HEWLETT hp PACKARD

HP-65

MACHINE DESIGN PAC 1

PRINTED IN U.S.A.

INTRODUCTION

Machine Design Pac I is a collection of programs to aid the engineer in the calculation of physical laws and machine element properties. Each program includes a general description, formulas used in the program solution, general user instructions, example problems with keystroke solutions, and a program listing. By using the keyboard functions of the HP-65 in combination with Machine Design Pac I, complex problems can be solved in an easy, consistent manner. We hope you find Machine Design Pac I a useful tool, and we welcome your comments and suggestions.

Machine Design Pac I has benefitted immeasurably from the comments and suggestions of practicing mechanical engineers. We especially wish to thank Mr. Dean Lampman for his assistance in reviewing this text and for contributing his engineering expertise.

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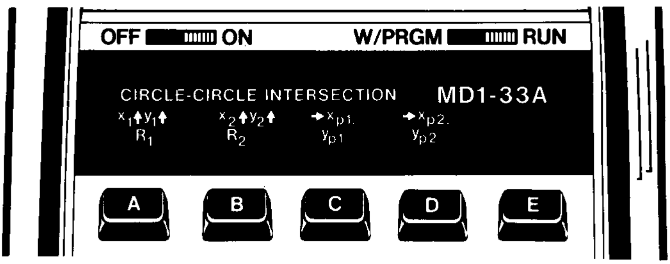
USING MACHINE DESIGN PAC 1

PRERECORDED MAGNETIC CARDS

The prerecorded magnetic cards supplied with Machine Design Pac I incorporate a shorthand set of operating instructions. Having familiarized yourself with a particular program, these notations will help in running the program without referencing the manual. A typical card inserted in the window slot of an HP-65 is shown below:



Above the **A** key are the input variables x_1, y_1, and R_1 separated by ↑, which is the symbol for **ENTER↑**. This means key in x_1, press **ENTER↑**; key in y_1, press **ENTER↑**; key in R_1, press **A**.

Similarly, the variables x_2, y_2, and R_2 are input with the **ENTER↑** and **B** keys.

In other programs, a variable by itself is input by keying in the value and pressing the corresponding program control key.

The → symbol pointing to variables above the **C** key means calculate. To calculate x_{p1}, press **C**. To calculate y_{p1}, press **R/S** In all cases throughout this pac where more than one output is found associated with one program control key, press **R/S** for each subsequent output after the first. In some cases, successive outputs as above rely on previous outputs left undisturbed in the display. An * in the INPUT DATA/UNITS column of the User Instructions page gives an indication in such instances. This is discussed further on page 6.

Another symbol used in the pac is an arrow pointing down to a variable ($\overset{\blacktriangledown}{F}_1$). This indicates the variable may be either input or calculated, following the user instructions. This allows for an interchangeable solution between several variables.

FORMAT OF USER INSTRUCTIONS

The completed User Instruction Form, which accompanies each program, is your guide to operating the programs in this pac.

The form is composed of five labeled columns. Reading from left to right, the first column, labeled STEP, gives the instruction step number.

The INSTRUCTIONS column gives instructions and comments concerning the operations to be performed.

The INPUT-DATA/UNITS column specifies the input data, and the units of data if applicable. Data input keys consist of [0] thru [9] and the decimal point (the numeric keys), [EEX] (enter exponent), and [CHS] (change sign).

The KEYS column specifies the function and program control keys to be used to operate on the input data.

The OUTPUT DATA/UNITS column describes the values which appear in the display as the various data are input and operated on by the function and program control keys.

For example, look at the User Instructions associated with the magnetic card on page 4:

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter program		[ ] [ ]	
2	Input the center coordinates	x_1	[↑] [ ]	x_1
	and radius of circle one.	y_1	[↑] [ ]	y_1
		R_1	[A] [ ]	x_1
3	Input the center coordinates	x_2	[↑] [ ]	x_2
	and radius of circle two	y_2	[↑] [ ]	y_2
		R_2	[B] [ ]	$\theta + \alpha$
4	Compute the coordinates of the		[C] [ ]	x_{p1}
	points of intersection	*	[R/S] [ ]	y_{p1}
			[D] [ ]	x_{p2}
		*	[R/S] [ ]	y_{p2}
5	For a new case, go to step 2.		[ ] [ ]	

STEP 1: "Enter program" is the instruction to enter the prerecorded magnetic card into the HP-65 (See Entering a Program on page 7).

STEP 2: This step specifies input of variables necessary for program operation. The first three variables are automatically stored when the **A** key is pressed.

STEP 3: This step indicates input of three more variables using the **B** key.

STEP 4: Step 4 indicates calculation of the points of intersection of two circles with the **C** and **D** keys. The y coordinate of each pair of points is obtained by pressing **R/S**. The *'s in the INPUT DATA/UNITS column indicate the display should be left undisturbed between calculations of x and y coordinates for proper operation. In this case, the x coordinate is necessary in the calculation of the y coordinate.

STEP 5: This step gives directions for starting the calculations with new input data.

ENTERING A PROGRAM

From the card case supplied with this application pac, select a program card.

Set W/PRGM-RUN switch to RUN.

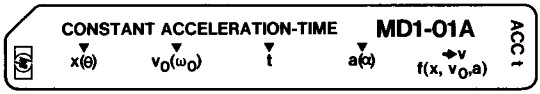
Turn the calculator ON. You should see 0.00.

Gently insert the card (printed side up) in the right, lower slot as shown. When the card is part way in, the motor engages it and passes it out the left side of the calculator. Sometimes the motor engages but does not pull the card in. If this happens, push the card a little farther into the machine. Do not impede or force the card; let it move freely. (The display will flash if the card reads improperly. In this case, press CLX and reinsert the card.)

When the motor stops, remove the card from the left side of the calculator and insert it in the upper "window slot" on the right side of the calculator.

The program is now stored in the calculator. It remains stored until another program is entered or the calculator is turned off.

CONSTANT ACCELERATION-TIME



This program calculates an interchangeable solution among the variables displacement, acceleration, initial velocity, and time, for an object that undergoes constant acceleration. The motion may be either circular or linear. Final velocity as a function of initial velocity, acceleration, and displacement may also be computed.

Equations:

	Linear	Angular
Displacement	$x = v_0 t + \frac{1}{2} at^2$	$\theta = \omega_0 t + \frac{1}{2} \alpha t^2$
Initial velocity	$v_0 = \frac{x}{t} - \frac{1}{2} at$	$\omega_0 = \frac{\theta}{t} - \frac{1}{2} \alpha t$
Acceleration	$a = \frac{x - v_0 t}{\frac{1}{2} t^2}$	$\alpha = \frac{\theta - \omega_0 t}{\frac{1}{2} t^2}$
Time	$t = \frac{\sqrt{v_0^2 + 2ax} - v_0}{a}$	$t = \frac{\sqrt{\omega_0^2 + 2\alpha\theta} - \omega_0}{\alpha}$
Final velocity	$v = \sqrt{v_0^2 + 2ax}$	$\omega = \sqrt{\omega_0^2 + 2\alpha\theta}$

Remarks:

Any consistent set of units may be used.

Displacement, acceleration, and velocity should be considered as signed (vector) quantities. For example, if initial velocity and acceleration are in opposite directions, one should be positive and the other negative.

All equations assume that the initial displacement, x_0 or θ_0, equals zero.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input three of the following:				
	Displacement	x (θ)	A		x (θ)
	Initial velocity	v_0 (ω_0)	B		v_0 (ω_0)
	Time	t	C		t
	Acceleration	a (α)	D		a (α)
3	Compute the remaining variable:				
	Displacement		A	R/S	x (θ)
	Initial velocity		B	R/S	v_0 (ω_0)
	Time		C	R/S	t
	Acceleration		D	R/S	a (α)
4	To change any inputs, go to				
	step 2 and input the changed				
	variables.				
5	Compute final velocity assuming				
	x, v_0, and a have been input or				
	calculated.		E		v

Example 1:

An automobile accelerates for 4 seconds from a speed of 35 mph and covers a distance of 264 feet. Assuming constant acceleration, what is the acceleration in ft/sec^2? (7.33 ft/sec^2) If the acceleration continues to be constant, what distance is covered in the next second? (84.33 ft)

Keystrokes:

264 [A] 35 [ENTER↑] 5280 [×] 3600 [÷] [B] 4

[C] [D] [R/S] ——→ 7.33

5 [C] [A] [R/S] ——→ 348.33

264 [−] ——→ 84.33

Example 2:

A flywheel turns 100 revolutions in 2.5 seconds. If the flywheel is under constant acceleration of 200 RPM^2, compute the initial velocity (2395.83 RPM), the velocity after 500 revolutions (2437.22 RPM), and the velocity after 1 minute has elapsed (2595.83 RPM).

Keystrokes:

100 [A] 2.5 [ENTER↑] 60 [÷] [C] 200 [D] [B] [R/S] ——→ 2395.83

500 [A] [E] ——→ 2437.22

To solve the final portion, input t and first solve for θ, since v is a function of $(\theta, \omega_0, \alpha)$.

1 [C] [A] [R/S] [E] ——→ 2595.83

CONSTANT ACCELERATION-VELOCITY

This program calculates an interchangeable solution among the variables displacement, acceleration, initial velocity, and final velocity, for an object undergoing constant acceleration. The motion may be either circular or linear.

Equations:

	Linear	Angular
Final velocity	$v = \sqrt{v_0^2 + 2ax}$	$\omega = \sqrt{\omega_0^2 + 2\alpha\theta}$
Initial velocity	$v_0 = \sqrt{v^2 - 2ax}$	$\omega_0 = \sqrt{\omega^2 - 2\alpha\theta}$
Displacement	$x = \dfrac{v^2 - v_0^2}{2a}$	$\theta = \dfrac{\omega^2 - \omega_0^2}{2\alpha}$
Acceleration	$a = \dfrac{v^2 - v_0^2}{2x}$	$\alpha = \dfrac{\omega^2 - \omega_0^2}{2\theta}$
Time	$t = \dfrac{\sqrt{v_0^2 + 2ax} - v_0}{a}$	$t = \dfrac{\sqrt{\omega_0^2 + 2\alpha\theta} - \omega_0}{\alpha}$

The relation $v = v_0 + at$ ($\omega = \omega_0 + \alpha t$) is not handled by this program. It may sometimes be necessary to eliminate t from the input data using the above relation.

Remarks:

Any consistent set of units may be used.

Displacement, acceleration, and velocity should be considered as signed (vector) quantities. For example, if initial velocity and acceleration are in opposite directions, one should be positive and the other negative.

All equations assume that the initial displacement, x_0 or θ_0, equals zero.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter program		[ ] [ ]	
2	Input three of the following:		[ ] [ ]	
	Displacement	x (θ)	[A] [ ]	x (θ)
	Initial velocity	v_0 (ω_0)	[B] [ ]	v_0 (ω_0)
	Final velocity	v (ω)	[C] [ ]	v (ω)
	Acceleration	a (α)	[D] [ ]	a (α)
3	Compute the remaining		[ ] [ ]	
	variables:		[ ] [ ]	
	Displacement		[A] [R/S]	x (θ)
	Initial velocity		[B] [R/S]	v_0 (ω_0)
	Final velocity		[C] [R/S]	v (ω)
	Acceleration		[D] [R/S]	a (α)
4	To change any inputs, go to		[ ] [ ]	
	step 2 and input the changed		[ ] [ ]	
	variables.		[ ] [ ]	
5	Compute time assuming x, v_0,		[ ] [ ]	
	and a have been input or		[ ] [ ]	
	calculated.		[E] [ ]	t

Example:

An automobile engine idling at 1000 RPM is accelerated to 5000 RPM in 1.6 seconds. Assuming constant angular acceleration, how many revolutions does the engine make in coming up to speed? (80 revs.) How much additional time would elapse to increase the speed to 6000 RPM? (0.4 sec.)

Keystrokes:

First, find the acceleration $\alpha = (\omega - \omega_0)/t$ where t = 1.6/60 min. (The velocities are also stored during the calculations of α)

5000 [C] 1000 [B] [−] 1.6 [ENTER↑] 60 [÷] [÷] [D] ——► 150000.00

[A] [R/S] ——► 80.00

To solve the final portion, input ω and first solve for θ, since t is a function of $(\theta, \omega_0, \alpha)$.

6000 [C] [A] [R/S] [E] 60 [×] ——► 2.00

1.6 [−] ——► 0.40

KINETIC ENERGY

This program calculates an interchangeable solution among the variables weight (or mass), velocity, and kinetic energy, for an object moving at constant velocity. The program operates in either English or metric units. For metric units, any consistent set of units may be used; the quantity mass must be used. For English units, the energy must be in foot-pounds, the velocity in feet per second, and the quantity weight in pounds.

K.E. = Kinetic energy
W = Weight (lb)
m = Mass (kg, g)
v = Velocity
g = Acceleration due to gravity = 32.17398 ft/sec^2

Equations:

English

$$K.E. = \frac{1}{2} \frac{W}{g} v^2$$

Metric

$$K.E. = \frac{1}{2} mv^2$$

$$1 \text{ ft-lb} = 1.98 \times 10^6 \text{ hp}$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter program		[ ] [ ]	
2	Choose system of units:		[ ] [ ]	
	Metric (SI)		[A] [ ]	2.00
	or		[ ] [ ]	
	English		[B] [ ]	64.35
3	Input two of the following		[ ] [ ]	
	variables:		[ ] [ ]	
	Kinetic energy	K.E.	[C] [ ]	K.E.
	Weight (mass)	W(m)	[D] [ ]	W(m)
	Velocity	v	[E] [ ]	v
4	Compute the remaining		[ ] [ ]	
	variables:		[ ] [ ]	
	Kinetic energy		[C] [R/S]	K.E.
	Optional: convert K.E. (ft-lb)		[ ] [ ]	
	to K.E. (hp)		[R/S] [ ]	K.E. (hp)
	Weight (mass)		[D] [R/S]	W(m)
	Velocity		[E] [R/S]	v
5	To change any input variable,		[ ] [ ]	
	go to step 3.		[ ] [ ]	
6	For a new case, go to step 2.		[ ] [ ]	

Example 1:

The slider of a slider-crank mechanism is used to punch holes in a slab of metal. It is found that the work required to punch a hole is 775 ft-lb. If the slider weighs 5 lb. 4 oz., how fast must it be moving when it strikes the metal? (97.46 ft/sec) What is the required work in horsepower? (3.91×10^{-4} hp)

Keystrokes:

[B] 775 [C] 5 [ENTER↑] 4 [ENTER↑] 16 [÷] [+]

[D] [E] [R/S] ——————→ 97.46

[DSP] 2 [C] [R/S] [R/S] ——————→ 3.91 –04

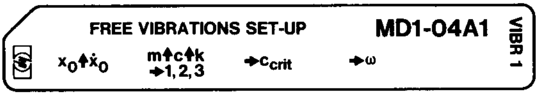
Example 2:

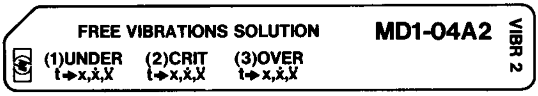
An object weighing 4.8 kg is moving with constant velocity of 3.5 m/sec. Find its kinetic energy. (29.40 joules)

Keystrokes:

[DSP] [•] 2 [A] 4.8 [D] 3.5 [E] [C] [R/S] ——————→ 29.40

FREE VIBRATIONS





This program provides an exact solution to the differential equation for a damped oscillator vibrating freely: $m\ddot{x} + cx + kx = 0$.

