[3] involuteΣ Worm Gear Design System

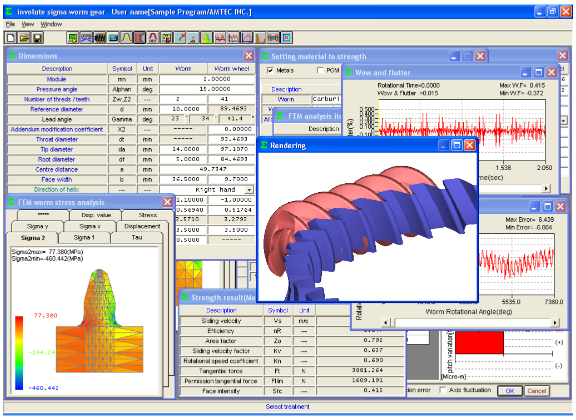


Fig. 3.1 involuteΣ Worm Gear Design System

3.1 Introduction

The ***involuteΣ Worm Gear Design System*** is a complete design system for worm gear sets (consisting of a worm and a worm wheel). For worm and helical gear combinations, please use the *involuteΣ Worm and Helical Gear Design System*.

3.2. Software Features

Table 3.1 shows the available software features.

Table 3.1. Software Features

Item	Page	Applicable
<1> Basic Rack Setting	13	○
<2> Worm Tooth Profile (Type 1)	13	○
<3> Worm Tooth Profile (Types 3 and 4)	13	◎
<4> Hob Setting	13	○
<5> Tooth Profile Calculation (Standard)	14	○
<6> Tooth Profile Calculation (Interference)	14	◎
<7> Gear Dimension	14	○
<8> Gear Meshing Drawing (2D-DXF, 3D-DXF)	14	○
<9> Tooth Profile Rendering (Image Display)	14	◎
<10> Tooth Profile Rendering (Mounting Error Adjustment)	14	◎
<11> Tooth Profile Rendering (Backlash Angle)	14	◎
<12> Tooth Profile Data File Output (2D-DXF, 3D-DXF)	14	○
<13> Tooth Profile Data File Output (3D-IGES)	14	◎
<14> Strength Calculation (Metal)	14	○
<15> Strength Calculation (POM)	14	○
<16> Strength Calculation (PA)	15	◎
<17> Gear Accuracy	–––	○
<18> 2D-FEM Tooth Profile Stress Analysis	15	◎
<19> Transmission Error Analysis	15	◎
<20> Sliding Speed Graph	15	◎
<21> Hertzian Stress Graph	16	◎
<22> Fourier Analysis	16	◎
<23> Design Data Management	––	○
<24> Tooth Contact Analysis	16	◎
<25> Bearing Load Calculation	16	○
<26> Center Distance Variation Analysis	16	◎
<27> Tooth Profile Modification	16	◎

○ (Supported as standard) ◎ (Optional)

3.3 Icon Buttons

The toolbar contains 17 icon buttons including [Dimension], [Tooth Profile], [Strength], [FEM], and [Transmission].

3.4 Basic Rack Setting

Before using the System, the user needs to configure the basic rack settings by selecting: (1) basic rack type (full depth, stub gear, or special), (2) worm tooth profile (Type 1, 3, or 4), (3) tooth profile reference (cross-sectional or normal), and (4) worm wheel shape. Fig. 3.2 shows the Initial dimension setting screen.

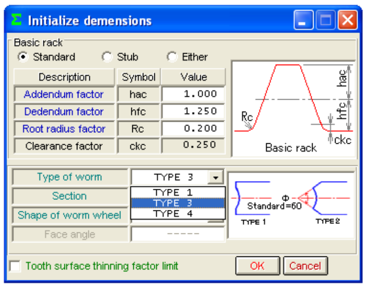


Fig. 3.2 Initial Dimension Settings

3.5 Gear Dimension Setting

Fig. 3.3 shows the Gear dimension setting screen. The user may change items such as the gorge radius, tip diameter, root diameter, and center distance. For the tooth thickness reduction and the tooth surface thinning factor , specifying one automatically sets the other.

