	A	B	C	Appendix A	E	F	G	H	I
1	**Kinematic_Coupling_3Groove_Design.xls**								
2	To design three groove kinematic couplings								
3	Written by Alex Slocum long ago. Last modified 2012/10/28 by Alex Slocum								
4	**Metric units only!** Enters numbers in **BOLD**, Results in **RED**					**Material properties**			
5	**Standard 120 degree equal size groove coupling?** (contact forces are inclined at 45 to the XY plane. For non					*User defined material*	***red oak***		
6	standard designs, enter geometry after results section)				**TRUE**	*Yield stress*			
7	**System geometry (XY plane is assumed to contain the ball centers)**					plastic	**3.45E+07**		
8	Dbeq (mm) =	**19.05**	**Equivalent diameter ball to contact the groove at the same points**			RC 62 Steel	**1.72E+09**		
9	Rbminor (mm) =	**9.525**	"Ball" minor radius			CARBIDE	**2.76E+09**		
10	Rbmajor (mm) =	**9.525**	"Ball" major radius			user defined	**6.00E+07**		
11	Rgroove (mm) =	**1.00E+06**	Groove radius (negative for a trough)			*Elastic modulus*			
12	Costheta =	**TRUE**	Is ball major radius along groove axis?			plastic	**2.07E+09**		
13	Dcoupling (mm) =	**127**	Coupling diameter			RC 62 Steel	**2.04E+11**		
14	Fpreload (N) =	**-1**	Preload force over each ball (negative pushes ball into groove)			CARBIDE	**3.10E+11**		
15	Xerr (mm) =	**0.0**	X location of error reporting			user defined	**8.00E+09**		
16	Yerr (mm) =	**0.0**	Y location of error reporting			*Poisson ratio*			
17	Zerr (mm) =	**0.0**	Z location of error reporting			plastic	**0.20**		
18	**Auto select material values (enter *other_4* to the right)**					RC 62 Steel	**0.29**		
19	Matlabball =	**4**	Enter 1 for plastic, 2 for steel, 3 for carbide, 4 for user defined, 5			CARBIDE	**0.30**		
20	Matlabgroove =	**4**	where each ball and groove is defined individually			user defined	**0.35**		
21	Min. yield strength (Pa, psi)		**6.00E+07**	**8,696**					
22	Largest contact ellipse major diameter (mm)		**0.462**						
23	Smallest contact ellipse major diameter (mm)		**0.461**						
24	Largest contact stress ratio		**0.70**						
25	RMS applied force (N)		**30**						
26	RMS stiffness (N/micron)		**10**						
27	Z displacement caused by preload (mm)		**0.001**						
28	Applied Z load at zero inclination (N)	**-30**							
29	inclination angle (degrees)	**0**							
30	**Applied force's Z,Y,Z values and coordinates**				**Coupling centroid location**				
31	FLx (N) =	**0.00**	XL (mm) =	**0**	xc (mm)	**0.000**		XL (m) =	**0.000**
32	FLy (N) =	**0**	YL (mm) =	**0**	yc (mm)	**0.000**		YL (m) =	**0.000**
33	FLz (N) =	**-30**	ZL (mm) =	**0**	zc (mm)	**0.000**		ZL (m) =	**0.000**
34	**Results: Hertz stresses and deformations**								
35	Error displacements at the point of interest due to applied load (preload displacement subtracted off) (micron)								
36	**DeltaX (mm)**	**0.0000**		**DeltaY (mm)**	**0.0000**		**DeltaZ (mm)**	**0.0031**	
37	**resulting rotation (degrees) wrt center)**	**0.0000**			**0.0000**				
38	**Vector displacement (mm)**	**0.0031**							

39	*Groove normal forces (preload + applied load) (N)*		*Contact stress (preload + applied load) (Pa)*		*stress/(ult. tensile/2)*	*Deflection (+into ball) (m)*		*Contact ellip*
40						*from:*	*Applied Load*	*Preload only*	*Rmajor*
41	*Ball-Groove 1*		*Ball-Groove 1*			*Ball-Groove 1*			*Ball-Groove 1*
42	Fbnone	***7.8***	sigone	***6.98E+07***	***0.698***	delone	***4.43E-06***	***1.12E-06***	***2.31E-04***
43	Fbntwo	***7.8***	sigtwo	***6.98E+07***	***0.698***	deltwo	***4.43E-06***	***1.12E-06***	***2.31E-04***
44	*Ball-Groove 2*		*Ball-Groove 2*			*Ball-Groove 2*			*Ball-Groove 2*
