Outputs of sub-model performing the computation related to the conformability study for different ring gap locations

20 text files are generated. They are specified below:

- res_theer.txt: Contains one column with the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring. This angles distribution will be used for the ring's coordinates and clearances results given in the text files: "res_hmin.txt", "res_zr.txt", "res_yr.txt", "res_alr.txt", "res_z0.txt", "res_uoc.txt", "res uic.txt", "res loc.txt", "res lic.txt".
- res_hmin.txt: Ring liner clearance in microns. Always non-negative. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_theer.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_zr.txt: Ring neutral axis lift in microns. The zero level is located at the middle of the groove inner region. The axial axis is positively pointing upwards. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_theer.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_yr.txt: Ring radial coordinate in microns. This is defined respect to the nominal radius defined by $R_r = \left(\frac{D_b}{2} arm\right)*(1 + \alpha_T(T_r 25))$. A positive radial coordinate means that the ring cross-section centroid is located outside the circle with a radius equal to the nominal one. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_theer.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_alr.txt: Ring twist angle in degrees. A positive ring twist angle means the ring cross section is rotated in the clockwise direction with the ring's outer-diameter (OD) on the left as shown in Figure 1 and Figure 2. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in

"res_theer.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.

- res_z0.txt: Minimum liner clearance point location with respect to the centroid in microns. A positive sign means that this point is located above the centroid axial level. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_theer.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_uoc.txt: Upper OD point clearance with the groove in microns. Always non-negative. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_theer.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_uic.txt: Upper ID point clearance with the groove in microns. Always non-negative. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_theer.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_loc.txt: Lower OD point clearance with the groove in microns. Always non-negative. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_theer.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_lic.txt: Lower ID point clearance with the groove in microns. Always non-negative. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_theer.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_thee.txt: Contains one column with the circumferential direction angles in degrees
 defined with respect to the fixed frame with respect to the ring. This angles distribution
 will be used for forces, moments and stresses results given in the text files: "res fy.txt",

- "res_fl.txt", "res_fz.txt", "res_m.txt", "res_Mfinal.txt", "res_S_uo.txt", "res_S_lo.txt", "res_S_ui.txt", "res_S_li.txt".
- res_fy.txt: Radial force in N/m (force per unit circumferential length of the ring). A positive sign corresponds to a compression force. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_thee.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_fl.txt: Ring-liner radial force in N/m (force per unit circumferential length of the ring). It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_thee.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_fz.txt: Axial force in N/m (force per unit circumferential length of the ring). The axial axis is positively pointing upwards. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_thee.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_m.txt: Twist moment in N (moment per unit circumferential length of the ring). The angular orientation is positive in the clockwise direction with the ring's outer-diameter (OD) on the left as shown in Figure 1 and Figure 2. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_thee.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_Mfinal.txt: Bending moment at the ring cross-section centroid in Nm. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_thee.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_S_uo.txt: Stress at upper OD point in MPa. A positive sign corresponds to extension. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_thee.txt" i.e. each column

corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.

- res_S_ui.txt: Stress at upper ID point in MPa. A positive sign corresponds to extension. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_thee.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_S_lo.txt: Stress at lower OD point in MPa. A positive sign corresponds to extension. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_thee.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.
- res_S_li.txt: Stress at lower ID point in MPa. A positive sign corresponds to extension. It has num_{Tg} columns. Each column contains the distribution corresponding to the circumferential direction angles in degrees given in "res_thee.txt" i.e. each column corresponds to the result obtained for a specific ring gap location among the equally spaced values between 0 (first column) and 359 (last column) degrees within bore fixed reference from thrust to thrust side that were considered.

Inputs of sub-model performing the radial plots related to the conformability study for different ring gap locations

Inputs that need to be provided by the user.

Nomenclature	Variable	Comment	Unit
	designation		
Magnification	mag1	Positive sign. Suggested value:	
coefficient for		3000	
radial plot of bore			
distortion and ring			
liner clearance			
Number of radial	numforce	Positive integer. Suggested value:	
forces to represent		200	
Maximum	fstop	Positive sign.	N/m
acceptable value			
for forces to be			
represented			

Frame rate of the	v.FrameRate	Number of frames per second for	frames/s
animation for the		the video that will be generated.	
total radial force		Suggested value: 1	
Frame rate of the	vl.FrameRate	Number of frames per second for	frames/s
animation for the		the video that will be generated.	
ring-liner radial		Suggested value: 1	
force			

This code also uses bore distortion, FEM related, ring gap size, ring-liner clearance, radial force and ring-liner force inputs and outputs of the sub-model performing the computation related to the conformability study for different ring gap locations.