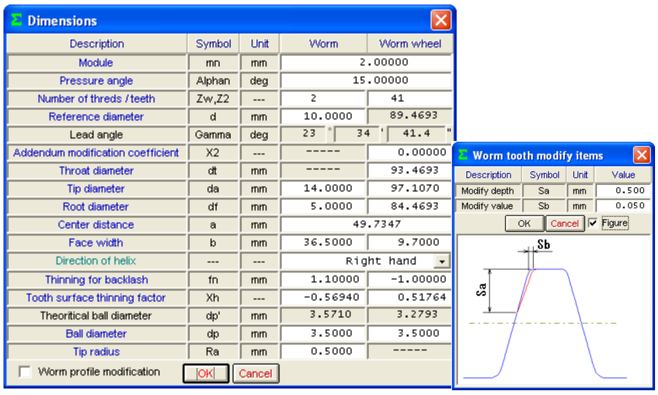


Fig. 3.3 Gear Dimension Settings

3.6 Tool Setting and Gear Dimension Calculation

Specify the specifications of the hob for cutting the worm wheel. The default setting angle of the hob is determined to match the axial pitch. The diameter and setting angle of the hob affect the tooth profile of the worm wheel to be cut. For the Type 3 worm, however, the diameter of the grinding wheel affects the tooth profile. Fig. 3.4 shows the Tool dimension setting screen and Fig. 3.5 shows the calculated worm gear dimensions.

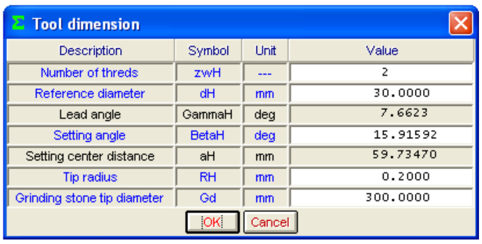


Fig.3.4 Hob specification Settings

Description	Symbol	Unit	Worm	Worm wheel
Addendum	ha	mm	2.0000	2.0000
Dedendum	hf	mm	2.5000	2.5000
Tooth depth	h	mm	4.5000	4.5000
Clearance	ck	mm	0.5000	0.5000
Base diameter	db	mm	-----	85.8746
Lead	pz	mm	13.7110	-----
Pitch	px	mm	6.8555	
Center distance	a	mm	49.7347	
Diameter factor	Q	---	4.5826	-----
Gorge radius	rt	mm	-----	13.0001
Tooth bottom width	Wn	mm	1.8018	-----
Chordal addendum	hj	mm	2.0395	2.0232
Theoritical chordal tooth thickness	Sjo	mm	3.1416	3.1411
Designed chordal tooth thickness	Sj	mm	2.0028	4.1764
Three pins distance(Pin to Tip)	dma	mm	12.8644	-----
Three pins distance(Pin to Pin)	dm	mm	11.7287	-----
Over ball distance	dmh	mm	-----	97.4491
Transverse contact ratio	Epsilon-a	---	1.7850	

Fig. 3.5 Calculated Worm Gear Dimensions

3.7 Tooth Profile Calculation

(1) Standard Tooth Profile Analysis

The System calculates the tooth profile of the worm wheel using the hob specifications specified in Fig. 3.4.

(2) Interference Analysis

Setting a large lead angle prevents the worm from contacting the worm wheel at the center of the tooth flank because of the lead difference between the worm and the hob. The Interference Analysis feature analyzes the tooth profile of the hob to help the user eliminate interference. For details, refer to Section 3.20.

Fig. 3.6 Tooth Profile Calculation

3.8 Gear Meshing Drawing

Fig. 3.7 shows the cross-sectional tooth profiles of the worm and the wheel meshed at the axial center of the worm. Even if the teeth seem to be meshed correctly in this 2D drawing, interference may occur in other sections. Incorrect tooth contact due to interference or assembly errors can be checked using the Tooth Profile Rendering feature in Section 3.9.

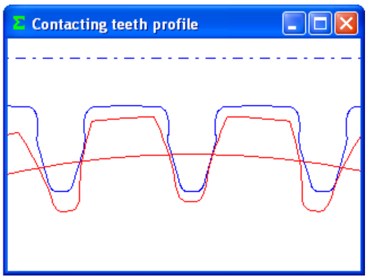
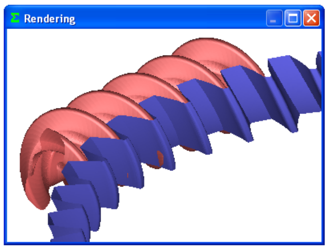


Fig. 3.7 Gear Meshing Drawing

3.9 Tooth Profile Rendering

Using the Tooth Profile Rendering feature may reveal severe interference on some tooth flanks of the wheel as shown in Fig. 3.8 and Fig. 3.9, even if it seems that there is no interference in this 2D drawing in Fig. 3.7. Fig. 3.10 shows the control form used for Tooth Profile Rendering. The user can not only change the viewing angle by specifying the X-, Y-, and Z-axis rotation angles, but also scale the image by entering the Z-axis travel distance. It is also possible to observe how the meshing state changes by varying the angle and position of the worm shaft.