45	Fbnthree	***7.8***	sigthree	***6.98E+07***	***0.698***	delthree	***4.43E-06***	***1.12E-06***	***2.31E-04***
46	Fbnfour	***7.8***	sigfour	***6.98E+07***	***0.698***	delfour	***4.43E-06***	***1.12E-06***	***2.31E-04***
47	Ball-Groove 3		Ball-Groove 3						Ball-Groove 3
48	Fbnfive	***7.8***	sigfive	***6.98E+07***	***0.698***	delfive	***4.43E-06***	***1.12E-06***	***2.31E-04***
49	Fbnsix	***7.8***	sigsix	***6.98E+07***	***0.698***	delsix	***4.43E-06***	***1.12E-06***	***2.31E-04***
50									
51									
52									

53	**Results: Error motions**			**Xerr**	**Yerr**	**Zerr**			
54	*Error motions are at X,Y,Z coordinates (m)*			***0.000***	***0.000***	***0.000***			
55	deltaX	**0.00E+00**		RMS	**3.13E-06**				
56	deltaY	**0.00E+00**		*Homogenous Transformation Matrix:*					
57	deltaZ	**3.13E-06**		**1.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**		
58	EpsX	**0.00E+00**	**0**	**0.00E+00**	**1.00E+00**	**0.00E+00**	**0.00E+00**		
59	EpsY	**0.00E+00**		**0.00E+00**	**0.00E+00**	**1.00E+00**	**3.13E-06**		
60	EpsZ	**0.00E+00**		**0.00E+00**	**0.00E+00**	**0.00E+00**	**1.00E+00**		
61	**Generic data entry for non-120 degree couplings**								
62	***NOTE! For calculation of angular errors, the coupling is assumed to lie in the XY plane.***								
63	***Ball 1 must lie in quadrants 1 0r 2, and Balls 2 & 3 must lie in quadrants 3 and 4***								
64	*Enter X,Y,Z coordinates and alpha, beta, gamma direction cosines for Ball 1*								
65	Dball (m)	**0.0191**							
66	Dcoupling (m)	**0.127**							
67		Contact point 1		Contact point 2					
68	Xba =	**0.006735**	Xbb =	**-0.006735**					
69	Yba =	**0.063500**	Ybb =	**0.063500**					
70	Zba =	**-0.006735**	Zbb =	**-0.006735**					
71	Aba =	**-0.707107**	Abb =	**0.707107**					
72	Bba =	**0.000000**	Bbb =	**0.000000**					
73	Gba =	**0.707107**	Gbb =	**0.707107**		User values if matlabs = 5			
74	*Enter characteristics for groove 1 and ball 1*								
75	Egone =	**8.00E+09**	Groove material elastic modulus, or enter value (mm):						
76	vgone =	**0.35000**	Groove material Poisson ratio, or enter value (mm):						
77	Rgone =	**1000**	Groove radius of curvature						
78	Ebone =	**8.00E+09**	Ball material elastic modulus, or enter value (Pa):						
79	vbone =	**0.35**	Ball material Poisson ratio, or enter value (Pa):						
80	Eeone =	**4.56E+09**	Equivelent modulus						
81	Dbone =	**1.91E-02**	Equivelent diameter ball that would contact the groove at the same points						
82	Rpone =	**0.009525**	"Ball" major radius of curvature, or enter value (mm):						
83	Raone =	**0.009525**	"Ball" minor radius of curvture, or enter value (mm):						
84	Reone =	**0.004762477**	Equivelent radius						
85	ctone =	**4.76248E-06**	Cos(theta)						
86	theta_1 =	**1.570791564**							
87	alpha_1 =	**1.003017671**							
88	beta_1 =	**1.001405398**							
89	lambda_1 =	**0.749037341**							
90	Sone =	**6.00E+07**	Allowable Hertz stress, or enter value:						
91	*Enter X,Y,Z coordinates and alpha, beta, gamma direction cosines for Ball 2*								
92		Contact point 3		Contact point 4					
93	Xbc =	**-0.058360**	Xbd =	**-0.051625**					
94	Ybc =	**-0.025917**	Ybd =	**-0.037583**					
95	Zbc =	**-0.006735**	Zbd =	**-0.006735**					
96	Abc =	**0.353553**	Abd =	**-0.353553**					
97	Bbc =	**-0.612372**	Bbd =	**0.612372**					
98	Gbc =	**0.707107**	Gbd =	**0.707107**		User values if matlabs = 5			
99	*Enter characteristics for groove 2 and pin 2*								
100	Egtwo =	**8.00E+09**	Groove material elastic modulus, or enter value (mm):						
101	vgtwo =	**0.35000**	Groove material Poisson ratio, or enter value (mm):						