The program employs two cards for a full solution. With the first card, the user inputs the mass m, spring constant k, and damping constant c; the value of c for critical damping, c_{crit}, can be displayed. The other inputs are the initial conditions, i.e., the displacement and velocity at time zero, x_0 and $\dot{x}_0$. The first card determines if the system is underdamped, critically damped, or overdamped. This is decided on the basis of a comparison between c and c_{crit} as follows:

If $c < c_{crit}$, the system is underdamped.

If $c = c_{crit}$, the system is critically damped.

If $c > c_{crit}$, the system is overdamped.

The second card allows the user to input any time t and solve for the displacement and velocity of the mass at that time. The type of damping must be specified.

Equations:

$$c_{crit} = 2\sqrt{km}$$

$$\omega = \sqrt{\frac{k}{m} - \left(\frac{c}{2m}\right)^2}$$

$$\ddot{x} = -(c\dot{x} + kx)/m$$

Underdamping $(c^2 - 4km < 0)$

$$x(t) = Re^{-\frac{c}{2m}t}\cos(\omega t - \delta)$$

$$\dot{x}(t) = -R\omega e^{-\frac{c}{2m}t}\sin(\omega t - \delta) - \frac{c}{2m} R e^{-\frac{c}{2m}t}\cos(\omega t - \delta)$$

where:

$$R\cos\delta = x_0$$

$$R\sin\delta = \frac{1}{\omega}\left[\dot{x}_0 + \frac{c}{2m}x_0\right]$$

Critical damping $(c = c_{crit}, \text{ or } c^2 = 4km)$

$$x(t) = (A_{cr} + B_{cr}t)e^{-\frac{c}{2m}t}$$

$$\dot{x}(t) = \left[B_{cr} - \frac{c}{2m}(A_{cr} + B_{cr}t)\right] e^{-\frac{c}{2m}t}$$

where:

$$A_{cr} = x_0$$

$$B_{cr} = \dot{x}_0 + \frac{c}{2m}x_0$$

Overdamping $(c^2 - 4km > 0)$

$$x(t) = A_{ov}e^{r_1 t} + B_{ov}e^{r_2 t}$$

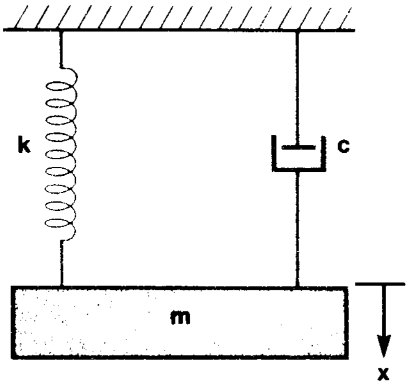
$$\dot{x}(t) = A_{ov}r_1 e^{r_1 t} + B_{ov}r_2 e^{r_2 t}$$

where:

$$r_1, r_2 = -\frac{c}{2m} \pm \sqrt{\left(\frac{c}{2m}\right)^2 - \frac{k}{m}}$$

$$A_{ov} = x_0 - B_{ov}$$

$$B_{ov} = \frac{\dot{x}_0 - r_1 x_0}{r_2 - r_1}$$



Remarks:

For overdamping, ω has no meaning and is, in fact, an imaginary number.

For $c = c_{crit}$, $\omega = 0$.

This program sets the angular mode of the calculator to radians. Erroneous answers will occur if **A** is mistakenly pressed on MD1-4A2 when the system is overdamped.

Reference: Elementary Differential Equations, W.E. Boyce and R.C. DiPrima, John Wiley and Sons, 1969.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter MD 1–04A1			
2	Input the initial position	x_0	↑	x_0
	and velocity	$\dot{x}_0$	A	x_0
3	Input Mass	m	↑	m
	Damping constant	c	↑	c
	Spring constant and	k	B	1, 2, or 3
	Determine the damping of the system			
	1 implies $c < c_{crit}$, system is underdamped			
	2 imples $c = c_{crit}$, system is critically damped			
	3 imples $c > c_{crit}$, system is overdamped			
4	Optional: compute c_{crit}		C	c_{crit}
	compute ω		D	ω
5	Enter MD 1–04A2			
6a	For underdamped system, input time and	t	A	x(t)
	calculate position, velocity			
	and	*	R/S	$\dot{x}(t)$
	acceleration	*	R/S	$\ddot{x}(t)$
6b	For critically damped system, input time and	t	B	x(t)
	calculate position, velocity			
	and	*	R/S	$\dot{x}(t)$
	acceleration	*	R/S	$\ddot{x}(t)$
6c	For overdamped system, input time and	t	C	x(t)
	calculate position, velocity	*	R/S	$\dot{x}(t)$
	and	*	R/S	$\ddot{x}(t)$
	acceleration			
7	Repeat step 6 for all desired values of t.			
8	For a new case, go to step 1.			

Example:

A mass of 20 g stretches a spiral spring 10 cm. The mass is pulled down an additional 4 cm, held, and then released. Find the mass' displacement and velocity at 0.1 second intervals up to 1 second for the cases in which (a) c = 50 dyne-sec/cm (b) $c = c_{crit}$ and (c) c = 400 dyne-sec/cm.

$$k = \frac{F}{x} = \frac{mg}{x} = \frac{20g\,(980\ cm/s^2)}{10\ cm} = \frac{20 \times 980}{10}\ dyne/cm$$

Solution (a) c = 50

t s	x cm	x cm/s	$\ddot{x}$ cm/s²
0	4.000	0.000	-392.000
.1	2.334	-29.296	-155.494
.2	-0.827	-28.715	152.880
.3	-2.629	-5.330	270.947
.4	-1.932	17.139	146.511
.5	0.153	20.950	-67.408
.6	1.655	7.187	-180.174
.7	1.503	-9.272	-124.104
.8	0.184	-14.685	18.677
.9	-0.990	-7.173	114.959
1.0	-1.114	4.406	98.133

Keystrokes:

Enter MD1-4A1

4 [ENTER↑] 0 [A] ⟶ 4.00

20 [ENTER↑] 50 [ENTER↑] 20 [ENTER↑] 980

[×] 10 [÷] [B] ⟶ 1.00

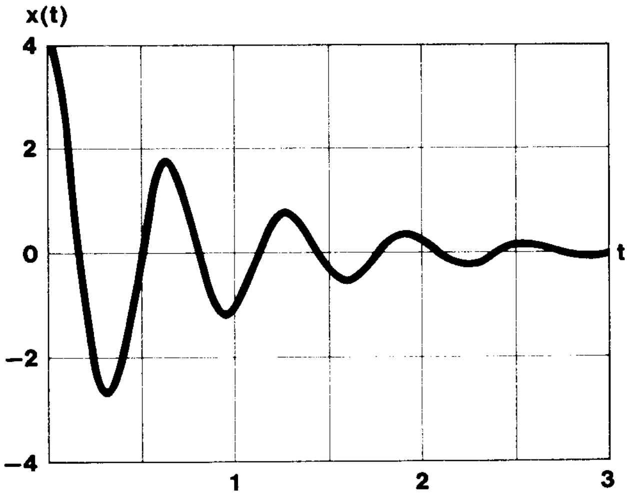
This indicates the system is underdamped.

Calculate c_{crit}:

[C] [DSP] [•] 7 ⟶ 395.9797974

Enter MD1-4A2

DSP [•] 3 0 A	4.000
R/S	0.000
R/S	–392.000
.1 A	2.334
R/S	–29.296
R/S	–155.494
⋮	⋮
1.0 A	–1.114
R/S	4.406
R/S	98.133



Solution (b) $c = c_{crit}$

t s	x cm	$\dot{x}$ cm/s	$\ddot{x}$ cm/s^2
0	4.000	0.000	–392.000
.1	2.958	–14.567	–1.464
.2	1.646	–10.826	53.041
.3	0.815	–6.034	39.621
.4	0.378	–2.990	22.122
.5	0.169	–1.389	10.970
.6	0.073	–0.619	5.098
.7	0.031	–0.268	2.274
.8	0.013	–0.114	0.986
.9	0.005	–0.048	0.419
1.0	0.002	–0.020	0.175

Keystrokes:

Enter MD1-4A1

4 [ENTER↑] 0 [A] ⟶ 4.000

20 [ENTER↑] 395.9797974 [ENTER↑] 20 [ENTER↑]

980 [×] 10 [÷] [B] ⟶ 2.000

This indicates the system is critically damped.

Enter MD1-4A2

0 [B] ⟶ 4.000

[R/S] ⟶ 0.000

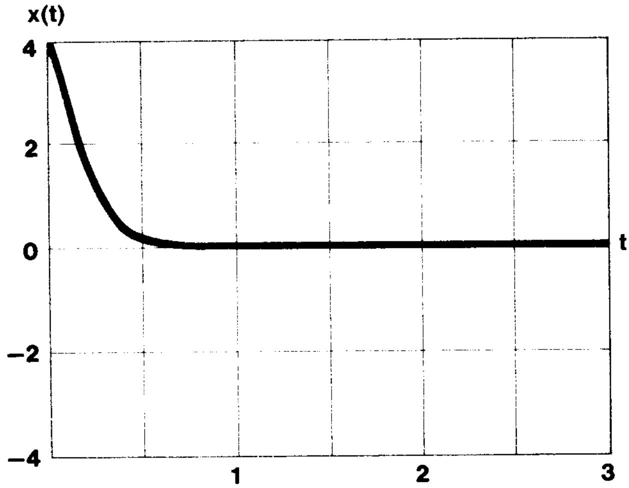
[R/S] ⟶ –392.000

.1 [B] ⟶ 2.958

[R/S] ⟶ –14.567

[R/S] ⟶ –1.464

and so on.



Solution (c) c = 400

t s	x cm	$\dot{x}$ cm/s	$\ddot{x}$ cm/s^2
0	4.000	0.000	–392.000
.1	2.963	–14.469	–0.963
.2	1.660	–10.752	52.336
.3	0.833	–6.032	39.022
.4	0.394	–3.028	21.916
.5	0.180	–1.433	11.005
.6	0.081	–0.656	5.212
.7	0.035	–0.293	2.384
.8	0.015	–0.129	1.066
.9	0.007	–0.056	0.470
1.0	0.003	–0.024	0.205

Keystrokes:

Enter MD1-4A1

4 [ENTER↑] 0 [A] ⟶ 4.000

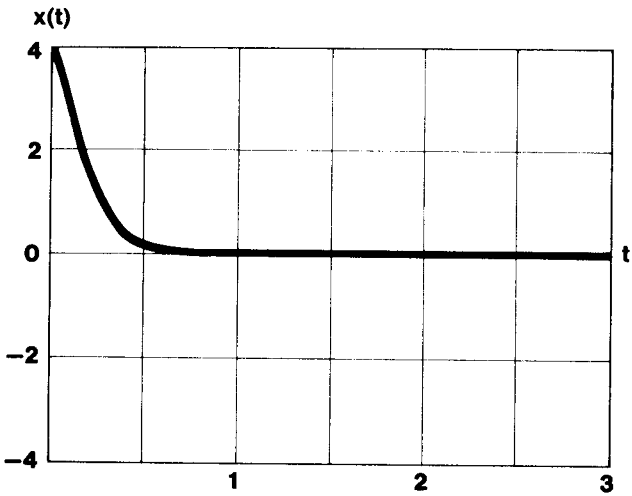
20 [ENTER↑] 400 [ENTER↑] 20 [ENTER↑] 980 [×]

10 [÷] [B] ⟶ 3.000

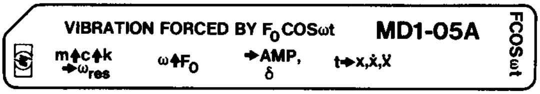
The system is overdamped.

0 [C] ——→ 4.000
[R/S] ——→ 0.000
[R/S] ——→ –392.000
.1 [C] ——→ 2.963
[R/S] ——→ –14.469
[R/S] ——→ –0.963

and so on.



VIBRATION FORCED BY F_0 COS ωt



This program finds the steady-state solution for an object undergoing damped forced oscillations from a periodic external force of the form $F_0 \cos \omega t$. The differential equation to be solved is

$$m\ddot{x} + c\dot{x} + kx = F_0 \cos \omega t$$

The program computes the following variables: the resonant frequency, ω_{res}, for which the amplitude of the resultant oscillation is greatest (i.e., the frequency which maximizes F_0/Δ); the amplitude F_0/Δ; the phase of the oscillations, δ; and the displacement, velocity and acceleration for any time t (steady-state only).

Equations:

The steady-state solution ($t \to \infty$) to this equation is

$$x(t) = \frac{F_0}{\Delta} \cos (\omega t - \delta)$$

$$\dot{x}(t) = -\omega \frac{F_0}{\Delta} \sin (\omega t - \delta)$$

where:

$$\Delta = \sqrt{m^2 (\omega_0{}^2 - \omega^2)^2 + c^2 \omega^2}$$

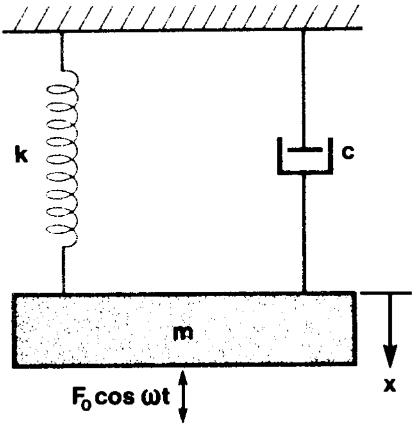
$$\omega_0 = \sqrt{\frac{k}{m}} = \text{natural frequency of undamped system}$$

$$\cos \delta = \frac{m (\omega_0{}^2 - \omega^2)}{\Delta}$$

$$\sin \delta = \frac{c\omega}{\Delta}$$

ω_{res} is computed from

$$\omega_{res}^2 = \omega_0^2 - \frac{1}{2}\left(\frac{c}{m}\right)^2$$



Remarks:

Flashing zeroes in the calculation for ω_{res} indicate that

$$\omega_0^2 - \frac{1}{2}\left(\frac{c}{m}\right)^2 < 0.$$

Simply stop the flashing by pressing any key, and continue with the rest of the problem.

The above solution does not take into account the initial conditions $(x(0), \dot{x}(0))$ of the system. This program assumes that initial conditions have already become negligible, and that the origin of time $(t = 0)$ is taken to be a time at which the driving force is at its maximum amplitude F_0. If a solution including initial conditions is necessary, program MD1-6A may be used.

This program sets the angular mode of the calculator to radians. Calculation of acceleration under **D** resets the angular mode to degrees.

Reference: Elementary Differential Equations, W.E. Boyce and R.C. DiPrima, John Wiley and Sons, 1969.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input mass, damping constant,				
	and spring constant, and	m	↑		m
	compute the	c	↑		c
	Resonant frequency	k	A		ω_{res}
3	Input the forcing frequency and	ω	↑		ω
	forcing amplitude	F_0	B		ω
4	Compute the amplitude of the				
	resultant oscillation		C		F_0/Δ
	Optional: display the phase of				
	oscillation		R/S		δ
5	Input time and compute the				
	position,	t	D		x(t)
	velocity and	*	R/S		$\dot{x}(t)$
	acceleration (steady-state				
	only)	*	R/S		$\ddot{x}(t)$
6	Repeat step 5 for all desired				
	values of t.				
7	To change ω or F_0, go to step 3.				
	To change m, c, or k, go to				
	step 2.				

