Part III: Gear Systems: Analysis

This section will review standard gear systems and will provide the basic tools to perform analysis on these systems. The areas covered in this section are:

- 1) Brief history of gears
- 2) Gears 101: The geometric details about standard gears (involute)
- 3) Salient features of involute gears
- 4) Gear-tooth geometry equations
- 5) Gear train systems: fixed-axis and Planetary
- 6) Types of Gears

Brief History:

27th Century BC: Earliest recorded use of gears on Chinese "South pointing Chariot" (also first use of a differential)

4th Century BC: Aristotle gave first known written description of gears

1st Century BC: Antikythera mechanism – geared mechanism to predict the locations of stars and planets in the sky. (A planetary gear train mechanism)

Prior to 1600's: Gears did not exist in modern form

1600's: Christian Huygens proposed the involute profile

- 1600's: International Challenge to build an accurate clock for sea travel led to the development of the wrist watch, and the basis for modern gears)
- 1700's: Leonhard Euler proposed the use of involutes for gear teeth
- 1835: Hobbing process patented

Gears 101: Fundamental Law of Gearing

"Angular velocity ratio between gears must remain constant throughout their mesh"

Why?

Constant velocity transmission \rightarrow no accelerations generated in transfer of motion (i.e., no forces) No speed or torque variations Kinematic requirement for constant velocity:

Consider two bodies connected with a higher pair joint. For constant velocity, the line of action and line of centers must intersect at a constant location:



Notes:

- 1) A common Normal and tangent (N, t) exist and are defined by the 2 surfaces
- 2) "Condition of contact": no relative motion can occur along the common normal
- 3) All sliding takes place along the common tangent
- 4) The result of these rules (plus some geometric construction not shown here):

$$\frac{\omega_3}{\omega_2} = \frac{O_2 K}{O_3 K}$$

5) Requirement for constant velocity:

6) Requirement for no sliding:

In summary:

Fundamental law of gearing \rightarrow

Rules for all Gears:

$$GR = m_{v} = \frac{\omega_{o}}{\omega_{i}} = \pm \frac{r_{i}}{r_{o}} = \pm \frac{N_{i}}{N_{o}}$$

Gears 102: Details about the involute gear profile:

A number options are available to satisfy the fundamental law of gearing, but the involute is preferred because of many special properties (to be discussed).



2) Consider two bodies to be connected with gears. Do the following:

1) First, represent these as base circles (the base of the teeth).

2) Create a line connecting their centers, this is constant.

3) create a line that will intersect the line of centers at a constant point. Choose a common tangent between the circles to do this. (note, as bodies rotate, this line is constant)4) note that if this line is the common normal of the gear teeth, than it would satisfy the law of

gearing.

5) Define your gear teeth such that their surface is perpendicular to this line (as they rotate).

6) Rotate the base circle to generate the tooth surface as an Involute profile.



See Wikipedia, involute gear for animation

3) A primary advantage of the Involute profile:

- 1. Velocity ratio of gears in mesh is constant
- 2. Velocity ratio is independent of center distance (just like belts and pulleys).
- 3. Line of Action: tangent to the base circles, all tooth contact takes place on this line.
- 4. Involutes conjugate to themselves

Gears 103: Gear tooth Terminology:

Based on this involute geometry of gear teeth, the geometry of a gear can be standardized and named, as in the following figures.







From khk gears (note, in module)

So gear teeth are involutes, is the entire surface of the gear tooth an involute?

Three cases:

1) all of the gear tooth is an involute (if $R_d > R_b$)

2) part of the gear tooth is involute, part is a straight line $(R_b > R_d)$

3) part of the gear tooth is involute, and part is undercut (see figure below).



Why is a gear tooth undercut?

Involutes apply to all gear types:

Consider helical gear



14½ degree Pressure Angle20 and 25 degree Pressure AnglesAddendum, a $a = \frac{1.0}{P}$ $a = \frac{1.0}{P}$ $a = \frac{1.0}{P}$ Addendum, a $a = \frac{1.0}{P}$ $a = \frac{1.0}{P}$ $a = \frac{1.0}{P}$ Dedendum, b $b = \frac{1.157}{P}$ $b = \frac{1.250}{P}$ Pitch diameter, D $D = \frac{N}{P}$ $D = \frac{N}{P}$ Outside diameter, $D_o = \frac{N+2}{P}$ $D_o = \frac{N+2}{P}$ Number of teeth, N $N = D \times P$ $N = D \times P$ Tooth thickness, t $t = \frac{1.5708}{P}$ $t = \frac{1.5708}{P}$ Whole depth, h_t $h_t = \frac{2.157}{P}$ $h_t = \frac{2.250}{P}$ Clearance, c $c = \frac{.157}{P}$ $c = \frac{.250}{P}$ Center distance, C $C = \frac{N_1 + N_2}{2 \times P}$ $C = \frac{N_1 + N_2}{2 \times P}$ Working depth, h_k $h_k = \frac{2}{P}$ $h_k = \frac{2}{P}$ Chordal tooth thickness, t_c $t_c = D \sin\left(\frac{90 \text{ degrees}}{N}\right)$ $t_c = D \sin\left(\frac{90 \text{ degrees}}{N}\right)$ Chordal addendum, a_c $a_c = a + \frac{t^2}{4D}$ $P = \frac{N}{D}$ Center distance, C $C = \frac{D_1 + D_2}{D}$ $P = \frac{N}{D}$ Chordal addendum, a_c $a_c = a + \frac{t^2}{4D}$ $P = \frac{N}{D}$		Spur Gear Formulas	
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Center distance, C $C = \frac{D_1 + D_2}{2}$ $C = \frac{D_1 + D_2}{2}$	Diametral pitch, P	$P = \frac{N}{D}$	$P = \frac{N}{D}$
	Center distance, C	$C = \frac{D_1 + D_2}{2}$	$C = \frac{D_1 + D_2}{2}$