Outputs of sub-model performing the radial plots related to the conformability study for different ring gap locations

Two videos are generated:

- The first one contains a fix radial plot of the bore and a moving one the ring based on its gap location using the specified magnification coefficient. For each ring gap location, it plots scaled lines showing the ring-liner forces based on the number of forces to be represented and the maximum acceptable value specified. For each ring gap location, it also displays separate message(s) if the bore or/and the ring is(are) misrepresented because of the magnification coefficient. It also shows the ring gap location within the bore fixed reference from thrust to thrust side and shows a message in case the force is truncated somewhere based on the maximum acceptable value for force to be represented that has been chosen.
- The second one contains a fix radial plot of the bore and a moving one the ring based on its gap location using the specified magnification coefficient. For each ring gap location, it plots scaled lines showing the radial forces based on the number of forces to be represented and the maximum acceptable value specified. For each ring gap location, it also displays separate message(s) if the bore or/and the ring is(are) misrepresented because of the magnification coefficient. It also shows the ring gap location within the bore fixed reference from thrust to thrust side and shows a message in case the force is truncated somewhere based on the maximum acceptable value for force to be represented that has been chosen.

Module 5: Ring static twist under FixOD or FixID constraint

This module performs the computation related to ring static twist under FixOD or FixID constraint. Inputs and outputs provided below.

Inputs

Inputs that need to be provided by the user.

Nomenclature	Variable designation	Comment	Unit
IsFreeshape	<u> </u>	1 to provide the free-shape coordinates or curvature and 0 to provide the radial pressure distribution for the circular bore	
Bore diameter	D_b		mm
Gap size when ring is closed to circular bore	gap		mm
Ring Young modulus	E_r		GPa
Ring density	$ ho_r$		kg/m^3
Ring Poisson ratio	$ u_r$		
Ring thermal expansion coefficient	$lpha_T$		1/ <i>K</i>
Number of elements for the FEM	Nbe	Positive integer	
Number of points within one element for contact and lubrication force calculation	Npe	Positive integer	
Liner Young modulus	E_l		GPa
Liner Poisson ratio	ν_l		
Plateau ratio	PR		
Liner surface roughness standard deviation	σ_p		μт
z coefficient for the asperity ring/liner and ring/groove contact interaction	Z	6.804 is the adopted value in the simplified formulation	
K coefficient for the asperity ring/liner and ring/groove contact interaction	K	1.198e-4 is the adopted value in the simplified formulation	

A coefficient for	A	4.4068e-5 is the adopted value in	
	А	•	
the asperity		the simplified formulation	
ring/liner and			
ring/groove			
contact interaction	0		
Ω coefficient for	Ω	4 is the adopted value in the	
the asperity		simplified formulation	
ring/liner and			
ring/groove			
contact interaction	C		
Friction coefficient	fc_{dry}		
for the asperity			
ring/liner and			
ring/groove			
contact interaction	<i>c</i> .		
Constant	cfct	1 is the adopted value in the	
coefficient for the		simplified formulation	
asperity ring/liner			
and ring/groove			
contact interaction			
IsFreeshaped		1 to provide the free-shape	
		coordinates and 0 to provide the	
		free-shape curvature. User has to	
		provide this value if	
		IsFreeshape=1.	
Free-shape		Text file with the first column	deg & mm
distribution		containing the circumferential	
		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the ring and	
		the second one contains the free-	
		shape coordinates in usual	
		representation in millimeters.	
		User has to provide this value if	
		IsFreeshape=1 and	
		IsFreeshaped=1.	1 0 1 /
Free-shape		Text file with the first column	deg & 1/m
curvature		containing the circumferential	
distribution		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the ring and	
		the second one contains the free-	
		shape curvature coordinates in	

		usual representation in 1/m. User	
		has to provide this value if	
		IsFreeshape=1 and	
		Isfreeshaped=0.	
Force distribution		Text file with the first column	deg & N/m
in radial bore		containing the circumferential	
		direction angles in degrees	
		defined with respect to the fixed	
		frame with respect to the ring and	
		the second one contains the	
		pressure times ring height (axial	
		width). User has to provide this	
		value if IsFreeshape=0.	
Tolerance for	$Newton_{tol}$	Positive sign. Suggested value:	
Newton-Raphson	000	10^{-6}	
algorithm			
convergence			
Maximum number	It_{Max}	Positive integer. Suggested value:	
of Newton-	1.2 0000	100	
Raphson algorithm			
iterations			

Inputs provided by the ring cross-section parameters calculation module.