Example:

A 400-lb. weight is suspended from a spring and stretches it a distance of 2 inches. The damping constant of the system is 0.5 lb-sec/ft. If the weight is driven by a periodic external force whose greatest value is 5 pounds, find (a) the resonant frequency of the system (13.90 rad/s) and (b) the amplitude and phase shift of the oscillation that will result if the mass is driven at the resonant frequency. (0.72 ft = 8.63 in.; 1.57 radians $\cong \pi/2$). Calculate the position, velocity, and acceleration for t = 6.0 sec. (0.71 ft, −1.46 ft/sec, −137.50 ft/sec^2).

Keystrokes:

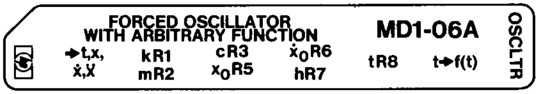
$$m = \frac{F}{g} = \frac{400 \text{ lb.}}{32.2 \text{ ft/sec}^2} \qquad k = \frac{F}{x} = \frac{400 \text{ lb}}{2 \text{ in}} \cdot \frac{12 \text{ in}}{1 \text{ ft}}$$

400 [ENTER↑] 32.2 [÷] .5 [ENTER↑] 400 [ENTER↑]
2 [÷] 12 [×] [A] ——→ 13.90

(To drive the system at the resonant frequency, leave 13.90 in the display and key in the driving force of 5 pounds).

5 [B] [C] ——→ 0.72
12 [×] ——→ 8.63
[R/S] ——→ 1.57
6.0 [D] ——→ 0.71
[R/S] ——→ –1.46
[R/S] ——→ –137.50

FORCED OSCILLATOR WITH ARBITRARY FUNCTION



This program determines the displacement x, velocity $\dot{x}$, and acceleration $\ddot{x}$ of a damped oscillating mass m that is being driven by some forcing function f. A numerical solution is computed for the nonhomogeneous differential equation

$$m\ddot{x} + c\dot{x} + kx = f(t)$$

where

c = Damping constant

k = Spring constant

f(t) = Driving force as a function of time.

There are 23 steps in memory available for f(t). The argument t is in the X-register when f(t) is evaluated. It is also available in R_8. The stack and R_9 are available for scratch registers. The solution is found using an improved Euler method:

Let $$x^{(1)} = x$$

$$x^{(2)} = \dot{x}^{(1)} = \dot{x}$$

Then $$\dot{x}^{(2)} = \ddot{x} = \frac{f(t) - cx^{(2)} - kx^{(1)}}{m}$$

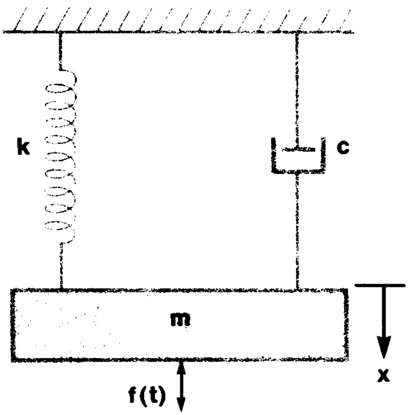
$$x_{n+1}^{(1)} = x_n^{(1)} + h\, x_{n+½}^{(2)}$$

$$x_{n+1}^{(2)} = x_n^{(2)} + \frac{h}{m}\left[f\left(t + \frac{1}{2}h\right) - cx_{n+½}^{(2)} - kx_{n+½}^{(1)}\right]$$

$$x_{n+½}^{(2)} = x_n^{(2)} + \frac{h}{2m}\left[f(t) - cx_n^{(2)} - kx_n^{(1)}\right]$$

$$x_{n+½}^{(1)} = x_n^{(1)} + \frac{h}{2}\, x_n^{(2)}$$

where h = time increment for solutions.



STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Key the function into memory:		GTO	E	
	Switch to W/PRGM mode				15
	Key in the function	f(t)			
	Press RTN		RTN		
	Switch to RUN mode				
	The argument of the function				
	is in x when the routine is				
	called.				
3	Store Spring constant	k	STO	1	k
	Mass	m	STO	2	m
	Damping constant	c	STO	3	c
	Initial position	x_0	STO	5	x_0
	Initial velocity	$\dot{x}_0$	STO	6	$\dot{x}_0$
	Time increment	h	STO	7	h
	Initial time	t	STO	8	t
4	Compute Time		A		t
	Position		R/S		x(t)
	Velocity		R/S		$\dot{x}(t)$
	Acceleration		R/S		$\ddot{x}(t)$
5	Repeat step 4 for next time				
	increment.				
6	Optional: input t and compute				
	f(t)	t	E		f(t)
7	To change any parameters of the				
	solution, go to step 3. The initial				
	conditions x_0 and $\dot{x}_0$ must be				
	re-stored to start a new problem.				
8	For a new case, go to step 2.				

Example 1:

A mass is being driven by a forcing function of the form

$$f(t) = t^3 + 7t^2 - 14t + 40$$

Constants for the system are m = 5, c = 2, and k = 12. The mass is held at an initial displacement of 20 at time zero. Determine the position, velocity, and acceleration of the mass at 0.05 second intervals for the first ¼ sec. of the object's motion.

Solution:

t sec	0.05	0.10	0.15	0.20	0.25
x	19.95	19.80	19.56	19.22	18.80
$\dot{x}$	-1.98	-3.92	-5.81	-7.62	-9.36
$\ddot{x}$	-39.22	-38.22	-37.00	-35.58	-33.97

Keystrokes:

GTO E

Switch to W/PRGM ⟶ 15

ENTER↑ ENTER↑ ENTER↑ 7 + × 14 − ×

40 + RTN

Switch to RUN

12 STO 1 ⟶ 12.00

5 STO 2 ⟶ 5.00

2 STO 3 ⟶ 2.00

20 STO 5 ⟶ 20.00

0 STO 6 ⟶ 0.00

.05 STO 7 ⟶ 0.05

0 STO 8 ⟶ 0.00

A ⟶ 0.05

R/S ⟶ 19.95

R/S ⟶ -1.98

R/S ⟶ -39.22

A ⟶ 0.10

R/S ⟶ 19.80

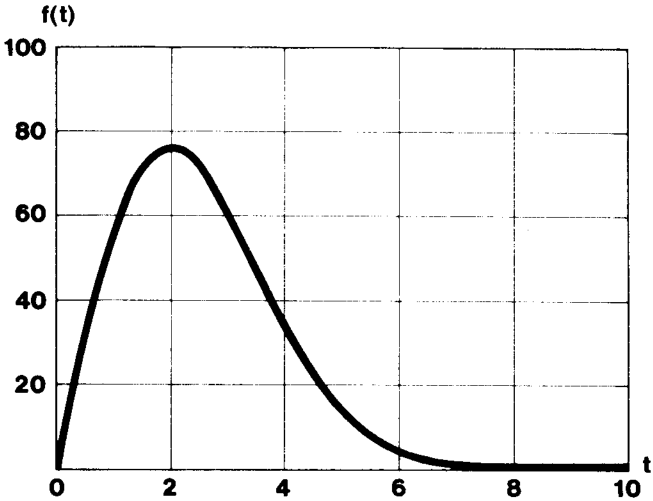
R/S ⟶ -3.92

R/S ⟶ -38.22

and so on.

Example 2:

This program can also be used to generate position, velocity, and acceleration for cases where the forcing function is not explicitly known, but where values for f(t) can be read from a graph. Consider the following graph:



Rather than keying in a function under **E**, we can put in **R/S** **RTN**, allowing us to enter values for the function from our graph each time the **E** routine is called. Three entries of f(t) are required for each set of computed values.

To demonstrate this procedure, generate position, velocity and acceleration data for the first 7 seconds of forcing in intervals of .5 seconds. Assume for $t = 0$, $x = \dot{x} = 0$ and $k = 10$, $m = 5$, and $c = 2$.

Solution:

t	x	$\dot{x}$	$\ddot{x}$
0.500	0.000	1.500	5.400
1.000	1.425	4.855	6.208
1.500	4.629	7.235	2.049
2.000	8.502	6.648	–4.463
2.500	11.268	2.878	–9.288
3.000	11.546	–2.521	–9.884
3.500	9.050	–7.139	–5.845
4.000	4.750	–8.684	0.773
4.500	0.505	–6.865	6.336
5.000	–2.136	–2.897	8.230
5.500	–2.556	1.131	6.259
6.000	–1.208	3.464	1.830
6.500	0.753	3.322	–2.435
7.000	2.110	1.346	–4.558

Keystrokes:

GTO E

Switch to W/PRGM mode ——→ 15

R/S RTN

Switch to RUN mode

10 STO 1 ——→ 10.00

5 STO 2 ——→ 5.00

2 STO 3 ——→ 2.00

0 STO 5 ——→ 0.00

0 STO 6 ——→ 0.00

.5 STO 7 ——→ 0.50

0 STO 8 ——→ 0.00

DSP • 3 A ——→ 0.000

(f(0) = 0 from the graph)

0 R/S ——→ 0.250

(f(.25) ≐ 15)

15 [R/S] → 0.500 (t)

[R/S] → 0.000 (x(.5))

[R/S] → 1.500 ($\dot{x}$(.5))

[R/S] → 0.500

(f(.5) ≐ 30)

30 [R/S] → 5.400 ($\ddot{x}$(.5))

[A] → 0.500

(f(.5) ≐ 30)

30 [R/S] → 0.750

(f(.75) ≐ 43)

43 [R/S] → 1.000 (t)

[R/S] → 1.425 (x(1))

[R/S] → 4.855 ($\dot{x}$(1))

[R/S] → 1.000

(f(1) ≐ 55)

55 [R/S] → 6.208 ($\ddot{x}$(1))

[A] → 1.000

(f(1) ≐ 55)

55 [R/S] → 1.250

(f(1.250) ≐ 63)

63 [R/S] → 1.500 (t)

[R/S] → 4.629 (x(1.5))

[R/S] → 7.235 ($\dot{x}$(1.5))

[R/S] → 1.500

(f(1.5) ≐ 71)

71 [R/S] → 2.049 ($\ddot{x}$(1.5))

and so on where

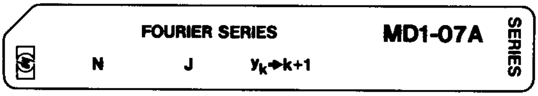
t	f(t)	t	f(t)
0.00	0.00	3.75	40
0.25	15	4.00	34
0.50	30	4.25	27
0.75	43	4.50	23
1.00	55	4.75	17
1.25	63	5.00	14
1.50	71	5.25	10
1.75	74	5.50	8
2.00	76	5.75	6
2.25	75	6.00	4
2.50	72	6.25	3
2.75	67	6.50	2
3.00	61	6.75	1.5
3.25	53	7.00	1
3.50	47		

The function actually represented by the graph is

$$f(t) = 62.5\ t\ e^{-(t^2/8)}$$

(62.5 [g] [x⇄y] [×] [g] [LST X] [ENTER↑] [×] 8 [÷] [f⁻¹] [LN] [÷])

FOURIER SERIES



Any periodic function, f(t), may be expressed as a sum of sines and cosines by the Fourier series

$$f(t) = \frac{a_0}{2} + \sum_{i=1}^{\infty} \left(a_i \cos \frac{i2\pi t}{T} + b_i \sin \frac{i2\pi t}{T} \right)$$

$$a_i = \frac{2}{T} \int_0^T f(t) \cos \frac{i2\pi t}{T}\, dt, \qquad i = 0, 1, 2, \ldots$$

$$b_i = \frac{2}{T} \int_0^T f(t) \sin \frac{i2\pi t}{T}\, dt, \qquad i = 1, 2, \ldots$$

and

$$T = \text{period of } f(t)$$

This program computes the Fourier coefficients from discrete versions of the above formulas given a large enough number of samples of a periodic function. Six consecutive sine or cosine coefficients are computed at one time from N equally spaced points in one period of the function.

The discrete formulas for the Fourier coefficients are

$$a_j = \frac{2}{T} \sum_{k=1}^{N} y_k \cos \frac{2\pi kj}{T}, j = J, J+1, \ldots, J+5$$

and

$$b_j = \frac{2}{T} \sum_{k=1}^{N} y_k \sin \frac{2\pi kj}{T}, j = J, J+1, ..., J+5$$

J = order of first coefficient to be computed

$$y_k = f(t_k)$$

$$t_k = \frac{kT}{N}$$

Remarks:

The value of N should be chosen to be more than twice the highest expected multiple of the fundamental frequency present in the waveform to be analyzed. A low estimate for N will cause energy above one-half the sampling rate to appear at a lower frequency (a phenomenon known as aliasing).

A single spectral value may be computed by setting flag 1.

For even functions $(f(x) = f(-x))$, $b_j = 0$, for all values of j.

For odd functions $(f(x) = -f(-x))$, $a_j = 0$, for all values of j.

For convenience, the program modified to compute sine coefficients may be recorded on the other track of the magnetic card by placing the card into the machine with the uncut end first.

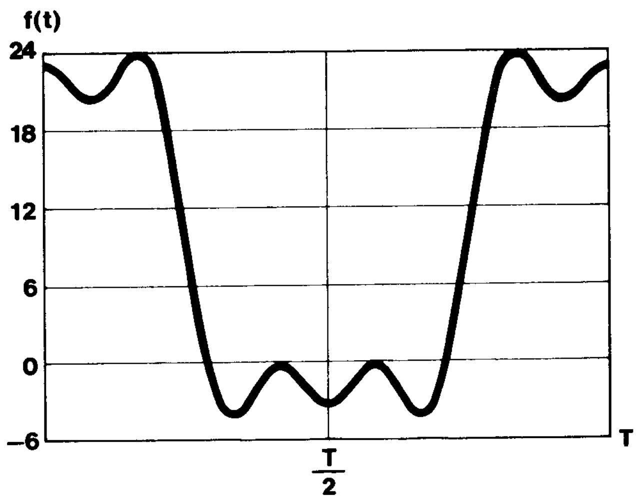
STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter program		[ ] [ ]	
2	For sine coefficients go to		[ ] [ ]	
	step 10.		[ ] [ ]	
3	Input number of points	N	[A] [ ]	N
4	Input order of first coefficient	J	[B] [ ]	1.00
5	If only one coefficient is desired		[f] [SF 1]	
6	Input y_k, k = 1, 2, ..., N	y_k	[C] [ ]	2, ..., N + 1
7	Repeat step 6 until display		[ ] [ ]	
	shows N + 1		[ ] [ ]	
8	Display coefficients (If flag 1		[ ] [ ]	
	was set, only a_j or b_j will have		[RCL] [1]	a_j or b_j
	been computed.)		[RCL] [2]	$a_j + 1$ or $b_j + 1$
			[RCL] [3]	$a_j + 2$ or $b_j + 2$
			[RCL] [4]	$a_j + 3$ or $b_j + 3$
			[RCL] [5]	$a_j + 4$ or $b_j + 4$
			[RCL] [6]	$a_j + 5$ or $b_j + 5$
9	For a new case, go to step 3.		[ ] [ ]	
10	To change to sine coefficients,		[ ] [ ]	
	perform the following steps:		[ ] [ ]	
	Branch to label 1		[GTO] [1]	
	Switch to W/PRGM		[ ] [ ]	01
	Single step twice		[SST] [SST]	05
	Delete cosine		[g] [DEL]	31
	Insert sine		[SIN] [ ]	04
	Record modified program on		[ ] [ ]	
	opposite track		[ ] [ ]	
11	Switch to RUN and go to step 3.		[ ] [ ]	

Example:

The following pressure data from a reciprocating compression process has been gathered:

N = 12	J = 0
k	y_k
1	20.4
2	24.0
3	10.0
4	–4.0
5	-0.4
6	-3.0
7	-0.4
8	–4.0
9	10.0
10	24.0
11	20.4
12	23.0

Synthesize the Fourier series to represent this process.