102	Rgtwo =	**1000**	Groove radius of curvature						
103	Ebtwo =	**8.00E+09**	Ball material elastic modulus, or enter value (Pa):						
104	vbtwo =	**0.35**	Ball material Poisson ratio, or enter value (Pa):						
105	Eetwo =	**4.56E+09**	Equivelent modulus						
106	Dbtwo =	**1.91E-02**	Equivelent diameter ball that would contact the groove at the same points						
107	Rptwo =	**0.009525**	"Ball" major radius of curvature, or enter value (mm):						
108	Ratwo =	**0.009525**	"Ball" minor radius of curvture, or enter value (mm):						
109	Retwo =	**0.004762477**	Equivelent radius						
110	cttwo =	**4.76248E-06**	Cos(theta)						
111	theta_2 =	**1.570791564**							
112	alpha_2 =	**1.003017671**							
113	beta_2 =	**1.001405398**							
114	lambda_2 =	**0.749037341**							

	A	B	C	Appendix A	E	F	G	H	I
115	Stwo =	**6.00E+07**	Allowable Hertz stress						
116	Enter X,Y,Z coordinates and alpha, beta, gamma direction cosines for Ball 3								
117		Contact point 5		Contact point 6					
118	Xbe =	**0.051625**	Xbf =	**0.058360**					
119	Ybe =	**-0.037583**	Ybf =	**-0.025917**					
120	Zbe =	**-0.006735**	Zbf =	**-0.006735**					
121	Abe =	**0.353553**	Abf =	**-0.353553**					
122	Bbe =	**0.612372**	Bbf =	**-0.612372**					
123	Gbe =	**0.707107**	Gbf =	**0.707107**		User values if matlabs =			
124	*Enter characteristics for groove 3 and ball 3*					5			
125	Egthree =	**8.00E+09**	Groove material elastic modulus, or enter value (mm):						
126	vgthree =	**0.35000**	Groove material Poisson ratio, or enter value (mm):						
127	Rgthree =	**1000**	Groove radius of curvature						
128	Ebthree =	**8.00E+09**	Ball material elastic modulus, or enter value (Pa):						
129	vbthree =	**0.35**	Ball material Poisson ratio, or enter value (Pa):						
130	Eethree =	**4.56E+09**	Equivelent modulus						
131	Dbthree =	**1.91E-02**	Equivelent diameter ball that would contact the groove at the same points						
132	Rpthree =	**0.009525**	"Ball" major radius of curvature, or enter value (mm):						
133	Rathree =	**0.009525**	"Ball" minor radius of curvture, or enter value (mm):						
134	Rethree =	**0.004762477**	Equivelent radius						
135	ctthree =	**4.76248E-06**	Cos(theta)						
136	theta_3 =	**1.570791564**							
137	alpha_3 =	**1.003017671**							
138	beta_3 =	**1.001405398**							
139	lambda_3 =	**0.749037341**							
140	Sthree =	**6.00E+07**	Allowable Hertz stress						
141	*Preload forces' X,Y,Z components and coordinates*								
142	Fpxone =	0	Fpxtwo =	0	Fpxthree =	0			
143	Fpyone =	0	Fpytwo =	0	Fpythree =	0			
144	Fpzone =	-1	Fpztwo =	-1	Fpzthree =	-1			
145	Xpone =	0	Xptwo =	-0.054992613	Xpthree =	0.054992613			
146	Ypone =	0.0635	Yptwo =	-0.03175	Ypthree =	-0.03175			
147	Zpone =	0.0381	Zptwo =	0.0381	Zpthree =	0.0381			
148	**Calculations:**								
149	Build Force Moment equilibrium matrices: AF = B (Equations 1-6)								
150	Matrix A						Matrix F	B with loads	B w/o loads
151	Fbn1	Fbn2	Fbn3	Fbn4	Fbn5	Fbn6			
152	-7.07E-01	7.07E-01	3.54E-01	-3.54E-01	3.54E-01	-3.54E-01	Fbn1	0.00E+00	0.00E+00
153	0.00E+00	0.00E+00	-6.12E-01	6.12E-01	6.12E-01	-6.12E-01	Fbn2	0.00E+00	0.00E+00
154	7.07E-01	7.07E-01	7.07E-01	7.07E-01	7.07E-01	7.07E-01	Fbn3	3.30E+01	3.00E+00
155	4.49E-02	4.49E-02	-2.25E-02	-2.25E-02	-2.25E-02	-2.25E-02	Fbn4	0.00E+00	0.00E+00
156	0.00E+00	0.00E+00	3.89E-02	3.89E-02	-3.89E-02	-3.89E-02	Fbn5	0.00E+00	0.00E+00
157	4.49E-02	-4.49E-02	4.49E-02	-4.49E-02	4.49E-02	-4.49E-02	Fbn6	0.00E+00	0.00E+00
158	Res. Forces with applied loads		Res forces with preload only						
159	fbnone	7.78	fone	0.71					
160	fbntwo	7.78	ftwo	0.71					
161	fbnthree	7.78	fthree	0.71					