The control form also offers optional features: The first feature provides (1) worm shaft angle, (2) worm shaft position, and (3) center distance adjustments. The second feature is used to display the backlash angle.



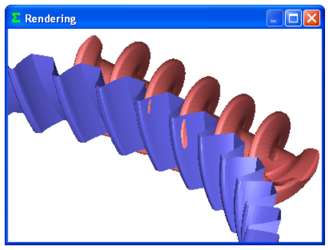


Fig. 3.8 Tooth Profile Rendering (Left) Fig. 3.9 Tooth Profile Rendering (Right)

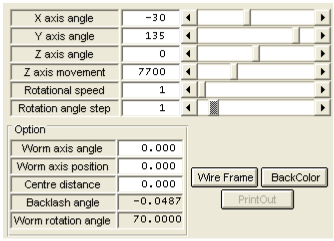
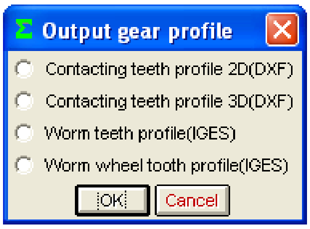


Fig 3.10 Tooth Profile Rendering Control Form

3.10 Tooth Profile Data File Output

As shown in Fig. 3.11, the user can choose to output worm and wheel tooth profile data into four kinds of CAD-format files. Fig. 3.12 is an example of a 3D worm wheel tooth profile displayed in a CAD system.



File 3.11 Tooth Profile File

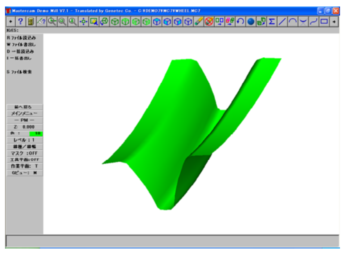


Fig. 3.12 3D Tooth Profile Data in a CAD System (IGES)

3.11 Initial Strength Calculation Setting

Fig. 3.13 shows the Initial strength calculation settings screen, in which the user can select the material used for the worm wheel. Clicking the [Select material] button displays the Metal material selection screen as shown in Fig. 3.14.

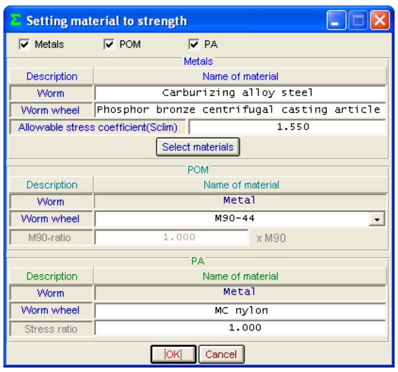
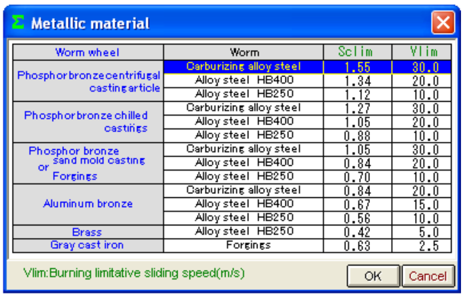


Fig. 3.13 Initial Strength Calculation Settings (with [Select Material] button)



Metallic material

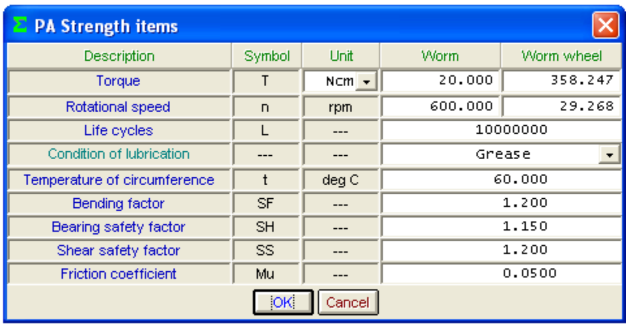
Worm wheel	Worm	Sclim	Vlim
Phosphor bronze centrifugal casting article	Carburizing alloy steel	1.55	30.0
	Alloy steel HB400	1.34	20.0
	Alloy steel HB250	1.12	10.0
Phosphor bronze chilled castings	Carburizing alloy steel	1.27	30.0
	Alloy steel HB400	1.05	20.0
	Alloy steel HB250	0.88	10.0
Phosphor bronze sand mold casting or Forgings	Carburizing alloy steel	1.05	30.0
	Alloy steel HB400	0.84	20.0
	Alloy steel HB250	0.70	10.0
Aluminum bronze	Carburizing alloy steel	0.84	20.0
	Alloy steel HB400	0.67	15.0
	Alloy steel HB250	0.56	10.0
Brass	Alloy steel HB250	0.42	5.0
Gray cast iron	Forgings	0.63	2.5