0 0 P 1

Salient Features of Involute Gears:

- 5. Velocity ratio of gears in mesh is constant and independent of center distance (just like belts and pulleys).
- 6. Line of Action: tangent to the base circles, all tooth contact takes place on this line.
- 7. Interference points: points where line of action meets the base circles.
- 8. If contact occurs outside the interference points, interference will occur between the gears.
- 9. A gear that can mesh with a rack with out undercutting can mesh with any other gear of equal or greater size without undercutting.
- 10. Standard gears with the same diametral pitch and same pressure angle are interchangeable.
- 11. Contact ratio, mp, is the average number of teeth in contact (in design, 1.2 is a minimum, the larger the better).
- 12. A rack is a gear with infinite diameter. On a rack, the involute becomes a straight line.
- 13. Common gear cutters: Hobs, and Shapers. Hobs act like a bit in a milling machine. Shapers have a translating cutting stroke.
- 14. The type of cutter determines the minimum number of teeth possible with out undercutting. The hob represents the worst case, since it is like a rack. For a gear cut with a shaper, the minimum number of teeth may be given by the shaper, if N of the shaper is known.
- 15. Salient: (sa' li-ent) *adj.* Standing out from the rest; noticeable; conspicuous; prominent. (Webster's, College Ed.)

Details of Involute Gears

<u>1. Equations not found in Norton:</u> (Refer to Fig. 1)

Base pitch (distance between one tooth set measured along base circle):

$$p_b = \frac{2\pi R_b}{N} \tag{1}$$

Length of action:

$$Z = \sqrt{R_{o1}^2 - R_{b1}^2} + \sqrt{R_{o2}^2 - R_{b2}^2} - C\sin(\phi)$$
(2)

Contact ratio (average number of teeth in contact):

$$m_p = \frac{Z}{p_b} \tag{3}$$

Diametral Pitch (number of teeth per inch):

$$P_d = \frac{N}{D} \tag{4}$$

Module (mm per tooth):

$$m = \frac{D(mm)}{N} \tag{5}$$

Minimum number of teeth to avoid interference: (*k*=1 for full depth teeth)

a) for a rack:

$$N = \frac{2k}{\sin^2(\phi)} \tag{6}$$

$$N_1^2 + 2N_2N_1 - \frac{4k}{\sin^2(\phi)}(N_2 + k) = 0$$
(7)

Center distance:

$$C = R_1 + R_2 = \frac{N_1 + N_2}{2P_d}$$
(8)

"operating" center distance and pressure angle:

$$C'\cos(\phi') = C\cos(\phi) \tag{9}$$

Backlash resulting from an increased operating center distance:

$$B = 2C'(inv(\phi') - inv(\phi)), \quad inv(\phi) = \tan(\phi) - \phi$$
(10)

Tooth thickness: (requires the tooth thickness at some radius to be known, generally at the pitch circle):

$$t_B = 2R_B \left[\frac{t_A}{2R_A} + inv(\phi_A) - inv(\phi_B) \right]$$
(11)

Radius and angle at various points along the involute:

$$R_b = R_A \cos(\phi_A) = R_B \cos(\phi_B) = R \cos(\phi) \tag{12}$$

Concept questions:

1. 2 gears are in mesh, 20deg. Pressure angle, pitch = 6, N1 = 24, N2 = 48, transmitting a torque. What is the ratio of the radial force on the bearings to the tangential force between the gears.

Gear-Train Systems:

Gears are used in combinations to create a desired torque/velocity ratio. Combinations of gears can be divided into two classes: Fixed-axis gear trains, and planetary gear trains.

Fixed-axis gear trains:

The sign change occurs for external gears. The diameters listed are the pitch diameters.



In this arrangement, the intermediate gears do not affect the overall velocity ratio, and therefore should be replaced with a more cost effective means of power transmission. Only the outer two gears are useful in achieving the desired velocity ratio. Since the velocity ratio of a single gear set is practically limited to 10:1 or less (actually, more like 5:1 greater), compound gears (two gears constrained to have the same angular velocity) are used in gears trains to achieve larger velocity ratios:







Gear train design:

Gear train synthesis or design is the process of selecting the design parameters in a gear train system to meet desired objectives. A portion of these are basic criteria for the design of gear-trains, and a portion of these objectives can be stated as constraints that exist as functions of the design parameters. First, the basic criteria:

- 1) Gears in mesh must have the same p_d , ϕ
- 2) Generally, all gears within a gear train will have the same p_d , ϕ (but this is preference only, not a requirement.
- 3) All gear teeth must be integer values, greater than a min. value, (perhaps stock size)

Next, the functional requirements:

- 1) Gear ratio
- 2) center distance requirements on gears
- 3) reverted gear train
- 4) relative direction of input/output

Design procedure

1) Select the number of stages

2) List the functional requirements as equations. Combine n equations to eliminate n design parameters