Solution:

$$f(t) \doteq \frac{20}{2} + 15 \cos \frac{2\pi t}{T} - 5 \cos \frac{6\pi t}{T} + 2.996 \cos \frac{10\pi t}{T}$$

Keystrokes:

The function is even, so $\{b_j\} = 0$.

12 [A] 0 [B] [DSP] 3 20.4 [C] 24 [C] 10 [C] 4 [CHS]
[C] .4 [CHS] [C] 3 [CHS] [C] .4 [CHS] [C] 4 [CHS] [C]
10 [C] 24 [C] 20.4 [C] 23 [C] ⟶ 1.300 01
[RCL] 1 ⟶ 2.000 01
[RCL] 2 ⟶ 1.500 01
[RCL] 3 ⟶ 3.300 –08
[RCL] 4 ⟶ –5.000 00
[RCL] 5 ⟶ 2.200 –08
[RCL] 6 ⟶ 2.996 00

That is, $\{a_j | j = 0, 1, \ldots, 5\} = \{20, 15, 3.3 \times 10^{-8}, -5, 2.2 \times 10^{-8}, 2.996\}$

CRITICAL SHAFT SPEED

Suppose a rotating shaft is simply supported at both ends and has a series of n weights, $W_1, \ldots, W_n$, attached. Then there are critical speeds at which the shaft will become dynamically unstable. This program finds the fundamental critical speed from the formula

$$f = \frac{1}{2\pi} \sqrt{\frac{g \sum_{i=1}^{n} W_i y_i}{\sum_{i=1}^{n} W_i y_i^2}} \quad \text{cycles/sec}$$

where

g = Acceleration due to gravity

y_i = Static deflection of weight W_i

The program is set up to accept the static deflections y_i as inputs. If the static deflections are not known, it computes y_{ij}, the static deflection of weight i due to W_j. Then the total deflection of weight i is the sum of the deflections from all the W_j's. That is,

$$y_i = \sum_{j=1}^{n} y_{ij}.$$

The individual y_{ij}'s are added to provide the y_i's which the program accepts as inputs. The y_{ij}'s are calculated as follows:

If $x_i < x_j$

$$y_{ij} = \frac{W_j (\ell - x_j) x_i}{6\ell EI} \left[\ell^2 - (\ell - x_j)^2 - x_i^2\right]$$

$$= \frac{W_j (\ell - x_j) x_i}{6\ell EI} \left[2\ell x_j - x_j^2 - x_i^2\right]$$

If $x_i \geqslant x_j$

$$y_{ij} = \frac{W_j x_j (\ell - x_i)}{6\ell EI} \left[\ell^2 - x_j^2 - (\ell - x_i)^2\right]$$

$$= \frac{W_j x_j (\ell - x_i)}{6\ell EI} \left[2\ell x_i - x_j^2 - x_i^2\right]$$

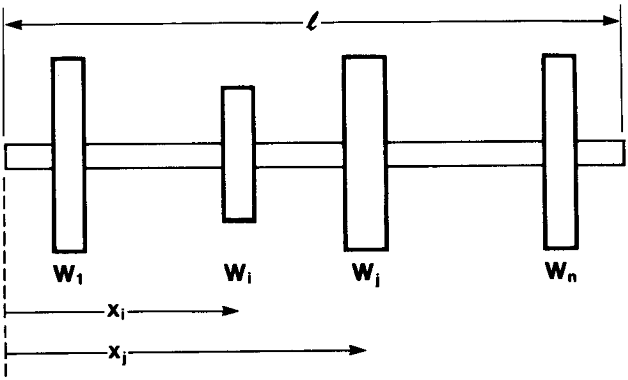
where

x_i, x_j = Distance of weights i, j from end of shaft

E = Modulus of elasticity

I = Moment of inertia

ℓ = Length of shaft



Remarks:

If I is not known and if the shaft is cylindrical, it may be calculated from the diameter d by a keystroke sequence shown on the User Instructions.

$$I = \frac{\pi d^4}{64}$$

Any consistent set of units may be used. The acceleration due to gravity, g, will of course change from one set of units to another. Some useful values are listed below:

$g = 32.1740$ ft/sec²
$= 386.088$ in/sec²
$= 9.80665$ m/sec²
$= 980.665$ cm/sec²

Reference: Design of Machine Elements, M.F. Spotts, Prentice-Hall, 1971.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2a	If the y_i are not known, input				
	Modulus of elasticity	E	↑		E
	Moment of inertia†	I	↑		I
	Length of shaft	ℓ	A		6ℓEI
3a	Input W_i	W_i	↑		W_i
	x_i	x_i	B		y_{ii}
4a	Input W_j	W_j	↑		W_j
	x_j where $j \neq i$	x_j	C		Σy_{ij}
5a	Repeat step 4a for all $j \neq i$				
6a	Store $\Sigma W_i y_i$ and $\Sigma W_i y_i^2$ (W_i				
	and y_i are automatically in				
	position after step 5a.)	*	D		$W_i y_i^2$
7a	Repeat steps 3a–6a for i = 1,...,n				
8a	Input acceleration of gravity and				
	compute critical speed.	g	E		f(cycles/sec)
2b	If the y_i are known, input length				
	of shaft	ℓ	A		
3b	Input W_i	W_i	↑		W_i
	y_i	y_i	D		$W_i y_i^2$
4b	Repeat step 3b for i = 1, ..., n				
5b	Input acceleration of gravity				
	and compute critical speed	g	E		f(cycles/sec)
9	For a new case go to step 2				
	†If I is not known, it may be	d	↑	x	d^2
	calculated from the diameter		↑	x	d^4
	d by $I = \pi d^4/64$ (solid cylin-		g	π	π
	drical shaft only).		x	6	
			4	÷	I

Example:

A 2 inch diameter steel shaft of total length 40 inches has a flywheel and a gear located respectively 15 and 25 inches from the end. The flywheel weighs 60 pounds and the gear 45 pounds. Assume the modulus of elasticity of the steel is 30 x 10^6 psi. Find the fundamental critical speed of the shaft. (44.15 cycles/sec, or 2648.85 RPM)

Keystrokes:

$W_1 = 60$ $x_1 = 15$

$W_2 = 45$ $x_2 = 25$

30 [EEX] 6 [ENTER↑] 2 [ENTER↑] [×] [ENTER↑] [×]

[g] [π] [×] 64 [÷] 40 [A] [DSP] 2 ⟶ 5.65 09

60 [ENTER↑] 15 [B] ⟶ 2.98 –03

45 [ENTER↑] 25 [C] ⟶ 5.04 –03

[D] ⟶ 1.53 –03

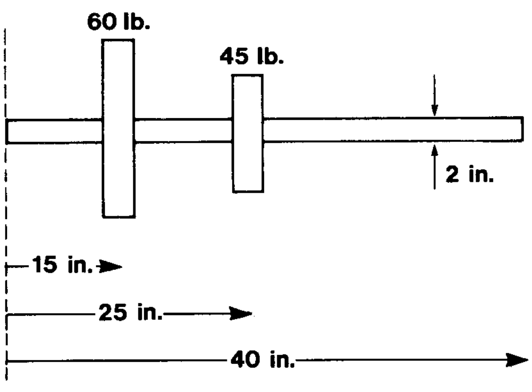
45 [ENTER↑] 25 [B] ⟶ 2.24 –03

60 [ENTER↑] 15 [C] ⟶ 4.98 –03

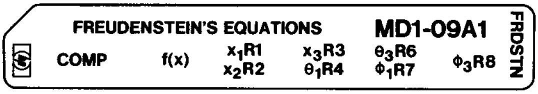
[D] ⟶ 1.12 –03

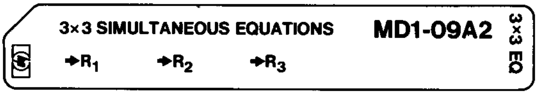
386.088 [E] [DSP] [•] 2 ⟶ 44.15

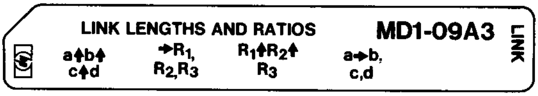
60 [×] ⟶ 2648.85



FOUR BAR FUNCTION GENERATOR







These programs may be used to design a four bar linkage which will approximate an arbitrary function of one variable. Freudenstein's approach is used in the solution. The second card of the three can be used independently to solve 3 x 3 linear systems.

Three precision points are used in the solution.

Freudenstein's equations

$$R_1 \cos\theta_1 - R_2 \cos\phi_1 + R_3 = \cos(\theta_1 - \phi_1)$$

$$R_1 \cos\theta_2 - R_2 \cos\phi_2 + R_3 = \cos(\theta_2 - \phi_2)$$

$$R_1 \cos\theta_3 - R_2 \cos\phi_3 + R_3 = \cos(\theta_3 - \phi_3)$$

are solved simultaneously for R_1, R_2 and R_3 which are defined as follows:

$$R_1 = a/d,\ R_2 = a/b,\ R_3 = \frac{a^2 + b^2 + d^2 - c^2}{2bd}$$

where a is the distance between fixed pivots, b is the length of the input link, c is the length of the coupler and d is the length of the output link. θ_1 refers to the angle of the input link at the first precision point, θ_2 the angle at the second point, and θ_3 the angle at the third. ϕ_1 is the angle of the output link at the first precision point, ϕ_2 is the angle at the second point, and ϕ_3 is the angle at the third precision point.

$$\theta_2 = \theta_1 + \frac{x_2 - x_1}{x_3 - x_1}(\theta_3 - \theta_1)$$

$$\phi_2 = \phi_1 + \frac{f(x_2) - f(x_1)}{f(x_3) - f(x_1)}(\phi_3 - \phi_1)$$

x_1, x_2 and x_3 are the precision points or the three points at which the mechanism will yield kinematically exact solutions to the function (f(x)) which is to be generated.

By manually storing values in appropriate registers, card 2 can be used as a general 3 x 3 system solver.

For a system of the form

$$a_1 R_1 + b_1 R_2 + c_1 R_3 = d_1$$

$$a_2 R_1 + b_2 R_2 + c_2 R_3 = d_2$$

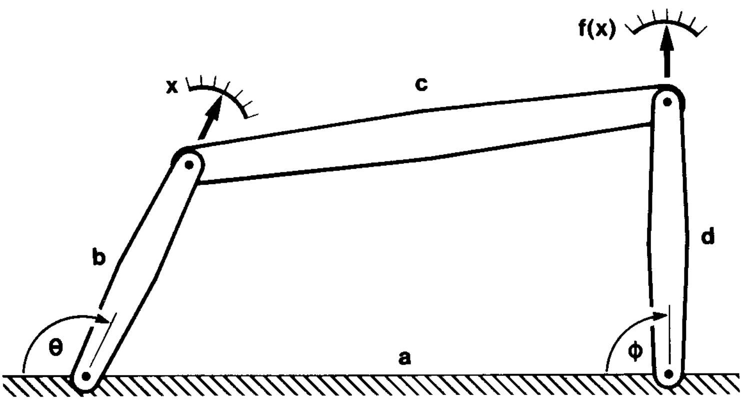
$$a_3 R_1 + b_3 R_2 + c_3 R_3 = d_3$$

where R_1, R_2 and R_3 are unknowns

store a_1/c_1 in R_4, b_1/c_1 in R_7, d_1/c_1 in R_1

a_2/c_2 in R_5, b_2/c_2 in R_8, d_2/c_2 in R_2

a_3/c_3 in R_6, b_3/c_3 in R_9, d_3/c_3 in R_3



Remarks:

f(x) must be stated in 21 or less HP-65 steps. θ_1 may not equal 90 or 270 degrees.

$$\left(\cos\phi_2 - \frac{\cos\phi_1\cos\theta_2}{\cos\theta_1}\right)\left(\frac{\cos\theta_3}{\cos\theta_1} - 1\right)$$

$$\neq \left(\frac{\cos\theta_2}{\cos\theta_1} - 1\right)\left(\cos\phi_3 - \frac{\cos\phi_1\cos\theta_3}{\cos\theta_1}\right)$$

Reference: Kinematics and Dynamics of Machines, G.H. Martin, McGraw-Hill, 1969.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter MD 1–09A1				
2	Key the function into memory:				
	Go to label B		GTO	B	
	Switch to W/PRGM mode				12
	Key in the function	f(x)			
	Press RTN		RTN		
	Switch to RUN mode				
	The argument of the function is				
	in x when the routine is called.				
3	Store the following values:				
	First precision point	x_1	STO	1	x_1
	Second precision point	x_2	STO	2	x_2
	Third precision point	x_3	STO	3	x_3
	Starting input angle				
	($\theta_1 \neq 90$ or 270)	θ_1	STO	4	θ_1
	Final input angle	θ_3	STO	6	θ_3
	Starting output angle	ϕ_1	STO	7	ϕ_1
	Final output angle	ϕ_3	STO	8	ϕ_3

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
4	Compute coefficients for				
	Freudenstein's equations		A		b_3
5	Optional: Review coefficients		RCL	1	d_1
			RCL	2	d_2
			RCL	3	d_3
			RCL	4	a_1
			RCL	5	a_2
			RCL	6	a_3
			RCL	7	b_1
			RCL	8	b_2
			RCL	9	b_3
6	Enter MD 1–09A2				
7	Compute Freudenstein's ratios		A		R_1
8	Optional: Display R_2		B		R_2
	and R_3		C		R_3
9	Enter MD 1–09A3				
10	Input fixed link length and com-				
	pute the remaining link lengths	a	D		b
			R/S		c
			R/S		d
11	For a new case, go to step 1.				
	The last program of this group				
	may be used alone to compute				
	the link ratios from the link				
	lengths, or the link lengths				
	from the link ratios, of the four-				
	bar mechanism.				

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter MD 1–09A3				
2	Input the link lengths	a	↑		a
		b	↑		b
		c	↑		c
		d	A		d
	and compute the link ratios		B		R_1
			R/S		R_2
			R/S		R_3
3	Input the link ratios	R_1	↑		R_1
		R_2	↑		R_2
		R_3	C		R_3
	and compute the link lengths				
	specifying the fixed link length	a	D		b
			R/S		c
			R/S		d
4	Step 2 or step 3 may be				
	repeated as required.				

Example 1:

Suppose the output of a linkage is to be the square root of the input. The input link is to move from 70° to 110° while the output moves from 100° to 140°. Precision points are $x_1 = 3$ (70°), $x_2 = 5$, and $x_3 = 9$ (110°). The distance between foundation pivots is 3.75. What are the remaining link lengths?

Solution:

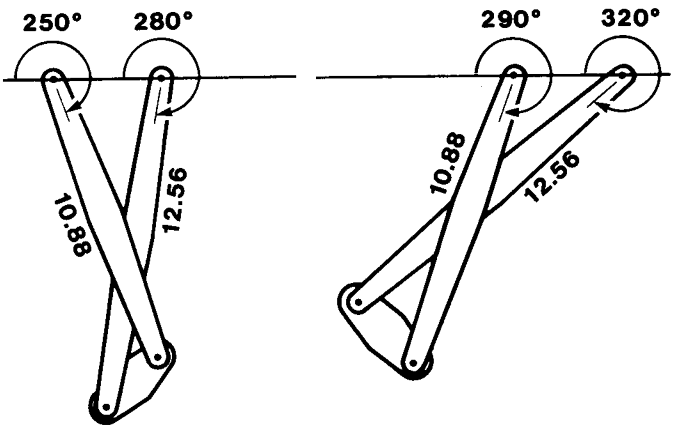
b = −10.88, c = 3.04, d = −12.56 (The negative signs indicate that the links are opposite to the assumed direction i.e., $\theta = 250°$ and $\phi = 280°$).