Vlim:Burning limitative sliding speed(m/s)

Fig. 3.14 Metal Material Selection

3.12 Strength Calculation

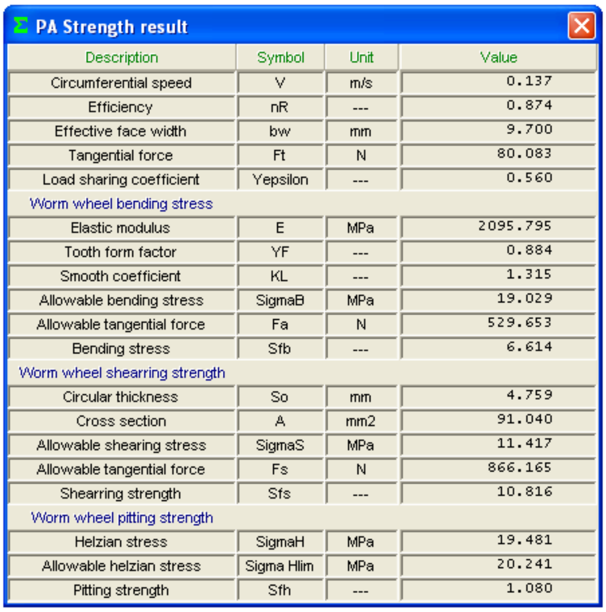
Fig. 3.15 shows the strength setting screen for resin (PA) materials. The results of the strength calculation for the resin and metal materials are shown in Fig. 3.16 and Fig. 3.17, respectively.



PA Strength items

Description	Symbol	Unit	Worm	Worm wheel
Torque	T	Ncm	20.000	358.247
Rotational speed	n	rpm	600.000	29.268
Life cycles	L	---	10000000	
Condition of lubrication	---	---	Grease	
Temperature of circumference	t	deg C	60.000	
Bending factor	SF	---	1.200	
Bearing safety factor	SH	---	1.150	
Shear safety factor	SS	---	1.200	
Friction coefficient	Mu	---	0.0500	

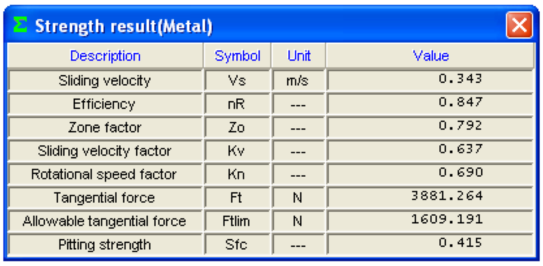
Fig. 3.15 Strength Specification Settings for Resin Material (PA)



PA Strength result

Description	Symbol	Unit	Value
Circumferential speed	V	m/s	0.137
Efficiency	nR	---	0.874
Effective face width	bw	mm	9.700
Tangential force	Ft	N	80.083
Load sharing coefficient	Yepsilon	---	0.560
Worm wheel bending stress			
Elastic modulus	E	MPa	2095.795
Tooth form factor	YF	---	0.884
Smooth coefficient	KL	---	1.315
Allowable bending stress	SigmaB	MPa	19.029
Allowable tangential force	Fa	N	529.653
Bending stress	Sfb	---	6.614
Worm wheel shearring strength			
Circular thickness	So	mm	4.759
Cross section	A	mm2	91.040
Allowable shearing stress	SigmaS	MPa	11.417
Allowable tangential force	Fs	N	866.165
Shearring strength	Sfs	---	10.816
Worm wheel pitting strength			
Helzian stress	SigmaH	MPa	19.481
Allowable helzian stress	Sigma Hlim	MPa	20.241
Pitting strength	Sfh	---	1.080

Fig. 3.16 Strength Calculation Result for Resin Material (PA)



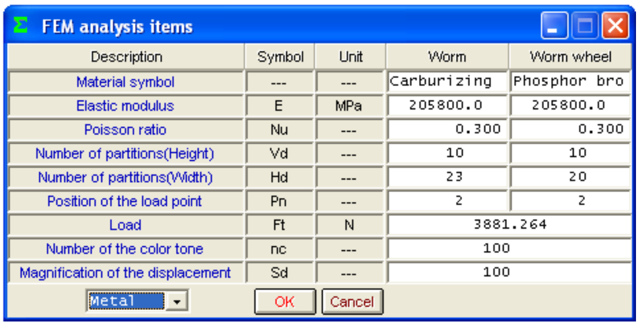
Strength result(Metal)