3) Solve for remaining design parameters

#	Requirement	Example	reference
1	Gear ratio	$m_{\nu} = \frac{N_3 N_5}{N_2 N_4}$	2-stage train
2	Center distance	$C_1 = R_2 + R_3 = \frac{N_2 + N_3}{2p_d}$	
3	Center distance	$C_2 = R_4 + R_5 = \frac{N_4 + N_5}{2p_d}$	
4	Reverted (equal center distance)	$C_{1} = C_{2}$ $\frac{N_{2} + N_{3}}{2p_{d}} = \frac{N_{4} + N_{5}}{2p_{d}}$ $N_{2} + N_{3} = N_{4} + N_{5}$	

Functional requirements on a Gear train:

#	Туре	Design parameters	reference
1	2 stage	4	
		$N_2, N_3 N_4, N_5$	
2	3 stage	6	
	8 stage		бен В лей Ф Ф Ф Ф Ф

Example: Design a gear mechanism to drive the hour/minute hands of a clock. Assume the minute hand is input, hour hand is output and input/output are inline. Select gears assuming p_d is 24 and find nominal center distance.



	Gear train	Design spr	eadsheet												
	Spreadshe	et for 4-ge	ar 2-stage	reverted to	rain		Gear Ratic	60							
NC (down	NF (across)	ur z stuge	reventeuro											
		, Table of N	Δ												
	60		۳ ۵	72	76	00	04	00	02	06	100	104	100	112	116
10	E 529462	C 204092	00	7 (2)(2)(4)	0 40201	00	10 02005	10 20100	11 70225	12 70599	12 (5054	14 C4070	100	10 00001	17 7077
12	5.538402	6.204082	0.903553	7.030304	8.40201	9.2	10.02985	10.89109	11.78325	12.70588	13.05854	14.04078	15.05217	10.09231	17.70077
13	5.214286	5.838863	6.495283	7.183099	7.901869	8.651163	9.430556	10.23963	11.07798	11.94521	12.84091	13.76471	14./1622	15.69507	16.70089
14	4.933333	5.522124	6.140969	6.789474	7.467249	8.173913	8.909091	9.672414	10.46352	11.28205	12.12766	13	13.89873	14.82353	15.77406
15	4.6875	5.244813	5.830579	6.444444	7.086066	7.755102	8.45122	9.174089	9.923387	10.6988	11.5	12.32669	13.17857	14.05534	14.95669
16	4.470588	5	5.55642	6.139535	6.749035	7.384615	8.045977	8.732824	9.444867	10.18182	10.9434	11.72932	12.53933	13.37313	14.23048
17	4.277778	4.782288	5.3125	5.868132	6.448905	7.054545	7.684783	8.33935	9.017986	9.72043	10.44643	11.19573	11.96809	12.76325	13.58099
18	4.105263	4.587413	5.094077	5.625	6.179931	6.758621	7.360825	7.986301	8.634812	9.306122	10	10.71622	11.45455	12.21477	12.99666
19	3,95	4,41196	4,897351	5,405941	5,9375	6,491803	7.068627	7.667752	8,288961	8,932039	9,596774	10.28296	10,99038	11.71885	12,46815
20	3 809524	1 253165	1 7192/3	5 207547	5 717868	6.25	6 803738	7 378882	7 975232	8 502503	9 230769	9 889571	10 56881	11 26829	11 9878/
20	3.003324	4.233103	4.719243	5.207347	5.717000	C 0200F1	0.003730	7.370002	7.00240	0.392393	9.230709	0.520702	10.30001	10.05714	11.50704
21	3.081818	4.108/01	4.557229	5.027027	5.51/904	6.029851	0.5025	7.115/2/	7.089349	8.283180	8.897059	9.530792	10.18421	10.85714	11.54942
22	3.56521/	3.976879	4.409222	4.862069	5.335244	5.8285/1	6.34188	6.875	7.427762	8	8.591549	9.202247	9.831933	10.48045	11.14/63
23	3.458333	3.855956	4.273481	4.710744	5.167582	5.643836	6.139344	6.653951	7.1875	7.739837	8.310811	8.90027	9.508065	10.13405	10.77807
24	3.36	3.744681	4.148541	4.571429	5.013193	5.473684	5.952756	6.450262	6.966057	7.5	8.051948	8.621762	9.209302	9.814433	10.43702
25	3.269231	3.641944	4.033163	4.442748	4.870558	5.316456	5.780303	6.261965	6.761307	7.278195	7.8125	8.36409	8.932836	9.51861	10.12129
26	3.185185	3.546798	3.92629	4.323529	4.738386	5.170732	5.620438	6.087379	6.571429	7.072464	7.590361	8.125	8.676259	9.244019	9.828162
		table of NE	3												
	60	64	68	72	76	80	84	88	92	96	100	104	108	112	116
12	66 46154	60 70502	72 00645	76 26264	70 50700	92.9	95 07015	90 10901	02 21675	05 20/12	08 2/1/6	101 2502	104 2479	107 2077	110 2202
12	00.40134	71 10114	73.09043	70.30304	01.00012	04.24004	07.50044	00 7007	02.02202	07.05470	100 1001	101.3352	104.3478	100.2040	112 2001