Keystrokes:

$f(x) = \sqrt{x}$

$x_1 = 3; x_2 = 5, x_3 = 9$

$\theta_1 = 70°; \theta_3 = 110°, \phi_1 = 100°, \phi_3 = 140°$



Enter MD1-9A1

GTO B

Switch to W/PRGM mode → 12

f √x RTN

Switch to RUN mode

3 STO 1 → 3.00

5 STO 2 → 5.00

9 STO 3 → 9.00

70 STO 4 → 70.00

110 STO 6 → 110.00

100 STO 7 → 100.00

140 STO 8 A → 0.77

Enter MD1-9A2

A → –0.30

Enter MD1-9A3

3.75 D → –10.88

R/S → 3.04

R/S → –12.56

Example 2:

Compute the link ratios for the following link lengths:

a = 1.0

b = 1.371

c = 2.12

d = 1.502

Solution:

R_1 = .6658

R_2 = .7294

R_3 = .1557

Keystrokes:

Enter MD1–9A3

DSP [•] 4 1 [ENTER↑] 1.371 [ENTER↑] 2.12

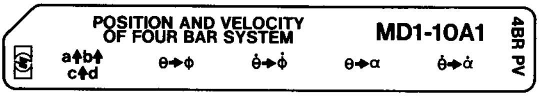
[ENTER↑] 1.502 A ——→ 1.5020

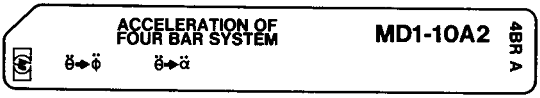
B ——→ .6658

R/S ——→ .7294

R/S ——→ .1557

PROGRESSION OF FOUR BAR SYSTEM





These two cards calculate the position, angular velocity, and angular acceleration of both the connecting and output links of a four bar mechanism, given the same values for the input link. The link lengths may be stored by the first card or by MD1-9A3.

$\theta, \dot{\theta}, \ddot{\theta}$ = Input link angle, angular velocity (RPM), and angular acceleration (RPM^2)

$\phi, \dot{\phi}, \ddot{\phi}$ = Output link angle, angular velocity (RPM), and angular acceleration (RPM^2)

$\alpha, \dot{\alpha}, \ddot{\alpha}$ = Connecting link angle, angular velocity (RPM), and angular acceleration (RPM^2)

a = Fixed link length

b = Input link length

c = Connecting link length

d = Output link length

Equations:

Output Link

$$\phi = \sin^{-1}\left(\frac{b}{e}\sin\theta\right) + \cos^{-1}\left(\frac{d^2 + e^2 - c^2}{2de}\right)$$

Connecting Link

$$\alpha = \sin^{-1}\left(\frac{b}{e}\sin\theta\right) + \cos^{-1}\left(\frac{c^2 + e^2 - d^2}{-2ce}\right)$$

where $e = \sqrt{a^2 + b^2 + 2ab\cos\theta}$

$$\frac{d\phi}{d\theta} = \frac{R_1 \sin\theta - \sin(\theta - \phi)}{R_2 \sin\phi - \sin(\theta - \phi)}$$

$$R_1 = \frac{a}{d} \qquad R_2 = \frac{a}{b}$$

$$\frac{d\alpha}{d\theta} = \frac{S_1 \sin\theta - \sin(\theta - \alpha)}{S_2 \sin\alpha - \sin(\theta - \alpha)}$$

$$S_1 = -\frac{a}{c} \qquad S_2 = \frac{a}{b}$$

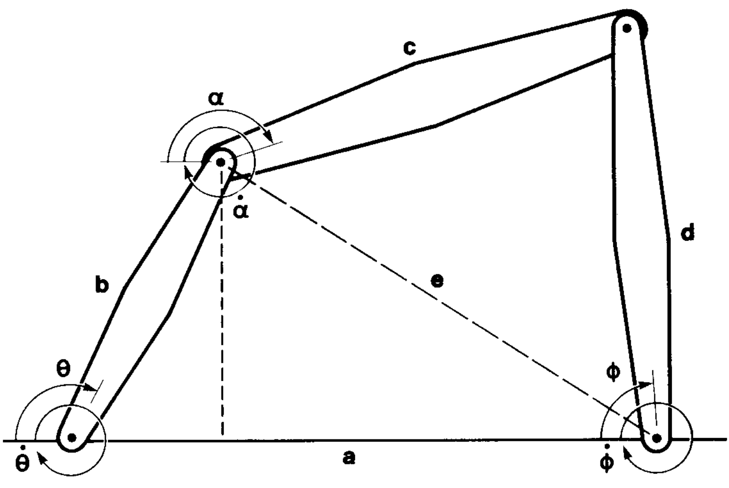
$$\frac{d^2\phi}{d\theta^2} = \frac{R_1 \cos\theta - R_2 \cos\phi \left(\frac{d\phi}{d\theta}\right)^2 - \left(1 - \frac{d\phi}{d\theta}\right)^2 \cos(\theta - \phi)}{R_2 \sin\phi - \sin(\theta - \phi)}$$

$$\frac{d^2\alpha}{d\theta^2} = \frac{S_1 \cos\theta - S_2 \cos\alpha \left(\frac{d\alpha}{d\theta}\right)^2 - \left(1 - \frac{d\alpha}{d\theta}\right)^2 \cos(\theta - \alpha)}{S_2 \sin\alpha - \sin(\theta - \alpha)}$$

$$\dot{\phi} = \frac{d\phi}{d\theta}\,\dot{\theta}$$

$$\ddot{\phi} = \frac{d^2\phi}{dt^2} = \frac{d^2\phi}{d\theta^2}\left(\frac{d\theta}{dt}\right)^2 + \frac{d^2\theta}{dt^2}\,\frac{d\phi}{d\theta} \qquad \dot{\alpha} = \frac{d\alpha}{d\theta}\,\dot{\theta}$$

$$= \dot{\theta}^2\,\frac{d^2\phi}{d\theta^2} + \ddot{\theta}\,\frac{d\phi}{d\theta} \qquad \ddot{\alpha} = \dot{\theta}^2\,\frac{d^2\alpha}{d\theta^2} + \ddot{\alpha}\,\frac{d\alpha}{d\theta}$$



Remarks:

ϕ has the units of θ, since $\frac{d\phi}{d\theta}$ is dimensionless.

$\frac{d^2\phi}{d\theta^2}$ has units of rad^{-1}. So that the dimensions making up $\ddot{\phi}$ agree, the program assumes $\frac{d^2\theta}{dt^2}$ is given in RPM^2, and $\frac{d^2\phi}{d\theta^2}$ is multiplied by $2\pi \frac{rad}{rev}$:

$$\ddot{\phi}\,\frac{rev}{min^2} = \dot{\theta}^2\,\frac{rev^2}{min^2}\,\frac{d^2\phi}{d\theta^2}\,rad^{-1}\left[\frac{2\pi\,rad}{rev}\right] + \ddot{\theta}\,\frac{rev}{min^2}\,\frac{d\phi}{d\theta}$$

The program could be altered by the appropriate constant change if $\dot{\theta}$ and $\ddot{\theta}$ are in units other than revolutions/time (e.g. for degrees/time change 2π to $\pi/180$ (radians/degree), or for radians/time, no constant necessary).

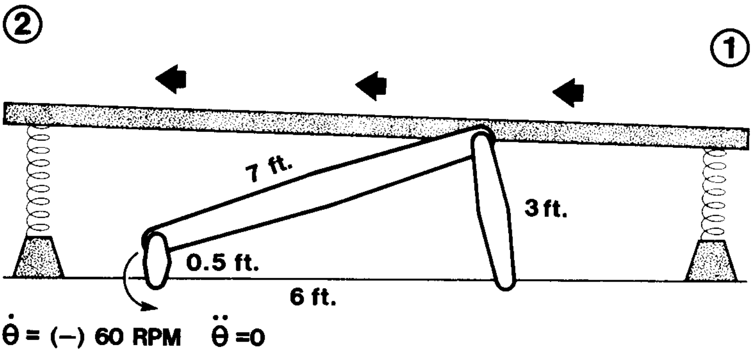
These same remarks apply to $\dot{\alpha}$ and $\ddot{\alpha}$.

Flashing zeroes during calculation of ϕ or α may indicate the linkage may not physically assume the input position.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter MD 1–10A1				
2	Input the link lengths	a	↑		a
		b	↑		b
		c	↑		c
		d	A		a
3a	Input the input link angle and				
	compute the output link angle	θ	B		ϕ
4a	Input the angular velocity in				
	RPM and compute the output				
	link velocity	$\dot{\theta}$ (RPM)	C		$\dot{\phi}$ (RPM)
5a	Optional: to compute the out-				
	put link acceleration, enter				
	MD 1–10A2, input the input				
	link acceleration and calculate				
	$\ddot{\phi}$ (Then re-enter MD1–10A1)	$\ddot{\theta}$ (RPM^2)	A		$\ddot{\phi}$ (RPM^2)
3b	Input the input link angle and				
	compute the connecting link				
	angle	θ	D		α
4b	Input the angular velocity in				
	RPM and compute the con-				
	necting link velocity	$\dot{\theta}$ (RPM)	E		$\dot{\alpha}$ (RPM)
5b	Optional: to compute the con-				
	necting link acceleration, enter				
	MD 1–10A2, input the input				
	link acceleration, and calculate				
	$\ddot{\alpha}$ (Then re-enter MD1–10A1)	$\ddot{\theta}$ (RPM^2)	B		$\ddot{\alpha}$ (RPM^2)
6	Repeat steps 3a-5a or 3b-5b for				
	all required values of (θ, $\dot{\theta}$, $\ddot{\theta}$,).				
7	For a new case, go to step 2.				

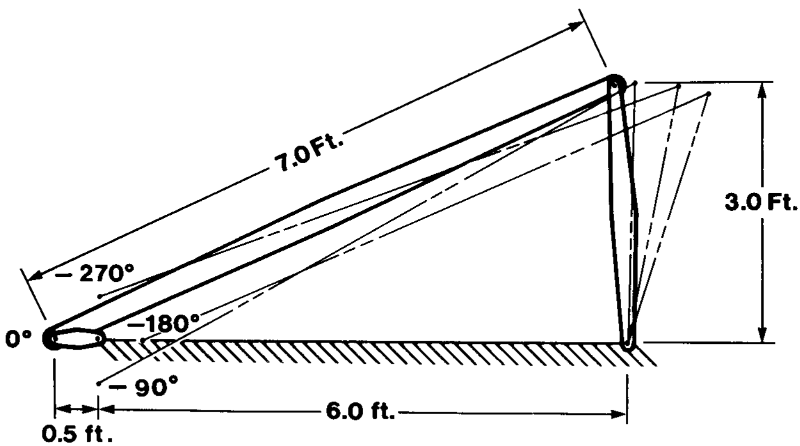
Example:

A four bar linkage is to be used to convert rotary motion from an electric motor to the reciprocating motion necessary to activate a shaking conveyor system which moves fruit between two process stations.



For the geometry shown above, what is the motion of the output link? Start at θ = 0° and go to –330° by –30° increments. (The negative sign is due to the sign convention for positive angles used in this program) Find the corresponding connecting link motion.

Four Bar Shaker Mechanism



Solution:

θ^0	ϕ^0	$\dot{\phi}$(RPM)	$\ddot{\phi}$(RPM^2)	α^0	$\dot{\alpha}$(RPM)	$\ddot{\alpha}$(RPM^2)
0	86.69	–4.62	3392.91	154.67	–4.62	–92.82
–30	85.63	0.46	3816.90	152.42	–4.20	713.38
–60	87.18	5.70	3615.33	150.67	–2.60	1594.02
–90	91.19	10.12	2592.67	150.01	0.10	2210.83
–120	96.94	12.38	449.28	150.84	3.19	2062.19
–150	102.95	10.93	–2597.20	153.04	5.34	887.00
–180	107.18	5.45	–4998.56	155.83	5.45	–693.75
–210	108.09	–1.86	–5112.85	158.18	3.73	–1628.64
–240	105.56	–7.86	–3351.37	159.45	1.32	–1738.45
–270	100.72	–10.95	–1099.60	159.53	–0.93	–1481.44
–300	95.11	–11.05	887.85	158.59	–2.75	–1133.46
–330	90.08	–8.70	2404.65	156.87	–4.04	–698.86

Keystrokes:

Enter MD1-10A1

6 [ENTER↑] .5 [ENTER↑] 7 [ENTER↑] 3 [A] ⟶ 6.00

0 [B] ⟶ 86.69

60 [CHS] [C] ⟶ –4.62

Enter MD1-10A2

0 [A] ⟶ 3392.91

Enter MD1-10A1

0 [D] ⟶ 154.67

60 [CHS] [E] ⟶ –4.62

Enter MD1-10A2

0 [B] ⟶ –92.82

Enter MD1-10A1

30 [CHS] [B] ⟶ 85.63

60 [CHS] [C] ⟶ 0.46

Enter MD1-10A2

0 [A] ——————————→ 3816.90

Enter MD1-10A1

30 [CHS] [D] ——————————→ 152.42

60 [CHS] [E] ——————————→ –4.20

Enter MD1-10A2

0 [B] ——————————→ 713.38

and so on.

LINEAR PROGRESSION OF SLIDER CRANK

This program computes the displacement, velocity, and acceleration of the slider in a slider crank mechanism, (e.g. the piston wrist-pin in an internal combustion engine) given crank radius, connecting rod length, slider offset, crankshaft speed, and crank position. The maximum and minimum displacements and the stroke are also calculated.

N = Crankshaft speed, RPM
E = Slider offset
L = Connecting rod length
R = Crank radius
ω = Crank angular velocity, radians/sec
θ = Crank angle
x = Slider displacement
x_{max} = Maximum slider displacement
x_{min} = Minimum slider displacement
Δx = Stroke
v = Slider velocity
a = Slider acceleration
ϕ = Connecting rod angle

Equations:

$$\omega = \frac{\pi N}{30}$$

$$x = R \cos\theta + L \cos\phi$$

$$x_{max} = (R + L) \cos\left[\sin^{-1}\left(\frac{E}{R + L}\right)\right]$$

$$x_{min} = (L - R) \cos\left[\sin^{-1}\left(\frac{E}{L - R}\right)\right]$$

$$\Delta x = x_{max} - x_{min}$$

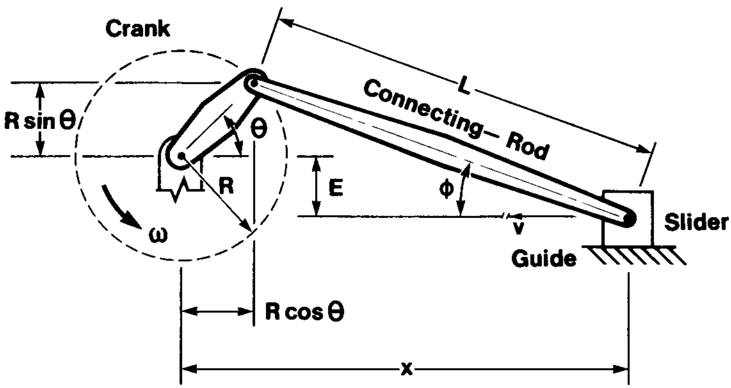
$$\phi = \sin^{-1}\left(\frac{E + R\sin\theta}{L}\right)$$

$$v = \frac{dx}{dt} = R\omega\left(\frac{-\sin(\theta + \phi)}{\cos\phi}\right)$$

$$a = \frac{d^2x}{dt^2} = R\omega^2\left(\frac{-\cos(\theta + \phi)}{\cos\phi} - \frac{R\cos^2\theta}{L\cos^3\phi}\right)$$

Remarks:

This program may halt on underflow for P→R in calculating $-R\sin(\theta + \phi)$ and $-R\cos(\theta + \phi)$. This occurs where $(\theta + \phi) = 90°$, $270°$ and $R < 1$, resulting in a display of 0.00. If this occurs, press R/S to continue the normal execution.