162	fbnfour	7.78	ffour	0.71					
163	fbnfive	7.78	ffive	0.71					
164	fbnsix	7.78	fsix	0.71					
165	Original ball corrdinates								
166	xboneO	0.0000000	xbtwoO	-0.0549926	xbthreeO	0.0549926			
167	yboneO	0.0635000	ybtwoO	-0.0317500	ybthreeO	-0.0317500			
168	zboneO	0.0000000	zbtwoO	0.0000000	zbthreeO	0.0000000			
169	New ball coordinates (=original + ball deflection*direction cosines)								
170	xboneN	0.00000000000	xbtwoN	-0.0549926	xbthreeN	0.0549926			
171	yboneN	0.0635000	ybtwoN	-0.0317500	ybthreeN	-0.0317500			
172	zboneN	0.0000031	zbtwoN	0.0000031	zbthreeN	0.0000031			
173	Ball centers' deflections								
174	dxone	0.0000E+00	dxtwo	0.0000E+00	dxthree	0.0000E+00			
175	dyone	0.0000E+00	dytwo	0.0000E+00	dythree	0.0000E+00			
176	dzone	3.1334E-06	dztwo	3.1334E-06	dzthree	3.1334E-06			
177	Theory applicability check:								
178	Initiial dist. between balls		Final dist. between balls		Difference				
179	LotI	1.0999E-01	LotN	1.0999E-01	DLotI	0.0000E+00			
180	LttI	1.0999E-01	LttN	1.0999E-01	DLttI	0.0000E+00			
181	LtoI	1.0999E-01	LtoN	1.0999E-01	DLtoI	0.0000E+00			
182	Change in length/distance between balls			Deflection/ball radius		Ratio (should be >5)			
183	0.00E+00			4.65E-04		#DIV/0!			
184	0.00E+00			4.65E-04		#DIV/0!			
185	0.00E+00			4.65E-04		#DIV/0!			
186									
187	Coupling centroid is assumed to be at intersection of coupling triangle's angle bisectors						but if only apply load over balls, gives erroroneous		
188	Initial centroid		Distance from ball to centroid		Error motion at centroid from weighted ball r		initial theory was dzone*(LotI-Dcone)/LotI+dztwo		
189	xci	0.000000000	Dcone	0.063500000	dxc	0.00E+00	0		
190	yci	0.000000000	Dctwo	0.063500000	dyc	0.00E+00			
191	zci	0.000000000	Dcthree	0.063500000	dzc	3.13E-06			
192	Original angles between balls			Original altitude lengths					
193	Angone	############	angle at ball 1	Aone	0.0953	Ball 1 to side 2 3			
194	Angtwo	############	angle at ball 2	Atwo	0.0953	Ball 2 to side 1 3			
195	Angthree	############	angle at ball 3	Athree	0.0953	Ball 3 to side 2 1			
196	New angles between balls			Original sides' angle with X axis					
197	AngoneN	60.0000	angle at ball 1	Aot	60	Side opposite ball 3			
198	AngtwoN	60.0000	angle at ball 2	Att	0	Side opposite ball 1			
199	AngthreeN	60.0000	angle at ball 3	Ato	120	Side opposite ball 2			
200	New sides' angle with X axis								
201	AotN	60	Side opposite ball 3		0				
202	AttN	0	Side opposite ball 1		0				
203	AtoN	120	Side opposite ball 2						
204	Original altitudes' slope angles and Y intercepts								
205	AmtwoO	30	AbtwoO	0					
206	AmthreeO	150	AbthreeO	0					
207	Rotation about opposite side (radians)								
208	Ttt	3.29E-05	rotation about side 23 due to Z motion at ball 1						
209	Tto	3.29E-05	rotation about side 13 due to Z motion at ball 2						
210	Tot	3.29E-05	rotation about side 12 due to Z motion at ball 3						
211	Coupling error rotations								
212	EpsX	0.00E+00		EpsZ1	0.00E+00	Z rot from ball 1			
213	EpsY	0.00E+00		EpsZ2	0.00E+00	Z rot from ball 2			
214	EpsZ	0.00E+00		EpsZ3	0.00E+00	Z rot from ball 3			
215	Coupling HTM					Point of interest			
216	**1.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	Xerr	0			
217	**0.00E+00**	**1.00E+00**	**0.00E+00**	**0.00E+00**	Yerr	0			
218	**0.00E+00**	**0.00E+00**	**1.00E+00**	**3.13E-06**	Zerr	0			
219	**0.00E+00**	**0.00E+00**	**0.00E+00**	**1.00E+00**	1	1			
220	Error displacements at the point of interest								
221	DeltaX	0.00E+00							
222	DeltaY	0.00E+00							
223	DeltaZ	3.13E-06							
224		0							

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