13	67.78571	/1.16114	74.50472	//.8169	81.09813	84.34884	87.56944	90.76037	93.92202	97.05479	100.1591	103.2353	106.2838	109.3049	112.2991
14	69.06667	/2.4//88	/5.85903	/9.21053	82.532/5	85.82609	89.09091	92.32/59	95.53648	98./1/95	101.8/23	105	108.1013	111.1/65	114.2259
15	70.3125	73.75519	77.16942	80.55556	83.91393	87.2449	90.54878	93.82591	97.07661	100.3012	103.5	106.6733	109.8214	112.9447	116.0433
16	71.52941	75	78.44358	81.86047	85.25097	88.61538	91.95402	95.26718	98.55513	101.8182	105.0566	108.2707	111.4607	114.6269	117.7695
17	72.72222	76.21771	79.6875	83.13187	86.55109	89.94545	93.31522	96.66065	99.98201	103.2796	106.5536	109.8043	113.0319	116.2367	119.419
18	73.89474	77.41259	80.90592	84.375	87.82007	91.24138	94.63918	98.0137	101.3652	104.6939	108	111.2838	114.5455	117.7852	121.0033
19	75.05	78,58804	82,10265	85,59406	89.0625	92,5082	95,93137	99.33225	102,711	106.068	109,4032	112,717	116.0096	119,2812	122,5318
20	76 19048	79 74684	83 28076	86 79245	90 28213	93 75	97 19626	100 6211	104 0248	107 4074	110 7692	114 1104	117 4312	120 7317	124 0122
20	77 21010	00.00134	04 44277	07.07207	01 40204	04 07015	00 4275	101.0042	105 2107	100 7100	112 1020	117.1104	110.0100	122.1420	125.4500
21	77.31818	80.89124	84.44277	87.97297	91.48204	94.97015	98.4375	101.8843	105.3107	108.7108	112.1029	115.4692	118.8158	122.1429	125.4500
22	/8.434/8	82.02312	85.59078	89.13793	92.66476	96.17143	99.65812	103.125	106.5722	110	113.4085	116.7978	120.1681	123.5196	126.8524
23	79.54167	83.14404	86.72652	90.28926	93.83242	97.35616	100.8607	104.346	107.8125	111.2602	114.6892	118.0997	121.4919	124.866	128.2219
24	80.64	84.25532	87.85146	91.42857	94.98681	98.52632	102.0472	105.5497	109.0339	112.5	115.9481	119.3782	122.7907	126.1856	129.563
25	81.73077	85.35806	88.96684	92.55725	96.12944	99.68354	103.2197	106.738	110.2387	113.7218	117.1875	120.6359	124.0672	127.4814	130.8787
26	82.81481	86.4532	90.07371	93.67647	97.26161	100.8293	104.3796	107.9126	111.4286	114.9275	118.4096	121.875	125.3237	128.756	132.1718
	Gear train	Design spr	eadsheet												
	Gear train Spreadshe	Design spr et for 4-ge	eadsheet ar 2-stage	reverted t	rain		Gear Ratic	12							
NC (down	Gear train Spreadshe NE (across	Design spr et for 4-ge)	eadsheet ar 2-stage	reverted t	rain		Gear Ratic								
NC (down	Gear train Spreadshe NE (across	Design spr et for 4-ge) Table of N	eadsheet ar 2-stage A	reverted t	rain		Gear Ratic	12							
NC (down	Gear train Spreadshe NE (across	Design spr et for 4-ge) Table of N. 64	eadsheet ar 2-stage A 68	reverted to	rain 76	80	Gear Ratic	12	92	96	100	104	108	112	116
NC (down	Gear train Spreadshe NE (across 60 21 17647	Design spr et for 4-ge) Table of N. 64 23 38462	eadsheet ar 2-stage A 68 25 66038	reverted to	rain 76 30 4	80	Gear Ratic 84	12 88 37 93103	92 40 54237	96 43.2	100 45 90164	104 48 64516	108 51 42857	112 54 25	116
NC (down 12	Gear train Spreadshe NE (across 60 21.17647 20.27778	Design spr et for 4-ge) Table of N. 64 23.38462 22.4	eadsheet ar 2-stage A 25.66038 24.58929	reverted to 72 28	rain 76 30.4	80 32.85714	Gear Ratic 84 35.36842 22.05	12 88 37.93103 26.42623	92 40.54237 28.95161	96 43.2	100 45.90164 44.14063	104 48.64516 46.8	108 51.42857 49.5	112 54.25	116 57.10769
NC (down 12 13	Gear train Spreadshe NE (across 60 21.17647 20.27778	Design spr et for 4-ge) Table of N. 64 23.38462 22.4	eadsheet ar 2-stage A 25.66038 24.58929	reverted to 72 28 26.84211	rain 76 30.4 29.15517	80 32.85714 31.52542	Gear Ratic 84 35.36842 33.95	12 88 37.93103 36.42623	92 40.54237 38.95161	96 43.2 41.52381	100 45.90164 44.14063	104 48.64516 46.8	108 51.42857 49.5	112 54.25 52.23881	116 57.10769 55.01471