Description	Symbol	Unit	Value
Sliding velocity	Vs	m/s	0.343
Efficiency	nR	---	0.847
Zone factor	Zo	---	0.792
Sliding velocity factor	Kv	---	0.637
Rotational speed factor	Kn	---	0.690
Tangential force	Ft	N	3881.264
Allowable tangential force	Ftlim	N	1609.191
Pitting strength	Sfc	---	0.415

Fig. 3.17 Strength Calculation Result for Metal Material

3.13 FEM Tooth Profile Stress Analysis

Stress analysis can be easily performed by simply clicking the [FEM] button after strength calculation. Fig. 3.18 shows the FEM analysis setting screen. The user may change the Young modulus, Poisson ratio, number of partitions, and load values. Fig. 3.19 and Fig. 3.20 show the results of FEM analysis on the worm and the wheel, respectively.



FEM analysis items

Description	Symbol	Unit	Worm	Worm wheel
Material symbol	---	---	Carburizing	Phosphor bro
Elastic modulus	E	MPa	205800.0	205800.0
Poisson ratio	Nu	---	0.300	0.300
Number of partitions(Height)	Vd	---	10	10
Number of partitions(Width)	Hd	---	23	20
Position of the load point	Pn	---	2	2
Load	Ft	N	3881.264	
Number of the color tone	nc	---	100	
Magnification of the displacement	Sd	---	100	

Fig. 3.18 FEM Analysis Settings

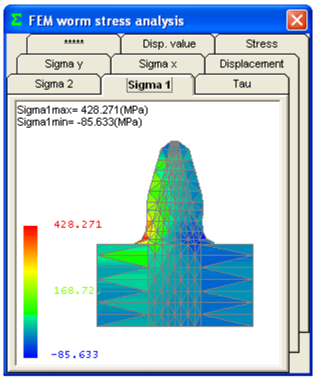


Fig. 3.19 FEM Analysis on Worm (Stress=ó$_1$)

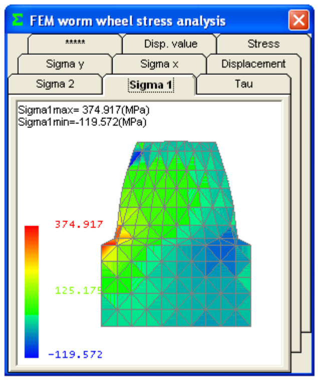


Fig. 3.20 FEM Analysis on Wheel (Stress=ó$_1$)

3.14 Transmission Error Analysis

Fig. 3.21 and Fig. 3.22 show the setting screens for transmission error analysis. The graphs in Fig. 3.23 and Fig. 3.24 show the results of analysis on the rotation transmission error and wow and flatter, respectively. These errors were raised by assembling the worm and wheel pair to have pitch and radial runout errors and rotating the worm by one turn. The graphs in Fig. 3.25 and Fig. 3.26 also show the results of analysis on the rotation transmission error and wow and flatter, respectively, but they were raised by rotating the wheel by one turn.

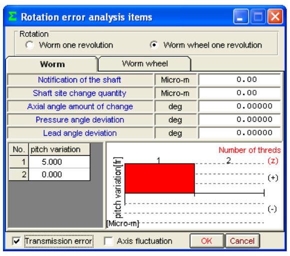


Fig. 3.21 Transmission Error Analysis Settings (Worm)

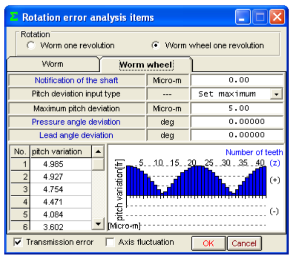


Fig. 3.22 Transmission Error Analysis Settings (Wheel)