References:

Mechanical Design and Systems Handbook, H.A. Rothbart, McGraw-Hill, 1964.

Kinematics, V.M. Faires, McGraw-Hill, 1959.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter program		[ ] [ ]	
2	Input the slider crank		[ ] [ ]	
	parameters	N	[↑] [ ]	N
		E	[↑] [ ]	E
		L	[↑] [ ]	L
	and display the crank angular		[ ] [ ]	
	velocity	R	[A] [ ]	ω
3	Input the crank angle and com-		[ ] [ ]	
	pute the slider displacement	θ	[B] [ ]	x
	Optional: calculate the maxi-		[ ] [ ]	
	mum displacement		[R/S] [ ]	x_{max}
	Optional: calculate the mini-		[ ] [ ]	
	mum displacement		[R/S] [ ]	x_{min}
	Optional: calculate the stroke	*	[–] [ ]	Δx
4	Calculate the slider velocity		[C] [ ]	v
5	Calculate the slider acceleration		[D] [ ]	a
6	Repeat step 3 for all desired		[ ] [ ]	
	values of θ.		[ ] [ ]	
	Steps 4 and 5 may be executed		[ ] [ ]	
	(in order) as required		[ ] [ ]	
7	For a new case, go to step 2.		[ ] [ ]	

Example 1:

Find the displacement, velocity and acceleration of the wrist-pin in the slider of a slider crank mechanism having a crank radius of 2.0 inches and connecting rod length of 7.0 inches, turning at 4800 RPM. Compute values for

$$\theta = 0^{\circ}, 15^{\circ}, 45^{\circ}, 90^{\circ}, 135^{\circ}, 180^{\circ}, 225^{\circ}.$$

Assume the slider crank mechanism is in-line (E = 0). Also find the maximum and minimum displacements and the stroke.

Solution:

$\theta°$	x (in)	v (in/sec)	a (in/sec²)
0	9.00	0.00	–649701.96
15	8.91	–332.20	–614226.44
45	8.27	–857.50	–360454.40
90	6.71	–1005.31	150658.43
135	5.44	–564.22	354181.29
180	5.00	0.00	360945.53
225	5.44	564.22	354181.29

x_{max} = 9.00 in.

x_{min} = 5.00 in.

Δx = 4.00 in.

Keystrokes:

4800 [ENTER↑] 0 [ENTER↑] 7 [ENTER↑] 2 [A] ⟶ 502.65
0 [B] ⟶ 9.00
[C] ⟶ 0.00
[D] ⟶ –649701.96
15 [B] ⟶ 8.91
[C] ⟶ –332.20
[D] ⟶ –614226.44
⋮ ⋮
225 [B] ⟶ 5.44
[C] ⟶ 564.22
[D] ⟶ 354181.29
[B] [R/S] ⟶ 9.00
[R/S] ⟶ 5.00
[–] ⟶ 4.00

Example 2:

Determine the same values as in example 1 for a slider crank with offset of 1.5 inches (E = 1.5 inches).

Solution:

$\theta°$	x (in)	v (in/sec)	a (in/sec^2)
0	8.84	-220.55	-660249.41
15	8.63	-552.49	-602160.36
45	7.78	-1036.35	-289750.94
90	6.06	-1005.31	291748.80
135	4.95	-385.37	424884.76
180	4.84	220.55	350398.08
225	5.59	719.57	280733.14

x_{max} = 8.87 in.

x_{min} = 4.77 in.

Δx = 4.10 in.

Keystrokes:

1.5 [STO] 3 ⟶ 1.50

(Having executed example 1, we can repeat step 2 or manually store E, since only one parameter is changed. See page 178 for register allocation.)

0 [B] ⟶ 8.84
[C] ⟶ -220.55
[D] ⟶ -660249.41
. .
. .
. .
225 [B] ⟶ 5.59
[C] ⟶ 719.57
[D] ⟶ 280733.14
[B] [R/S] ⟶ 8.87
[R/S] ⟶ 4.77
[−] ⟶ 4.10

ANGULAR PROGRESSION OF SLIDER CRANK

This program computes the connecting rod angle, velocity, and acceleration in a slider crank mechanism (e.g. the connecting rod in an internal combustion engine), given crank radius, connecting rod length, slider offset, crankshaft speed (RPM) and crank position. The maximum and minimum angular values for ϕ and the total angular throw of the connecting rod are also calculated.

N = Crankshaft speed, RPM

E = Slider offset

L = Connecting rod length

R = Crank radius

ω = Crank angular velocity, radians/sec

θ = Crank angle

ϕ = Connecting rod angular displacement

ϕmax = Maximum connecting rod angular displacement

ϕmin = Minimum connecting rod angular displacement

$\Delta\phi$ = Total angular throw of connecting rod

$\dot{\phi}$ = Angular velocity of connecting rod

$\ddot{\phi}$ = Angular acceleration of connecting rod

Equations:

$$\omega = \frac{\pi N}{30}$$

$$\phi = \sin^{-1}\left(\frac{E + R\sin\theta}{L}\right)$$

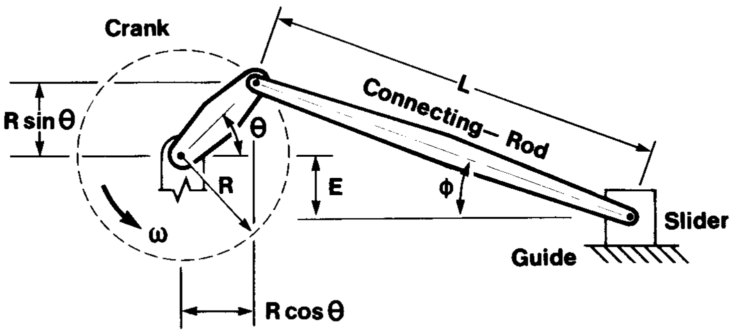
$$\phi\text{max} = \sin^{-1}\left(\frac{E + R}{L}\right)$$

$$\phi\text{min} = \sin^{-1}\left(\frac{E - R}{L}\right)$$

$$\Delta\phi = \phi\text{max} - \phi\text{min}$$

$$\dot{\phi} = \frac{d\phi}{dt} = \omega \frac{R\cos\theta}{L\cos\phi}$$

$$\ddot{\phi} = \frac{d^2\phi}{dt^2} = \omega^2 \left[\left(\frac{d\phi}{d\theta}\right)^2 \tan\phi - \frac{R\sin\theta}{L\cos\phi}\right]$$



References

Mechanical Design and Systems Handbook, H.A. Rothbart, McGraw-Hill, 1964.

Kinematics, V.M. Faires, McGraw-Hill, 1959.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter program			
2	Input the slider crank			
	parameters	N	↑	N
		E	↑	E
		L	↑	L
	and display the crank angular			
	velocity	R	A	ω
3	Input the crank angle and com-			
	pute the connecting rod angular			
	displacement	θ	B	ϕ
	Optional: calculate the maxi-			
	mum connecting rod angular			
	displacement		R/S	ϕmax
	Optional: calculate the mini-			
	mum connecting rod angular			
	displacement		R/S	ϕmin
	Optional: calculate the total			
	angular throw of the connecting			
	rod		R/S	$\Delta\phi$
4	Calculate the angular velocity		C	$\dot{\phi}$
5	Calculate the angular accelera-			
	tion		D	$\ddot{\phi}$
6	Repeat step 3 for all desired			
	values of θ.			
	Steps 4 and 5 may be executed			
	(in order) as required.			
7	For a new case, go to step 2.			

Example 1:

Find the angular displacement, velocity, and acceleration of the connecting rod of a slider crank mechanism having a crank radius of 2.0 inches and connecting rod length of 7.0 inches, turning at 4800 RPM. Compute values for

$$\theta = 0°, 15°, 45°, 90°, 135°, 180°, 225°.$$

Assume the slider crank mechanism is in-line (E = 0). Also find the maximum and minimum displacements and the total angular throw of the connecting rod.

Solution:

$\theta°$	$\phi°$	$\dot{\phi}$ (rad/sec)	$\ddot{\phi}$ (rad/sec^2)
0	0.00	143.62	0.00
15	4.24	139.10	-17300.41
45	11.66	103.69	-49902.29
90	16.60	0.00	-75329.22
135	11.66	-103.69	-49902.29
180	0.00	-143.62	0.00
225	-11.66	-103.69	49902.29

$\phi max = 16.60°$

$\phi min = -16.60°$

$\Delta\phi = 33.20°$

Keystrokes:

4800 [ENTER↑] 0 [ENTER↑] 7 [ENTER↑] 2 [A] ——→ 502.65
0 [B] ——→ 0.00
[C] ——→ 143.62
[D] ——→ 0.00
15 [B] ——→ 4.24
[C] ——→ 139.10
[D] ——→ -17300.41
⋮ ⋮

225 B ⟶ –11.66

C ⟶ –103.69

D ⟶ 49902.29

B R/S ⟶ 16.60

R/S ⟶ –16.60

R/S ⟶ 33.20

Example 2:

Determine the same values as in example 1 for a slider crank with offset of 1.5 inches (E = 1.5 inches).

Solution:

$\theta°$	$\phi°$	$\dot{\phi}$ (rad/sec)	$\ddot{\phi}$ (rad/sec^2)
0	12.37	147.03	4742.62
15	16.75	144.87	–13194.60
45	24.60	111.69	–50429.96
90	30.00	0.00	–83356.80
135	24.60	–111.69	–50429.96
180	12.37	–147.03	4742.62
225	0.70	–101.56	51175.65

$\phi max = 30.00°$

$\phi min = –4.10°$

$\Delta\phi = 34.10°$

Keystrokes:

1.5 STO 3 ⟶ 1.50

(Having executed example 1, we can repeat step 2, or manually store E since only one parameter is changed. See page 178 for register allocation.)

0 B ⟶ 12.37

C ⟶ 147.03

D ⟶ 4742.62

⋮ ⋮

225 B ⟶ 0.70

C ⟶ –101.56

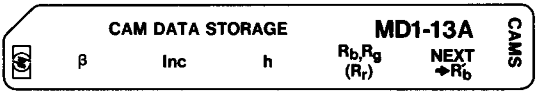
D ⟶ 51175.65

B R/S ⟶ 30.00

R/S ⟶ –4.10

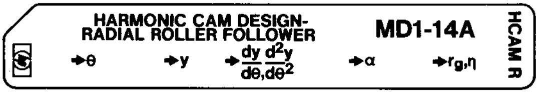
R/S ⟶ 34.10

CAM DATA STORAGE



This program stores the cam data for programs 14 through 18 in this Pac. A description is given with each of the programs for using this program to set up the required cam parameters. It is also used to link between different portions of a cam design.

HARMONIC CAM DESIGN-RADIAL ROLLER FOLLOWER



This program computes the parameters necessary for the design of a harmonic circular cam with radial roller or point follower. MD1-13A stores the required cam data for each portion of the design.

β = Duration of lift h

Inc = Angular increment of calculation

h = Total cam lift over angle β

R_b = Base circle radius

R_g = Grinder radius

R_r = Roller radius

θ = Cam angle

y = Follower lift

$\frac{dy}{d\theta}$ = Follower velocity

$\frac{d^2y}{d\theta^2}$ = Follower acceleration

α = Pressure angle

r_g = Center to center distance of grinder and cam

η = Angle correction for grinder

Equations:

$$y = \frac{h}{2}\left(1 - \cos\frac{180\theta}{\beta}\right)$$

$$\frac{dy}{d\theta} = \frac{\pi h}{2\beta}\sin\frac{180\theta}{\beta} \qquad \left[\frac{dy}{dt} = \omega\,\frac{dy}{d\theta}\right]$$

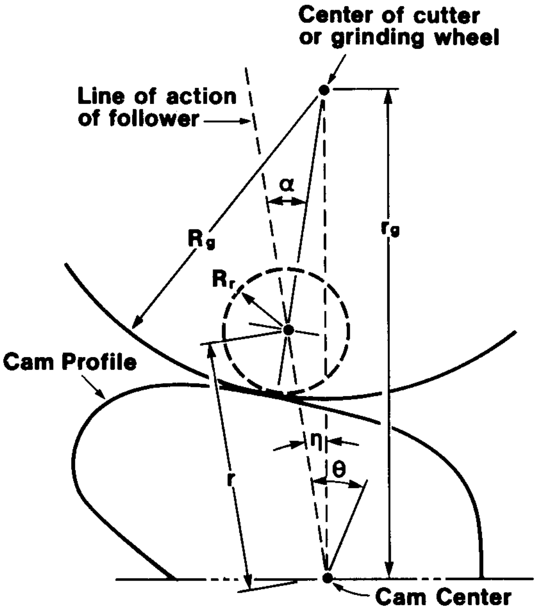
$$\frac{d^2y}{d\theta^2} = \frac{\pi^2 h}{2\beta^2}\cos\frac{180\theta}{\beta} \qquad \left[\frac{d^2y}{dt^2} = \omega^2\,\frac{d^2y}{d\theta^2}\right]$$

$$\alpha = \tan^{-1}\left(\frac{180}{\pi r}\ \frac{dy}{d\theta}\right)$$

$$r = R_b + y$$

$$r_g = \left[r^2 + (R_g - R_r)^2 + 2r\,(R_g - R_r)\cos\alpha\right]^{1/2}$$

$$\eta = \sin^{-1}\left(\frac{R_g - R_r}{r_g}\ \sin\alpha\right)$$



Remarks:

A roller follower will not properly follow a cam profile with concave section whose radius $< R_r$, e.g. See Figure 1.

The values calculated for r_g are at an angle $\theta - \eta$ because of the lead or lag of the roller surface.

Values calculated for y are with reference to the beginning of each portion of the design.