NC (down 12 13 14	Gear train Spreadshe NE (across 60 21.17647 20.27778 19.47368	Design spr et for 4-ge) Table of N. 64 23.38462 22.4 21.51724	eadsheet ar 2-stage A 25.66038 24.58929 23.62712	reverted to 72 28 26.84211 25.8	rain 76 30.4 29.15517 28.03279	80 32.85714 31.52542 30.32258	Gear Ratic 84 35.36842 33.95 32.66667	12 88 37.93103 36.42623 35.0625	92 40.54237 38.95161 37.50769	96 43.2 41.52381 40	100 45.90164 44.14063 42.53731	104 48.64516 46.8 45.11765	108 51.42857 49.5 47.73913	112 54.25 52.23881 50.4	116 57.10769 55.01471 53.09859
NC (down 12 13 14 15	Gear train Spreadshe NE (across 60 21.17647 20.27778 19.47368 18.75	Design spr et for 4-ge) Table of N. 64 23.38462 22.4 21.51724 20.72131	eadsheet ar 2-stage A 25.66038 24.58929 23.62712 22.75806	reverted to 72 28 26.84211 25.8 24.85714	rain 76 30.4 29.15517 28.03279 27.01563	80 32.85714 31.52542 30.32258 29.23077	Gear Ratic 84 35.36842 33.95 32.66667 31.5	12 88 37.93103 36.42623 35.0625 33.8209	92 40.54237 38.95161 37.50769 36.19118	96 43.2 41.52381 40 38.6087	100 45.90164 44.14063 42.53731 41.07143	104 48.64516 46.8 45.11765 43.57746	108 51.42857 49.5 47.73913 46.125	112 54.25 52.23881 50.4 48.71233	116 57.10769 55.01471 53.09859 51.33784
NC (down 12 13 14 15 16	Gear train Spreadshe NE (across 60 21.17647 20.27778 19.47368 18.75 18.09524	Design spr et for 4-ge) Table of N. 64 23.38462 22.4 21.51724 20.72131 20	eadsheet ar 2-stage A 25.66038 24.58929 23.62712 22.75806 21.96923	reverted to 72 28 26.84211 25.8 24.85714 24	rain 76 30.4 29.15517 28.03279 27.01563 26.08955	80 32.85714 31.52542 30.32258 29.23077 28.23529	Gear Ratic 84 35.36842 33.95 32.66667 31.5 30.43478	12 88 37.93103 36.42623 35.0625 33.8209 32.68571	92 40.54237 38.95161 37.50769 36.19118 34.98592	96 43.2 41.52381 40 38.6087 37.33333	100 45.90164 44.14063 42.53731 41.07143 39.72603	104 48.64516 46.8 45.11765 43.57746 42.16216	108 51.42857 49.5 47.73913 46.125 44.64	112 54.25 52.23881 50.4 48.71233 47.15789	116 57.10769 55.01471 53.09859 51.33784 49.71429
NC (down 12 13 14 15 16 17	Gear train Spreadshe NE (across 60 21.17647 20.27778 19.47368 18.75 18.09524 17.5	Design spr et for 4-ge) Table of N. 64 23.38462 22.4 21.51724 20.72131 20 19.34328	eadsheet ar 2-stage A 25.66038 24.58929 23.62712 22.75806 21.96923 21.25	reverted to 72 28 26.84211 25.8 24.85714 24 23.21739	rain 76 30.4 29.15517 28.03279 27.01563 26.08955 25.24286	80 32.85714 31.52542 30.32258 29.23077 28.23529 27.32394	Gear Ratic 84 35.36842 33.95 32.66667 31.5 30.43478 29.45833	12 88 37.93103 36.42623 35.0625 33.8209 32.68571 31.64384	92 40.54237 38.95161 37.50769 36.19118 34.98592 33.87838	96 43.2 41.52381 40 38.6087 37.33333 36.16	100 45.90164 44.14063 42.53731 41.07143 39.72603 38.48684	104 48.64516 46.8 45.11765 43.57746 42.16216 40.85714	108 51.42857 49.5 47.73913 46.125 44.64 43.26923	112 54.25 52.23881 50.4 48.71233 47.15789 45.72152	116 57.10769 55.01471 53.09859 51.33784 49.71429 48.2125
NC (down 12 13 14 15 16 17 18	Gear train Spreadshe NE (across 0 21.17647 20.27778 19.47368 19.47368 18.75 18.09524 17.5 16.95652	Design spr et for 4-ge) Table of N. 64 23.38462 22.4 21.51724 20.72131 20 19.34328 18.74286	eadsheet ar 2-stage A 25.66038 24.58929 23.62712 22.75806 21.96923 21.25 20.59155	reverted to 72 28 26.84211 25.8 24.85714 24 23.21739 22.5	rain 76 30.4 29.15517 28.03279 27.01563 26.08955 25.24286 24.46575	80 32.85714 31.52542 30.32258 29.23077 28.23529 27.32394 26.48649	Gear Ratic 84 35.36842 33.95 32.66667 31.5 30.43478 29.45833 28.56	12 88 37.93103 36.42623 35.0625 33.8209 32.68571 31.64384 30.68421	92 40.54237 38.95161 37.50769 36.19118 34.98592 33.87838 32.85714	96 43.2 41.52381 40 38.6087 37.33333 36.16 35.07692	100 45.90164 44.14063 42.53731 41.07143 39.72603 38.48684 37.34177	104 48.64516 46.8 45.11765 43.57746 42.16216 40.85714 39.65	108 51.42857 49.5 47.73913 46.125 44.64 43.26923 42	112 54.25 52.23881 50.4 48.71233 47.15789 45.72152 44.39024	116 57.10769 55.01471 53.09859 51.33784 49.71429 48.2125 46.81928