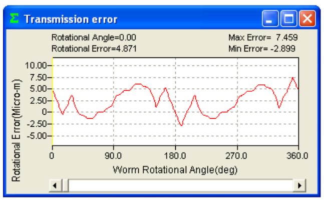


Fig. 3.23 Rotation Transmission Error 1

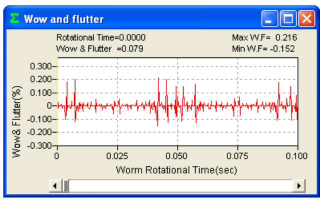


Fig. 3.24 Wow & Flatter 1

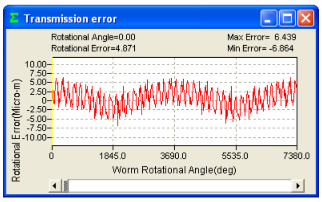


Fig. 3.25 Rotation Transmission Error 2

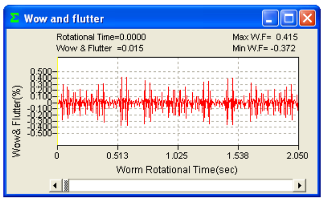


Fig. 3.26 Wow & Flatter 2

3.15 Frequency Analysis

Fig. 3.27 shows the result of analysis on the frequency measured when the worm is rotated by one turn; Fig. 3.28 shows the result of analysis on the frequency measured when the wheel is rotated by one turn.

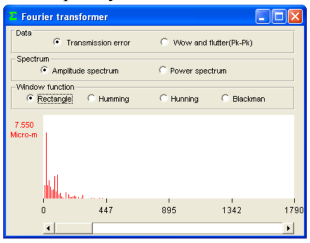


Fig. 3.27 Fourier Analysis 1

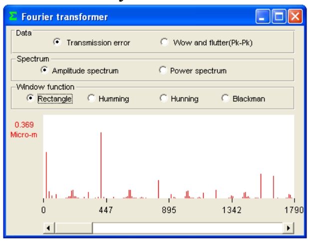


Fig. 3.28 Fourier Analysis 2

3.16 Hertzian Stress and Sliding Speed Graphs

Fig. 3.29 shows the Hertzian stress exerted on the tooth flank surface when the worm is rotated by one turn; the graph in Fig. 3.30 shows the sliding speed measured during that time.
These graphs are useful after the transmission error analysis.

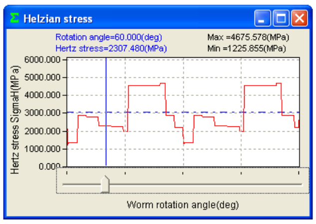


Fig. 3.29 Hertzian Stress Graph

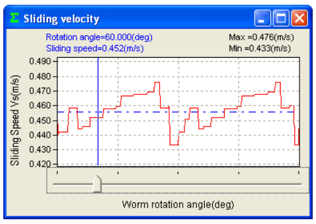


Fig. 3.30 Sliding Speed Graph

3.17 Center Distance Variation

This feature simulates how the center distance changes when, like on a double-flank gear rolling tester, the worm and the wheel rotate while mutually pressing each other's tooth flanks. The results of this simulation are shown in Fig. 3.31 (circle graph) and Fig. 3.32 (line graph), respectively.

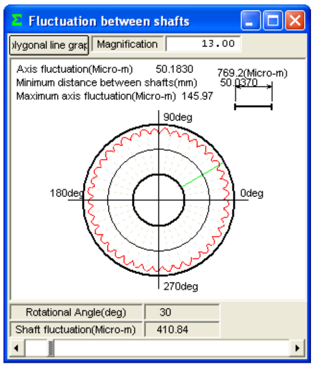


Fig. 3.31 Center Distance Variation Graph 1

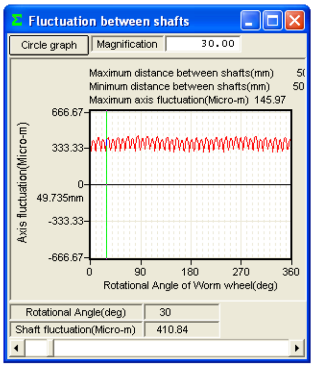


Fig. 3.32 Center Distance Variation Graph 2

3.18 Bearing Load Calculation

Fig. 3.33 shows the bearing load setting screen; Fig. 3.34 shows the result of the bearing load calculation.

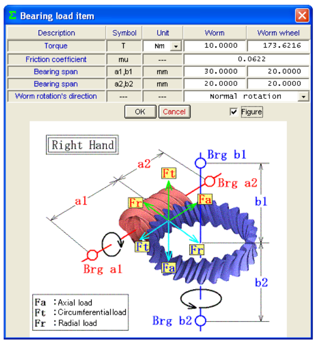


Fig. 3.33 Bearing Load Calculation Settings

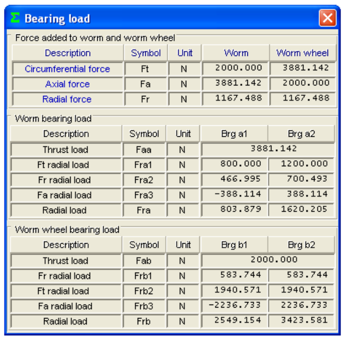


Fig. 3.34 Bearing Load Calculation Result

3.19 Tooth Contact Analysis

An example of analysis on the tooth flanks of the worm and worm wheel is shown below. The setting screen in Fig. 3.35 provides various settings for tooth contact analysis. In this example, analysis will be made on the tooth contact of the worm and wheel specified in Fig. 3.3. Here, the number of rotation position partitions is set to "4" although it accepts values in a range of 3 to 20. Fig. 3.36 shows a tooth contact state between the worm and the wheel and Figs. 3.37 to 3.40 show their tooth contact states by 1/4 pitch. This example, however, does not take the deflection of the teeth and the pitch error into account.