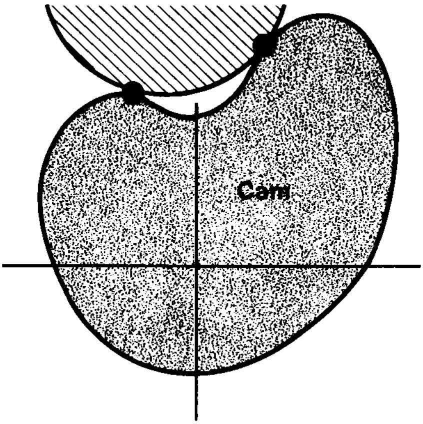


Figure 1
Note two points of contact

Reference: Design of Machine Elements, M.F. Spotts, Prentice-Hall, 1971.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter MD 1–13A		[ ] [ ]	
2	Input the following:		[ ] [ ]	
	Duration	β	[A] [ ]	β
	Increment	Inc	[B] [ ]	Inc
	Total lift	h	[C] [ ]	h
	Base radius	R_b	[D] [ ]	R_b
	Grinder radius	R_g	[D] [ ]	R_g
	Roller radius	R_r	[D] [ ]	R_r
3	Enter MD 1–14A		[ ] [ ]	
4	Calculate the cam parameters:		[ ] [ ]	
	Cam angle		[A] [ ]	θ
	Lift		[B] [ ]	y
	Follower velocity		[C] [ ]	$dy/d\theta$
	Follower acceleration	*	[R/S] [ ]	$d^2y/d\theta^2$
	Pressure angle		[D] [ ]	α
	Grinder-cam center/center		[ ] [ ]	
	distance		[E] [ ]	r_g
	Grinder correction angle		[R/S] [ ]	η
5	Repeat step 4 for all $\theta \leqslant \beta$.		[ ] [ ]	
6	To continue cam design when		[ ] [ ]	
	$\theta = \beta$, re-enter MD 1–13A, press		[ ] [ ]	
	NEXT, and change duration,		[ ] [ ]	
	increment and/or lift as required.		[ ] [ ]	
	Then go to step 3.		[E] [ ]	R_b'
7	For an entirely new case, go to		[ ] [ ]	
	step 1.		[ ] [ ]	

Example:

Design a cam with a 1.0 inch roller follower which develops harmonic motion, dropping from a base radius of 12.0 inches to 7.5 inches in 130° of rotation. From 130° to 170°, increase the lift to the original base radius. Using 10° increments, generate the cam profile by letting $R_g = 0$.

Solution:

	θ°	y (in)	dy/dθ (in/deg)	d²y/dθ² (in/deg²)	α°	r_g (in)	η°
	0.0000	0.0000	0.0000	–0.0013	0.0000	11.0000	0.0000
	10.0000	–0.0654	–0.0130	–0.0013	–3.5746	10.9367	0.3266
	20.0000	–0.2577	–0.0253	–0.0012	–7.0289	10.7505	0.6522
	30.0000	–0.5659	–0.0361	–0.0010	–10.2415	10.4516	0.9747
	40.0000	–0.9719	–0.0447	–0.0007	–13.0881	10.0567	1.2903
	50.0000	–1.4521	–0.0508	–0.0005	–15.4382	9.5876	1.5910
	60.0000	–1.9788	–0.0540	–0.0002	–17.1509	9.0705	1.8631
	70.0000	–2.5212	–0.0540	0.0002	–18.0701	8.5338	2.0830
	80.0000	–3.0479	–0.0508	0.0005	–18.0244	8.0072	2.2146
	90.0000	–3.5281	–0.0447	0.0007	–16.8378	7.5203	2.2074
	100.0000	–3.9341	–0.0361	0.0010	–14.3662	7.1015	2.0023
	110.0000	–4.2423	–0.0253	0.0012	–10.5713	6.7772	1.5512
	120.0000	–4.4346	–0.0130	0.0013	–5.6283	6.5709	0.8552
	130.0000	–4.5000	0.0000	0.0013	0.0000	6.5000	0.0000
(130)	0.0000	0.0000	0.0000	0.0139	0.0000	6.5000	0.0000
(140)	10.0000	0.6590	0.1250	0.0098	41.2667	7.4367	–5.0883
(150)	20.0000	2.2500	0.1767	0.0000	46.0809	9.0850	–4.5476
(160)	30.0000	3.8410	0.1250	–0.0098	32.2638	10.5090	–2.9117
(170)	40.0000	4.5000	0.0000	–0.0139	0.0000	11.0000	0.0000

Keystrokes:

Enter MD1-13A

130 [A] 10 [B] 4.5 [CHS] [C] 12 [D] 0 [D] 1 [D] ⟶ 1.00

Enter MD1-14A

[DSP] [•] 4

[A] ⟶ 0.0000

[B] ⟶ 0.0000

[C] ⟶ 0.0000

[R/S] ⟶ –0.0013

[D] ⟶ 0.0000

[E] ⟶ 11.0000

[R/S] ⟶ 0.0000

⋮

[A] ⟶ 130.0000

[B] ⟶ –4.5000

[C] ⟶ 0.0000

[R/S] ⟶ 0.0013

D ——→ 0.0000

E ——→ 6.5000

R/S ——→ 0.0000

Enter MD1-13A

E ——→ 7.5000

40 A ——→ 40.0000

4.5 C ——→ 4.5000

Enter MD1-14A

A ——→ 0.0000

B ——→ 0.0000

C ——→ 0.0000

R/S ——→ 0.0139

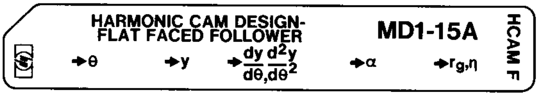
D ——→ 0.0000

E ——→ 6.5000

R/S ——→ 0.0000

and so on.

HARMONIC CAM DESIGN-FLAT FACED FOLLOWER



This program computes the parameters necessary for the design of a cam with radial flat-faced follower. MD1-13A stores the required cam data for each portion of the design.

β = Duration of lift h

Inc = Angular increment of calculation

h = Total cam lift over angle β

R_b = Base circle radius

R_g = Grinder radius

θ = Cam angle

y = Follower lift

$\frac{dy}{d\theta}$ = Follower velocity

$\frac{d^2y}{d\theta^2}$ = Follower acceleration

α = Pressure angle

r_g = Center to center distance of grinder and cam

η = Angle correction for grinder

Equations:

$$y = \frac{h}{2}\left(1 - \cos\frac{180\theta}{\beta}\right)$$

$$\frac{dy}{d\theta} = \frac{\pi h}{2\beta}\sin\frac{180\theta}{\beta} \qquad \left[\frac{dy}{dt} = \omega\frac{dy}{d\theta}\right]$$

$$\frac{d^2y}{d\theta^2} = \frac{\pi^2 h}{2\beta^2}\cos\frac{180\theta}{\beta} \qquad \left[\frac{d^2y}{dt^2} = \omega^2\frac{d^2y}{d\theta^2}\right]$$

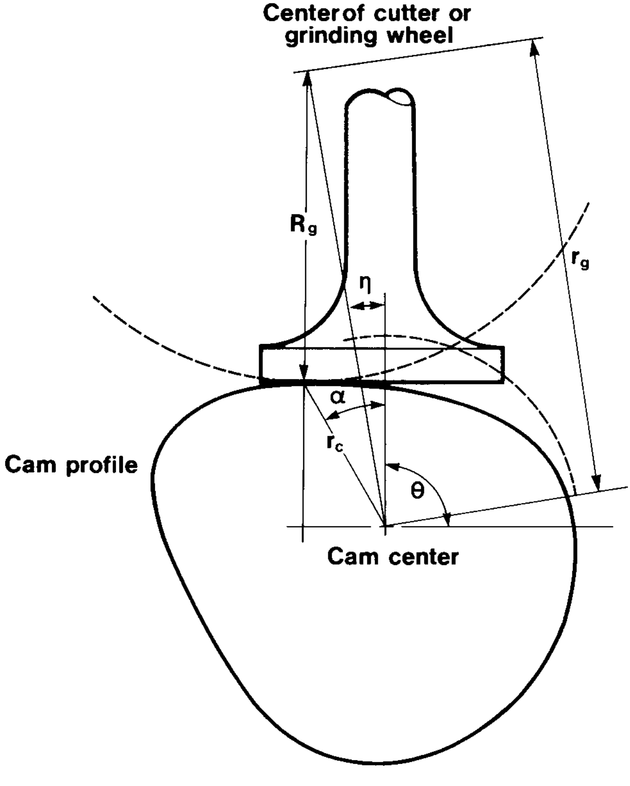
$$\alpha = \tan^{-1}\left(\frac{180}{\pi r}\frac{dy}{d\theta}\right)$$

$$r = R_b + y$$

$$r_g = (R_g^2 + r_c^2 + 2R_g r_c \cos\alpha)^{1/2}$$

$$r_c = \left(r^2 + \frac{180}{\pi}\left(\frac{dy}{d\theta}\right)^2\right)^{1/2}$$

$$\eta = \cos^{-1}\left(\frac{r_c + R_g \cos\alpha}{r_g}\right) - \alpha$$



Remarks:

A flat follower will not properly follow a cam profile with any concave section, e.g. see figure 1. The values calculated for r_g are at an angle $\theta - \eta$ because of the lead or lag of the roller surface.

The program may halt on underflow during calculation of r_g if the pressure angle $\alpha = 90°$.

Values calculated for y are with reference to the beginning of each portion of the design.

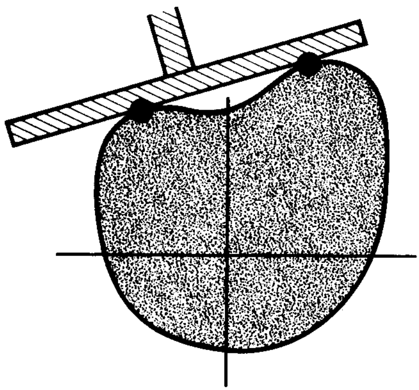


Figure 1
Note two points of contact

Reference: Design of Machine Elements, M.F. Spotts, Prentice-Hall 1971.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter MD 1–13A				
2	Input the following:				
	Duration	β	A		β
	Increment	Inc	B		Inc
	Total Lift	h	C		h
	Base Radius	R_b	D		R_b
	Grinder Radius	R_g	D		R_g
3	Enter MD 1–15A				
4	Calculate the cam parameters:				
	Cam Angle		A		θ
	Lift		B		y
	Follower Velocity		C		$dy/d\theta$
	Follower Acceleration	*	R/S		$d^2y/d\theta^2$
	Pressure Angle		D		α
	Grinder-Cam Center/Center				
	Distance		E		r_g
	Grinder Correction Angle	*	R/S		η
5	Repeat step 4 for all $\theta \leqslant \beta$.				
6	To continue cam design when				
	$\theta = \beta$, re-enter MD 1–13A, press				
	NEXT, and change duration,				
	increment and/or lift as required.				
	Then go to step 3.		E		R_b'
7	For an entirely new case, go to				
	step 1.				

Example:

Design a plastic cam starting at a 5.0 inch base radius, develop a harmonic motion for the first 110° of rotation, with a total lift of 1.0 inches.

Solution:

$\theta°$	y (in)	$dy/d\theta$ (in/deg)	$d^2y/d\theta$ (in/deg^2)	$\alpha°$	r_g (in)	$\eta°$
0.0000	0.0000	0.0000	0.0004	0.0000	5.0000	0.0000
10.0000	0.0203	0.0040	0.0004	2.6289	5.0203	–2.6289
20.0000	0.0794	0.0077	0.0003	4.9771	5.0794	–4.9771
30.0000	0.1726	0.0108	0.0003	6.8169	5.1726	–6.8169
40.0000	0.2923	0.0130	0.0002	8.0049	5.2923	–8.0049
50.0000	0.4288	0.0141	0.0001	8.4846	5.4289	–8.4846
60.0000	0.5712	0.0141	–0.0001	8.2709	5.5712	–8.2709
70.0000	0.7077	0.0130	–0.0002	7.4290	5.7077	–7.4290
80.0000	0.8274	0.0108	–0.0003	6.0569	5.8274	–6.0569
90.0000	0.9206	0.0077	–0.0003	4.2728	5.9206	–4.2728
100.0000	0.9797	0.0040	–0.0004	2.2076	5.9797	–2.2076
110.0000	1.0000	0.0000	–0.0004	0.0000	6.0000	0.0000

Keystrokes:

Enter MD1-13A

DSP [•] 4

110 A 10 B 1 C 5 D 0 D → 0.0000

Enter MD1-15A

A → 0.0000
B → 0.0000
C → 0.0000
R/S → 0.0004
D → 0.0000
E → 5.0000
R/S → 0.0000
A → 10.0000
B → 0.0203
C → 0.0040
R/S → 0.0004
D → 2.6289
E → 5.0203
R/S → –2.6289

⋮

A → 110.0000
B → 1.0000

C → 0.0000

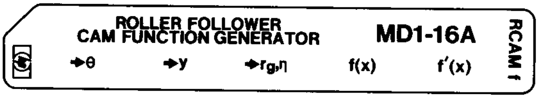
R/S → –0.0004

D → 0.0000

E → 6.0000

R/S → 0.0000

ROLLER FOLLOWER CAM FUNCTION GENERATOR



This program generates roller follower circular cam data for an arbitrary function. The user specifies the follower function and its derivative by keying them in memory. Values are then calculated for grinding the cam. MD1-13A is used to store the necessary cam parameters. The values calculated for r_g are at an angle $\theta - \eta$ because of the lead or lag of the roller surface. 35 steps are available to the user for the function and its derivative.

β = Duration of lift h

Inc = Angular increment of calculation

h = Total lift over angle β

R_b = Base circle radius

R_r = Roller radius

θ = Cam angle

y = Follower lift

$\frac{dy}{d\theta}$ = Follower velocity

α = Pressure angle

r_g = Center to center distance of grinder and cam

η = Angle correction for grinder

Equations:

$$y = hf(\theta/\beta)$$

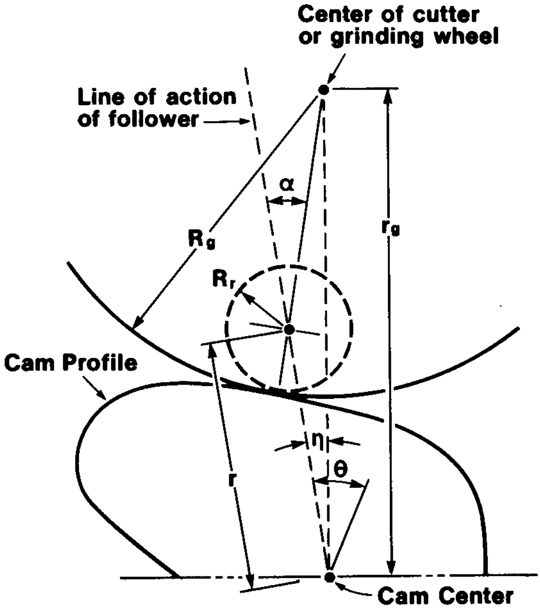
$$\frac{dy}{d\theta} = \frac{dy}{dx}\frac{dx}{d\theta} = \frac{h}{\beta}\frac{dy}{dx}$$

$$r = R_b + y$$

$$\alpha = \tan^{-1}\left(\frac{180}{\pi r}\frac{dy}{d\theta}\right)$$

$$r_g = (r^2 + (R_g - R_r)^2 - 2r(R_g - R_r)\cos\alpha)^{1/2}$$

$$\eta = \sin^{-1}\left(\frac{R_g - R_r}{r_g}\sin\alpha\right)$$



Remarks:

This program may halt on underflow during calculation of r_g if the pressure angle $\alpha = 90°$.

Values calculated for y are with reference to the beginning of each portion of the design.