NC (down 12 13 14 15 16 17 18 19	Gear train Spreadshe NE (across 60 21.17647 20.27778 19.47368 18.09524 17.5 16.95652 16.45833	Design spr et for 4-ge) Table of N. 64 23.38462 22.4 21.51724 20.72131 20 19.34328 818.74286 18.19178	eadsheet ar 2-stage A 25.66038 24.58929 23.62712 22.75806 21.96923 21.959155 20.59155 19.98649	reverted ti 72 28 26.84211 25.8 24.85714 24 23.21739 22.5 21.84	rain 76 30.4 29.15517 28.03279 27.01563 26.08955 25.24286 24.46575 23.75	80 32.85714 31.52542 30.32258 29.23077 28.23529 27.32394 26.48649 25.71429	Gear Ratic 84 35.36842 33.95 32.66667 31.5 30.43478 29.45833 28.56 27.73077	88 37.93103 36.42623 35.0625 33.8209 32.68571 31.64384 30.68421 29.79747	92 40.54237 38.95161 37.50769 36.19118 34.98592 33.87838 32.85714 31.9125	96 41.52381 40 38.6087 37.3333 36.16 35.07692 34.07407	100 45.90164 44.14063 42.53731 41.07143 39.72603 38.48684 37.34177 36.28049	104 48.64516 46.8 45.11765 43.57746 42.16216 40.85714 39.65 38.53012	108 51.42857 49.5 47.73913 46.125 44.64 43.26923 42 40.82143	112 54.25 52.23881 50.4 48.71233 47.15789 45.72152 44.39024 43.315294	116 57.10769 55.01471 53.09859 51.33784 49.71429 48.2125 46.81928 45.52326
NC (down 12 13 14 15 16 17 18 19 200	Gear train Spreadshe NE (across 60 21.17647 20.27778 19.47368 18.75 18.09524 17.5 16.95652 16.45833 16	Design spr et for 4-ge) Table of N 64 23.38462 22.4 21.51724 20.72131 20 19.34328 18.74286 18.19178	eadsheet ar 2-stage 68 25.66038 24.58929 23.62712 22.75806 21.96923 21.25 20.59155 19.98649 19.98649	reverted ti 72 28 26.84211 25.8 24.85714 24 23.21739 22.5 21.84 21.2307	rain 76 30.4 29.15517 28.03279 27.01563 26.08955 25.24286 24.46575 23.75 23.75 23.75 23.08861	80 32.85714 31.52542 30.32258 29.23077 28.23529 27.32394 26.48649 25.71429 25.71429	Gear Ratic 84 35.36842 33.95 32.66667 31.5 30.43478 29.45833 28.56 27.73077 26.96796	88 37.93103 36.42623 35.0625 33.8209 32.68571 31.64384 30.68421 29.979747	92 40.54237 38.95161 37.50769 36.19118 34.98592 33.87838 32.85714 31.9125 31.03614	96 43.2 41.52381 40 38.6087 37.3333 36.16 35.07692 34.07407 33,14286	100 45.90164 44.14063 42.53731 41.07143 39.72603 38.48684 37.34177 36.28049 35.29412	104 48.64516 46.8 45.11765 43.57746 42.16216 40.85714 39.65 38.53012	108 51.42857 49.5 47.73913 46.125 44.64 43.26923 42 40.82143 39.72414	112 54.25 52.23881 50.4 48.71233 47.15789 45.72152 44.39024 43.15294 43.15294	116 57.10769 55.01471 53.09859 51.33784 49.71429 48.2125 46.8128 45.52326
NC (down 12 13 14 15 16 17 18 19 20 21	Gear train Spreadshe NE (across 60 21.17647 20.27778 19.47368 18.09524 17.5 16.95652 16.45833 16 15.57602	Design spr et for 4-ge) Table of N 64 23.38462 22.4 20.72131 20 19.34328 18.74286 18.19178 17.68421 17.21510	eadsheet ar 2-stage A 25.66038 24.58929 23.62712 22.75806 21.96923 21.25 20.59155 19.98649 19.42857 18.9125	reverted ti 72 28 26.84211 25.8 24.85714 24 23.21739 22.5 21.84 21.23077 20 66667	rain 76 30.4 29.15517 28.03279 27.01563 26.08955 25.24286 24.46575 23.75 23.08861 22.42561	80 32.85714 31.52542 30.32258 29.23077 28.23529 27.32394 26.48649 25.71429 25.71429 25.43275 24.33755	Gear Ratic 84 35.36842 33.95 32.66667 31.5 30.43478 29.45833 28.56 27.73077 26.96296 26.25	12 88 37.93103 36.42623 35.0625 33.8209 32.68571 31.64384 30.68421 29.79747 28.97561 28.97561	92 40.54237 38.95161 37.50769 36.19118 34.98592 33.87838 32.85714 31.03614 31.03614	96 43.2 41.52381 40 38.6087 37.3333 36.16 35.07692 34.07407 33.14286 32.27586	100 45.90164 44.14063 42.53731 41.07143 39.72603 38.48684 37.34177 36.28049 35.29412 36.29412	104 48.64516 46.8 45.11765 43.57746 42.16216 40.85714 39.65 38.53012 37.48837 36.51685	108 51.42857 49.5 47.73913 46.125 44.64 43.26923 42 40.82143 39.72414 38.7	112 54.25 52.23881 50.4 48.71233 47.15789 45.72152 44.39024 43.15294 42 40.92308	116 57.10769 55.01471 53.09859 51.33784 49.71429 48.2125 46.81928 45.5226 44.31461 43.318478