It is noticeable that tooth contact pattern in Fig. 3.36 slightly differs from the tooth profile rendering image shown in Fig. 3.8. The reason for this is that the analysis in this example was made at a fineness that is two times (up to five times allowed) greater than that of the number of tooth profile partitions setting used for the tooth profile rendering image of the wheel.

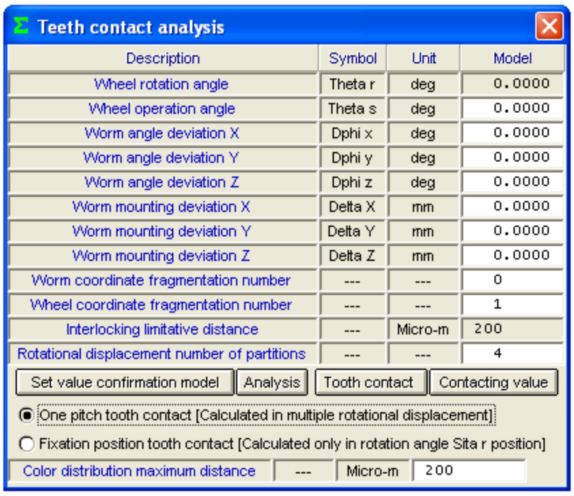


Fig. 3.35 Tooth Contact Analysis Settings

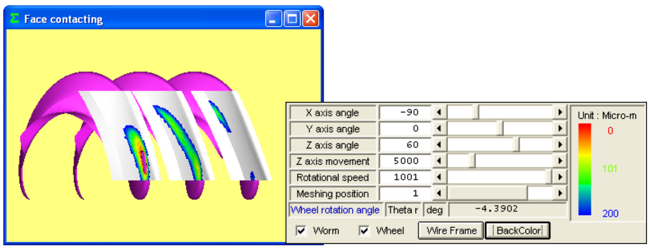


Fig. 3.36 Tooth Contact State (Worm and Wheel)

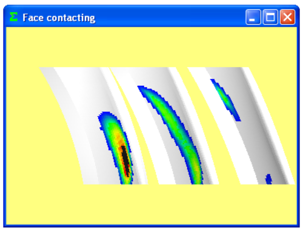


Fig. 3.37 Tooth Contact State 1

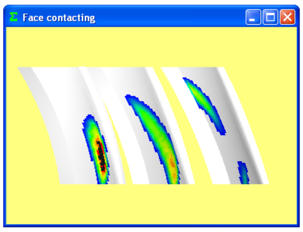


Fig. 3.38 Tooth Contact State 2

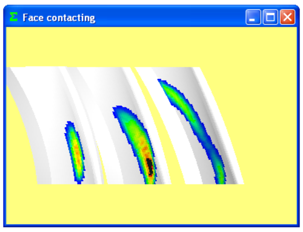


Fig. 3.39 Tooth Contact State 3

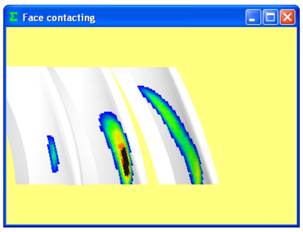


Fig. 3.40 Tooth Contact State 4

In addition to viewing the tooth contact state as a color pattern as shown in Fig. 3.36, to examine it in more detail, the user may click the [Tooth contact value] button in Fig. 3.35 to display the contact clearance values in Fig. 3.41. The slider control bar at the bottom of the screen can be used to change the target rotation position (1 to 4 in this example).