Nomenclature	Variable	Comment	Unit
	designation		
Upper OD width	аио	Positive sign	mm
Upper OD height	huo	Positive sign	mm
Upper ID width	aui	Positive sign	mm
Upper ID height	hui	Positive sign	mm
Lower ID width	ali	Positive sign	mm
Lower ID height	hli	Positive sign	mm
Lower OD width	alo	Positive sign	mm
Lower OD height	hlo	Positive sign	mm
Ring upper flank	$ heta_{rt}$	Positive sign. Analogous to $ heta_{rb}$	deg
angle		shown in Figure 2.	
Ring lower flank	$ heta_{rb}$	Positive sign. Shown in Figure 2.	deg
angle			
Lower edge width	rb1	Positive sign. Axial distance	mm
		between lower end point (#3 in	
		Figure 1) and minimum point (#4	
		in Figure 1)	

Upper edge width	rb2	Positive sign. Axial distance	mm
		between upper end point (#5 in	
		Figure 1) and minimum point (#4	
Minimum naint	rbn	in Figure 1)	22222
Minimum point axial location	TDIL	Positive sign if minimum point	mm
axiai iocationi		located above the gravity center	
		point of the cross section and	
		negative otherwise (negative sign in Figure 1)	
Quadratic	a	iii Figure 1)	mm
coefficient for	a_{22}		Hilli
upper edge shape			
factor			
Quadratic	<i>a</i>		mm
coefficient for	a_{12}		Hilli
lower edge shape			
factor			
Linear coefficient	a .		
for upper edge	a_{21}		
shape factor			
Linear coefficient	a_{11}		
for lower edge	a_{11}		
shape factor			
Minimum point	arm	Positive sign	mm
width	Wi III	1 Ositive sign	110110
Cross section area	Ac		mm^2
Principal moment	I_{zp}		mm^4
of inertia in plane	- zp		110110
Principal moment	I_{yp}		mm^4
of inertia out of	- <i>yp</i>		
plane			
Moment of inertia	I_z		mm^4
in plane	- <u>Z</u>		-
Principal angle	α_p		deg
Polar moment of	I_p		mm^4
inertia	- <i>p</i>		-
Torsional factor	J_t		mm^4

Outputs

One text file is generated res_stat_twist.txt. It contains 9 columns, specified below from the left to the right:

- Column 1: Circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring. This angles distribution will be used for the ring's coordinates, clearances, forces and moment results from column 2 to column 9.
- Column 2: Ring radial coordinate in microns. This is defined respect to the nominal radius defined by $R_r = \left(\frac{D_b}{2} arm\right)*(1 + \alpha_T(T_r 25))$. A positive radial coordinate means that the ring cross-section centroid is located outside the circle with a radius equal to the nominal one.
- Column 3: Ring liner clearance in microns. Always non-negative.
- Column 4: Ring twist angle in degrees. A positive ring twist angle means the ring cross section is rotated in the clockwise direction with the ring's outer-diameter (OD) on the left as shown in Figure 1 and Figure 2.
- Column 5: Lower OD point clearance with the groove in microns. Always non-negative.
- Column 6: Lower ID point clearance with the groove in microns. Always non-negative.
- Column 7: Radial force in N/m (force per unit circumferential length of the ring). A positive sign corresponds to a compression force.
- Column 8: Axial force in N/m (force per unit circumferential length of the ring). The axial axis is positively pointing upwards.
- Column 9: Twist moment in N (moment per unit circumferential length of the ring). The angular orientation is positive in the clockwise direction with the ring's outer-diameter (OD) on the left as shown in Figure 1 and Figure 2.

Three plots are generated:

- The first one contains the curve of the ring radial coordinate and the ring-liner clearance as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring. Both are plotted in microns. It also gives the ring twist angle in degrees as a function of the same circumferential direction angles in degrees.
- The second plot displays the 2 curves of lower OD/ID clearances with the lower plate, both in microns and as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring.
- The third plot contains the curve of the radial force and axial one, both in N/m as a function of the circumferential direction angles in degrees defined with respect to the fixed frame with respect to the ring. It also gives the twist moment in N as a function of the same circumferential direction angles in degrees.

The code also displays the tangential load determined from the force distribution computed.