NC (down 12 13 14 15 16 17 18 19 20 20 21	Gear train Spreadshe NE (across 60 21.17647 20.27778 19.47368 18.09524 17.5 16.95652 16.45833 16 15.57692	Design spr et for 4-ge) Table of N. 64 23.38462 22.4 20.72131 20 19.34328 18.74286 18.19178 17.68421 17.21519	eadsheet ar 2-stage 4 55.66038 24.58929 23.62712 22.75806 21.96923 21.25 20.59155 19.98649 19.42857 18.9125 18.42327	reverted ti 72 28 26.84211 25.8 24.85714 23.21739 22.5 21.84 21.23077 20.6667 20.14965	rain 76 30.4 29.15517 28.03279 27.01563 26.08955 25.24286 24.46575 23.08861 22.47561 21.0055	80 32.85714 31.52542 30.32258 29.23077 28.23529 27.32394 26.48649 25.71429 25 24.33735 23.72000	Gear Ratic 84 35.36842 33.95 32.66667 31.5 30.43478 29.45833 28.56 27.73077 26.96296 26.25 25.55 25.55	12 88 37.93103 36.42623 35.0625 33.8209 32.68571 31.64384 30.68421 29.79747 28.97561 28.21176	92 40.54237 38.95161 37.50769 36.19118 34.98592 33.87838 32.85714 31.9125 31.03614 30.22093 20.46657	96 43.2 41.52381 40 38.6087 37.3333 36.16 35.07692 34.07407 33.14286 32.27586	100 45.90164 44.14063 42.53731 41.07143 39.72603 38.48684 37.34177 36.28049 35.29412 34.375 33.51640	104 48.64516 46.8 45.11765 43.57746 42.16216 40.85714 39.65 38.53012 37.4837 36.51685	108 51.42857 49.5 47.73913 46.125 44.64 43.26923 42 40.82143 39.72414 37.7414	112 54.25 52.23881 50.4 48.71233 47.15789 45.72152 44.39024 43.15294 42.92018 42.92018	116 57.10769 55.01471 53.09859 51.33784 49.71429 48.2125 46.81928 45.52326 44.31461 43.18461 43.1847
NC (down 12 13 14 15 16 17 18 19 20 21 22	Gear train Spreadshe NE (across 60 21.17647 20.27778 19.47368 18.09524 17.5 16.95652 16.45833 16 15.57692 15.18519	Design spr et for 4-ge) Table of N. 64 23.38462 22.4 21.51724 20.72131 20 0 19.34328 18.74286 18.19178 17.68421 17.21519 16.7809	eadsheet ar 2-stage 4 25.66038 24.58929 23.62712 22.75806 21.96923 21.25 20.59155 19.98649 19.42857 18.43373 12.2025	reverted ti 72 28 26.84211 25.8 24.85714 24 23.21739 22.5 21.84 21.23077 20.66667 20.14286	rain 76 30.4 29.15517 28.03279 27.01563 26.08955 25.24286 24.46575 23.08861 22.47561 21.90588	80 32.85714 31.52542 30.32258 29.23077 28.23529 27.32394 26.48649 25.71429 25 24.33735 23.72092	Gear Ratic 84 35.36842 33.95 32.6667 31.5 30.43478 29.45833 28.56 27.73077 26.96296 26.25 25.58621	88 37.93103 36.42623 35.0625 33.8209 32.68571 31.64384 30.68421 29.79747 28.97561 28.21176 27.5	92 40.54237 38.95161 37.50769 36.19118 34.98592 33.87838 32.85714 31.9125 31.03614 30.22093 29.46067	96 43.2 41.52381 40 38.6087 37.3333 36.16 35.07692 34.07407 33.14286 32.27586 31.4665 31.4655	100 45.90164 44.14063 42.53731 41.07143 39.72603 38.48684 37.34177 36.28049 35.29412 33.5164 33.5164 33.2145	104 48.64516 46.8 45.11765 43.57746 42.16216 40.85714 39.65 38.53012 37.48837 36.51685 35.6687	108 51.42857 49.5 47.73913 46.125 44.64 43.26923 42 40.82143 39.72414 38.7 37.74194	112 54.25 52.23881 50.4 48.71233 47.15789 45.72152 44.39024 43.15294 40.92308 39.91489 29.0000	116 57.10769 55.01471 53.09859 51.33784 49.71429 48.2125 46.81928 45.52326 44.31461 43.18478 42.12632 41.12032
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Gear	RPM at Transmission Ratio Output Shaft with Engi at 3,000 rpm					
1st	2.315:1	1,295				
2nd	1.568:1	1,913				
3rd	1.195:1	2,510				
4th	1.000:1	3,000				
5th	0.915:1	3,278				