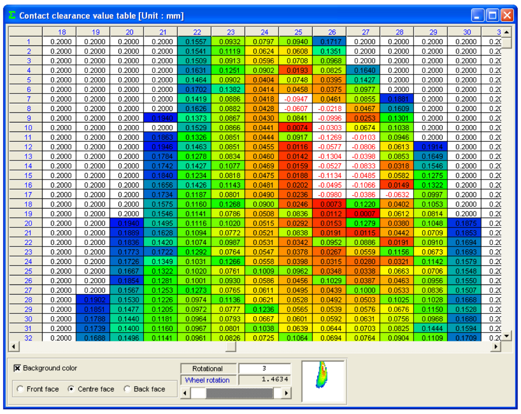


Fig. 3.41 Contact Clearance Values

3.20 Example of Hob Tooth Profile Analysis Simulation[1)]

3.20.1 Introduction

The tooth contact state between the worm and the worm wheel in mesh will be influenced by the hob used to cut them. The contact point will be deviated to a great extent particularly if the lead angle of the worm is large or if there is a significant difference between the diameters of the worm and the hob. Since this is caused by the lead difference between the worm and the hob, to obtain a proper tooth contact, it is necessary to modify the tooth profile of the hob. The following is the result of examination on the tooth contact and backlash of the worm gear using the ***involuteΣ Worm Gear Design System***.

3.20.2 Examined Gear Set

The specifications of the examined gear set are shown in Table 3.2. Compared with the worm's pitch diameter of 12 mm, the pitch diameter of the hob used to cut the worm wheel (shown in Fig. 3.42) is 36 mm. This requires the hob to be installed at a setting angle of 14.5916 (degrees) to match the axial pitch.

Normal module	= 1.8mm
Number of starts	= 1
Pitch circle dia.	= 36mm
Lead angle	= 2.86598deg
Hob set angle	= 14.5916deg
Hob tip radius	= 0.2mm

Fig. 3.42 Hob Dimensions

Table 3.2 Worm Gear Specifications

Item	Symbol	Unit	Worm	Wheel
Worm type	--	--	1 and 4	
Module pitch	mn	mm	1.8	
Pressure angle	αn	deg	14.5	
Number of starts	Zw	--	2	--
Number of teeth	Z	--	--	40
Pitch circle dia.	d	mm	12.000	75.4765
Lead angle	γ	deg	17.4576	
Addendum modification coef.	Xn	--	--	0.2
Center distance	a	mm	44.0983	
Tooth thinning for backlash	fn	mm	0.871	-0.871

3.20.3 Tooth Profile Rendering

Fig. 3.43 and Fig. 3.44 show the tooth profile rendering images of the Type 1 worm and worm wheel. It can be seen that, while there are three occurrences of major interference on the worm and wheel cut using the non-modified hob, the modified hob has no interference and the worm and wheel mesh without interference around the center of the tooth flank.

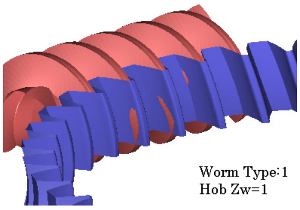


Fig. 3.43 Tooth Profile Rendering (Non-Modified Hob)

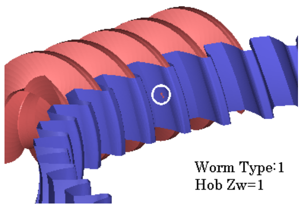


Fig. 3.44 Tooth Profile Rendering (Modified Hob)

3.20.4 Relationship between Hob Diameter and Backlash

Fig. 3.45 shows the change in the backlash amount when the diameter of the non-modified hob is increased from 12 to 100 mm. The graph shows that the backlash becomes the maximum at a hob diameter of 18 mm and decreases as the hob diameter increases. With the modified hob (shown in Fig. 3.47), the amount of change in backlash improves significantly and the backlash becomes approximately constant as shown in Fig. 3.26.

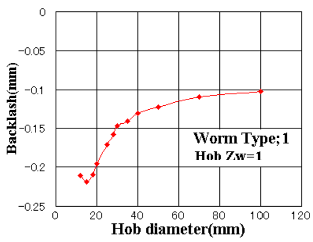


Fig. 3.45 Hob Diameter versus Backlash Graph 1

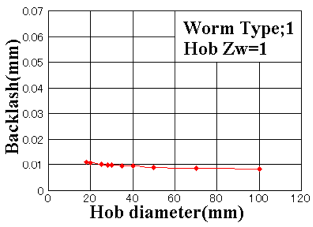


Fig. 3.46 Hob Diameter versus Backlash Graph 2

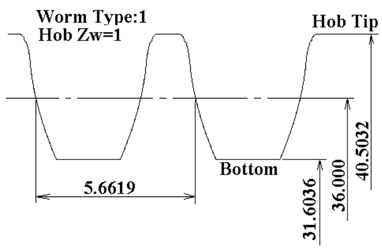


Fig. 3.47 Tooth Profile of Modified Hob

1) MPT2001-Fukuoka, Excerpt from Amtec Catalog, 2001