Select pd and tooth numbers. What is efficiency assuming Eo = 0.95?



Planetary Gear Trains:

A Planetary gear train (see Fig. below) results when certain gears in the train (called the planet gears) have moving axes. The arm, while not a gear, is an essential part of the planetary because it defines the motion of the moving planet gear axes. The planetary is also unique to a standard gear train in that it requires two inputs to define one output (verify this using mobility). A good example is your car's differential, which has two inputs: one the drive-shaft, and the second a constraint between the two driven wheels provided by whatever you are driving on (e.g. dry pavement, one wheel on ice, etc.)



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Planetary Gear Equation:

The planetary gear train equation must be used to solve the angular velocities of elements in the planetary. The equation is:



Given this gear train, find the speed and direction of the drum. What is train efficiency for $E_0 = 0.97$ (Norton 9-35).



Given the planetary gear train above with inputs, what is the velocity of ring gear D?



Given the planetary gear train above with inputs: Arm CCW at 50 rpm and gear A fixed to ground, find the speed of gear D. (Norton 9-37),



This is a schematic of an automotive differential. Notice that this is a planetary gear train. Assume that the engine is being driven at 2000 rpm, the transmission is in 4^{th} gear (direct drive, 1:1 ratio) to the driveshaft.

Gears 4,5,6,7 = 15 teeth, Gear 3 = 43 teeth, Gear 2 = 12 teeth, rear wheels = 40.64 cm

- 1) Assuming the vehicle is traveling straight down the road, what is its velocity
- 2) Vehicle is stuck in the mud, (right wheel in slippery mud, left wheel on firm pavement), what is speed of left and right wheel.
- 3) Turn the engine off, jack up the car, turn the left wheel + 1 rpm, what is right wheel speed?



Shaft 1 is input, find velocity of gear M.

Choosing *f*, *l*, and *a*:

Choosing elements for the first, last, and arm is the first step in solving a planetary. Solving will fall into one of the three following scenarios (remember that you must know two pieces of information to solve the planetary equation).

case i You want to find the arm velocity, (wa is not known) knowing the velocity of two gears: Choose f and l as the two known gears, and the arm as a, an unknown. Solve for *wa*.

case ii You want to find the velocity of a gear, and you know the velocity of the arm and one other gear:

Choose I as the desired unknown gear, choose f as the known gear and a as the known arm. Solve for *wl*.

case iii You want to find the velocity of a gear, and you know the velocity of two gears but not the arm.

First, choose f and l as the known gears and solve the arm velocity, wa. Then go to case ii.

Mixed Gear trains:

A general gear train can include both fixed axis and planetary gear trains, or multiple planetaries. Solving systems like these requires using the procedures outlined above and looking for elements that share the same angular velocity between the mixed gear trains.

Gear Types:

A gear train consists of one or more gear sets intended to give a specific velocity ratio, or change direction of motion. Gear and gear train types can be grouped based on their application and tooth geometry.

Categories of Gears	Types of Gears	Efficiency (%)	Isometrics
Parallel Axis Gears	Spur Gear		Contraction of the second
3h	Helical Gear		Õ
	Rack • Helical Rack	90.0 99.5	CONTRACTOR OF STREET
\rightarrow	Internal Gear		
Intersecting Axis Gears	Miter Gear		
90"	Straight Bevel Gear	98.0–99.0	
	Spiral Bevel Gear		
Nonparallel and Nonintersecting Axis Gears	Screw Gear (Crossed Helical Gear)	70.0–95.0	
22	Worm	30.0-90.0	
	Worm Wheel	50.0 90.0	

Table I: Gear Types Grouped According to Shaft Arrangement

(from khkgears.co.jp)

Spur gears (Fig. 1): Spur gears connect parallel shafts, have involute teeth that are parallel to the shafts, and can have either internal or external teeth. Notes:

FIGURE 4.1 Spur gears. (Courtesy of Philadelphia Gear Works.)

1. 2. . 3. **Helical gears** (Fig. 2): Helical gears also connect parallel shafts, but the involute teeth are cut at an angle (called the helix angle) to the axis of rotation. Note that two mating helical gears must have equal helix angle but opposite hand. These are found in automotive transmissions, and any application requiring high speed rotation and good performance. Notes:

- 1.
- 2. 3.
- 4.



FIGURE 6.16 Helical gears (a) for parallel shafts and (b) for crossed shafts. (Courtesy of D. O. James Gear Manufacturing Company.)

Herringbone gears (Fig. 3): To avoid axial thrust, two helical gears of opposite hand can be mounted side by side, to cancel resulting thrust forces. These are called double helical or herringbone gears



FIGURE 6.22 Herringbone gears. (Courtesy of D. O. James Gear Manufacturing Company.)

Bevel gears (Fig. 4): Bevel gears connect intersecting axes, and come in several types (listed below). For bevel gears, the pitch surface is a cone, (it was a cylinder in spur and helical gears) and mating spiral gears can be modeled as two cones in rolling contact. Types of bevel gears:

- 1. Straight bevel: These are like spur gears, the teeth have no helix angle. Straight bevel gears can be
 - a. Miter gears, equal size gears with a 90 degree shaft angle,
 - b. Angular bevel gears, shaft angle other than 90 degrees, or
 - c. Crown gears, one gear is flat, has a pitch angle of 90 degree.
- 2. Spiral bevel gears(Fig. 4a): Teeth have a spiral angle which gives performance improvements much like helical gears
- 3. Zerol bevel gears (Fig. 4b): Teeth are crowned, so that tooth contact takes place first at the tooth center.





FIGURE 6.12 Spiral bevel gears. (Courtesy of Gleason Works.)

(b)

(b) Zerol bevel gears showing localized contact. (Courtesy



Shaft Angle 45°



Shaft Angle 60°



Shaft Angle 90°



Shaft Angle 120°

Hypoid gears (Fig. 5): Similar to spiral bevel gears, but connect non-parallel shafts that do not intersect. The pitch surface of a hypoid gear is a hyperboloid of revolution (rather than a cone, the pitch surface in bevel gears), hence the name.



FIGURE 6.14 Hypoid gears. (Courtesy of Gleason Works.)

Crossed helical gears (Fig. 6): Helical gears that connect skew shafts. The teeth have sliding motion and therefore lower efficiency. One application is connecting distributer to cam shaft in pre-electronic ignition vehicles.

Worm Gears (Fig. 7): The driving gear is called a worm, and typically has 1, 2, or four teeth. The low number of teeth on the worm can result in a very large velocity ratio. These can also be designed to be non-backdriveable, and can carry high loads. Because of sliding action, efficiency is low.





Rack and Pinion (Fig. 8): These transmit rotary motion (from the pinion) to translational motion (of the rack). The rack is a gear with infinite radius; its teeth, although flat sided, are involute. The rack and pinion is commonly used in steering units and jacks.