Reference: Design of Machine Elements, M.F. Spotts, Prentice-Hall, 1971.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter MD 1–13A				
2	Input the following:				
	Duration	β	A		β
	Increment	Inc	B		Inc
	Total lift	h	C		h
	Base radius	R_b	D		R_b
	Grinder radius	R_g	D		R_g
	Roller radius	R_r	D		R_r
3	Enter MD 1–16A				
4	Key the function and its deriva-				
	tive into memory:		GTO	D	
	Switch to W/PRGM mode				14
	Key in the function	function			
	Press RTN LBL		RTN		
	E		LBL	E	
	Key in the derivative	derivative			
	Press RTN		RTN		
	Switch to RUN mode				
	The argument of the function				
	and the derivative is in X when				
	the routines are called. The				
	argument is also available in R_6.				
5	Calculate the cam parameters:				
	Cam angle		A		θ
	Lift		B		y
	Grinder-cam center/center				
	distance		C		r_g
	Grinder correction angle		R/S		η
6	Repeat step 5 for all $\theta < \beta$				

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
7	To continue cam design, enter		[E] [ ]	R_b'
	MD 1–13A, press NEXT, and		[ ] [ ]	
	change duration, increment and/		[ ] [ ]	
	or lift as required. Then go to		[ ] [ ]	
	step 3.		[ ] [ ]	
8	For an entirely new case, go to		[ ] [ ]	
	step 2.		[ ] [ ]	

Example:

A cam with a roller follower is to convert an angular input between 0° and 90° to a linear output according to the following equation and its derivative:

$$y = \left(\frac{\theta}{\beta}\right)^{1/2}$$

$$\dot{y} = \frac{1}{2}\left(\frac{\theta}{\beta}\right)^{-1/2}$$

If h is 1 inch and θ is incremented 10° at a time, generate the cam profile by setting R_g to zero. Skip the 0° calculations since $\dot{y}$ is undefined at this point.

$$R_r = 0.20 \text{ inches}$$

$$R_b = 3.0 \text{ inches}$$

Solution:

$\theta°$	y (in)	r_g (in)	$\eta°$
10.00	0.33	3.14	-1.00
20.00	0.47	3.28	-0.67
30.00	0.58	3.38	-0.52
40.00	0.67	3.47	-0.43
50.00	0.75	3.55	-0.37
60.00	0.82	3.62	-0.32
70.00	0.88	3.68	-0.29
80.00	0.94	3.74	-0.26
90.00	1.00	3.80	-0.24

Keystrokes:

Enter MD1-13A

90 A 10 B 1 C 3 D 0 D .2 D → 0.20

Enter MD1-16A

GTO D

Switch to W/PRGM mode → 14

f √x RTN LBL E f √x 2 × g 1/x RTN

Switch back to RUN mode

A → 0.00
(Skip calculating for 0°)

A → 10.00

B → 0.33

C → 3.14

R/S → –1.00

A → 20.00

B → 0.47

C → 3.28

R/S → –0.67

A → 30.00

B → 0.58

C → 3.38

R/S → –0.52

A → 40.00

B → 0.67

C → 3.47

R/S → –0.43

A → 50.00

B → 0.75

C → 3.55

R/S → –0.37

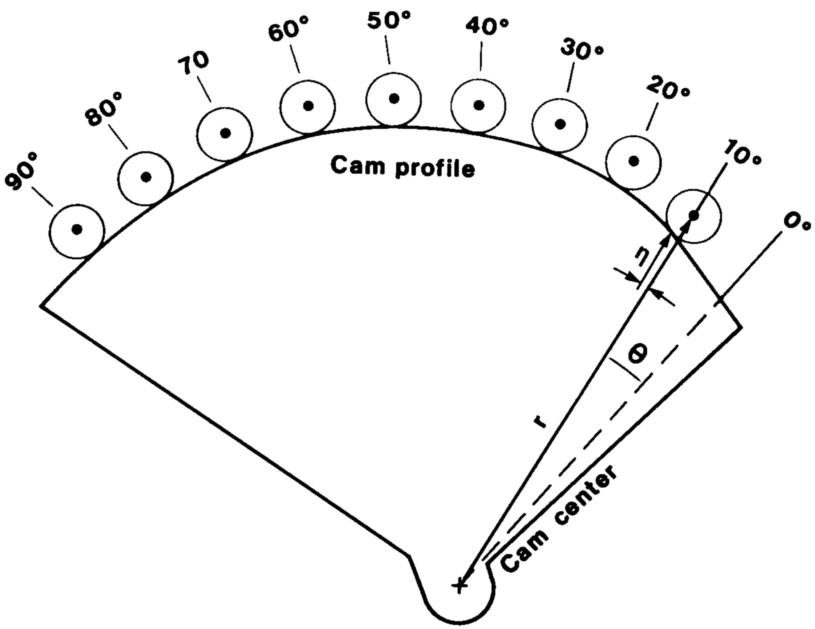
A → 60.00

B → 0.82

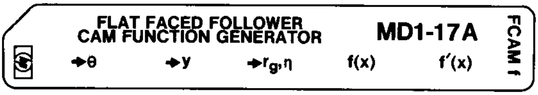
C → 3.62

R/S	–0.32
A	70.00
B	0.88
C	3.68
R/S	–0.29
A	80.00
B	0.94
C	3.74
R/S	–0.26
A	90.00
B	1.00
C	3.80
R/S	–0.24

The cam profile is plotted below:



FLAT FACED FOLLOWER CAM FUNCTION GENERATOR



This program generates flat faced follower circular cam data for an arbitrary function. The user specifies the follower function and its derivative by keying them in memory. Values are then calculated for grinding the cam. MD1-13A is used to store the necessary cam parameters. The values calculated for r_g are at an angle $\theta - \eta$ because of the lead or lag of the follower surface. 29 steps are available to the user for the function and its derivative.

β = Duration of lift h

Inc = Angular increment of calculation

h = Total lift over angle β

R_b = Base circle radius

θ = Cam angle

y = Follower lift

$\frac{dy}{d\theta}$ = Follower velocity

α = Pressure angle

r_g = Center to center distance of grinder and cam

η = Angle correction for grinder

Equations:

$$y = hf(\theta/\beta)$$

$$\frac{dy}{d\theta} = \frac{dy}{dx}\frac{dx}{d\theta} = \frac{h}{\beta}\frac{dy}{dx}$$

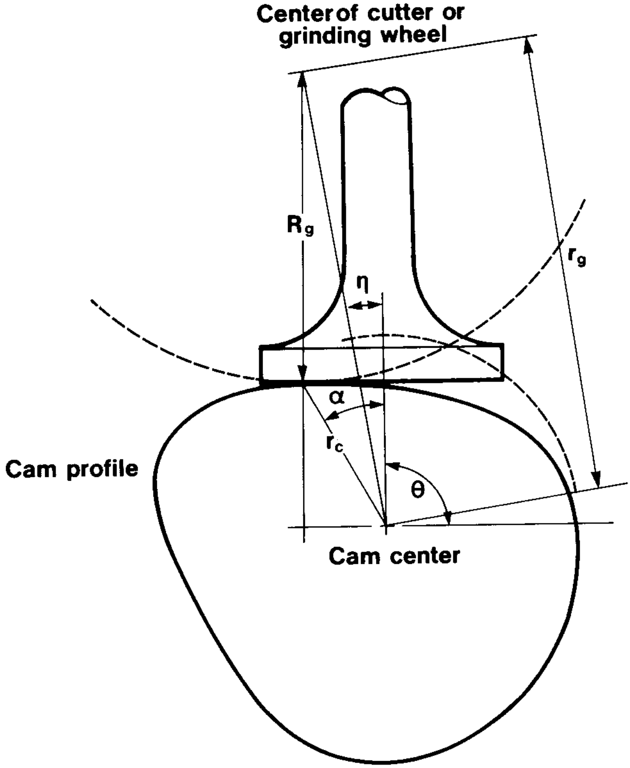
$$r = R_b + y$$

$$\alpha = \tan^{-1}\left(\frac{180}{\pi r}\frac{dy}{d\theta}\right)$$

$$r_c = \left(r^2 + \left(\frac{180}{\pi}\frac{dy}{d\theta}\right)^2\right)^{1/2}$$

$$r_g = (R_g^2 + r_c^2 + 2R_g r_c \cos\alpha)^{1/2}$$

$$\eta = \cos^{-1}\left(\frac{r_c + R_g \cos\alpha}{r_g}\right) - \alpha$$



Remarks:

This program may halt on underflow during calculation of r_g if the pressure angle $\alpha = 90°$.

Values calculated for y are with reference to the beginning of each portion of the design.

Reference: Design of Machine Elements, M.F. Spotts, Prentice-Hall, 1971.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter MD 1–13A				
2	Input the following:				
	Duration	β	A		β
	Increment	Inc	B		Inc
	Total lift	h	C		h
	Base radius	R_b	D		R_b
	Grinder radius	R_g	D		R_g
3	Enter MD 1–17A				
4	Key in the function and its				
	derivative into memory:		GTO	D	
	Switch to W/PRGM mode				14
	Key in the function	function			
	Press RTN LBL		RTN		
	E		LBL	E	
	Key in the derivative, press RTN	derivative	RTN		
	Switch to RUN mode				
	The argument of the function				
	and its derivative is in X when				
	the routines are called. The				
	argument is also available in R_6.				
5	Calculate the cam data:				
	Cam angle		A		θ
	Lift		B		y
	Grinder-cam center/center				
	distance		C		r_g
	Grinder correction angle	*	R/S		η
6	Repeat step 5 for all $\theta \leqslant \beta$.				
7	To continue cam design, enter				
	MD 1–13A, press NEXT and				
	change duration, increment and/				
	or lift as required. Then go to				
	step 3.		E		R_b'
8	For an entirely new case, go to				
	step 2.				

Example:

A cam with a flat-faced follower is to convert an angular input to a linear output according to the following equation and its derivative.

$$y = \left(\frac{\theta}{\beta}\right)^{1/2}$$

$$\dot{y} = \frac{1}{2}\left(\frac{\theta}{\beta}\right)^{-1/2}$$

Let β = 90° and h = 1 inch. Generate the cam profile from 10° to 90° in increments of 10° by setting R_g = 0. Skip the 0° calculations since $\dot{y}$ is undefined at this point.

R_b = 3.0 inches
h = 1.0 inches

Solution:

$\theta°$	y (in)	r_g (in)	$\eta°$
10.00	0.33	3.47	–15.99
20.00	0.47	3.54	–11.01
30.00	0.58	3.62	–8.76
40.00	0.67	3.70	–7.42
50.00	0.75	3.77	–6.50
60.00	0.82	3.84	–5.83
70.00	0.88	3.90	–5.31
80.00	0.94	3.96	–4.89
90.00	1.00	4.01	–4.55

Keystrokes:

Enter MD1-13A

90 [A] 10 [B] 1 [C] 3 [D] 0 [D] ——→ 0.00

Enter MD1-17A

[GTO] [D]

Switch to W/PRGM mode ——→ 14

[f] [√x] [RTN] [LBL] [E] [f] [√x] 2 [×] [g] [1/x] [RTN]

Switch back to RUN mode

A →	0.00
	(Skip calculating for 0°)
A →	10.00
B →	0.33
C →	3.47
R/S →	–15.99
A →	20.00
B →	0.47
C →	3.54
R/S →	–11.01
A →	30.00
B →	0.58
C →	3.62
R/S →	–8.76
A →	40.00
B →	0.67
C →	3.70
R/S →	–7.42
A →	50.00
B →	0.75
C →	3.77
R/S →	–6.50
A →	60.00
B →	0.82
C →	3.84
R/S →	–5.83
A →	70.00
B →	0.88
C →	3.90
R/S →	–5.31

A → 80.00

B → 0.94

C → 3.96

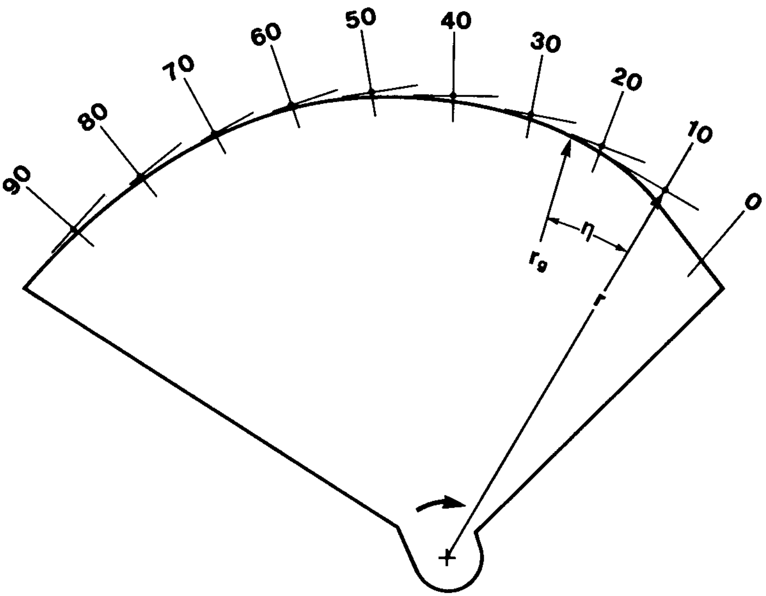
R/S → –4.89

A → 90.00

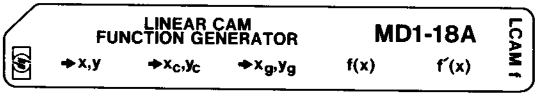
B → 1.00

C → 4.01

R/S → –4.55



LINEAR CAM FUNCTION GENERATOR



This program generates roller or point follower cam data for an arbitrary function on a linear cam. The user specifies the follower function and its derivative by keying them in memory. Values are then calculated for the cam profile, pitch curve (or roller path) and grinder path. MD1-13A is used to store the necessary cam parameters. 28 steps are available to the user for the function and its derivative.

L = Duration of lift h

Inc = Linear increment of calculation

h = Total follower lift over length L

R_b = Base height

R_r = Roller radius

R_g = Grinder radius

x = Linear displacement of cam

y = Roller center height above datum

x_c, y_c = Roller contact point coordinates for displacement x

x_g, y_g = Grinder center for displacement x

α = Pressure angle

Equations:

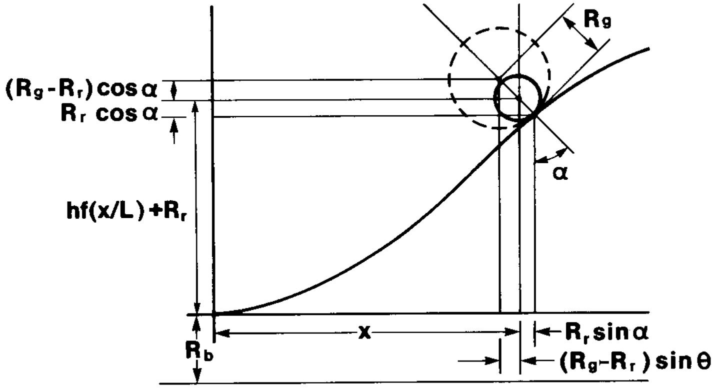
$$y = hf(x/L) + R_b + R_r$$

$$x_c = x + R_r \sin \alpha \qquad y_c = y - R_r \cos \alpha$$

$$x_g = x - (R_g - R_r) \sin \alpha \qquad y_g = y + (R_g - R_r) \cos \alpha$$

$$\alpha = \tan^{-1} \left(\frac{dy}{dx}\right)$$

$$= \tan^{-1} \left(\frac{h}{L} f'\ (x/L)\right)$$



Remarks:

This program may halt during calculation of (x_c, y_c) and (x_g, y_g) if the pressure angle $\alpha = 90°$.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter MD 1–13A1				
2	Input the cam parameters:				
	Duration	L	A		L
	Increment	Inc	B		Inc
	Lift	h	C		h
	Base height	R_b	D		R_b
	Grinder radius	R_g	D		R_g
	Roller radius	R_r	D		R_r
3	Enter MD 1–18A				
4	Key in the function and its				
	derivative into memory:		GTO	D	
	Switch to W/PRGM mode				14
	Key in the function	function			
	Press RTN LBL		RTN		
	E		LBL	E	
	Key in the derivative	derivative			
	Press RTN		RTN		
	Switch to RUN mode				

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
	The argument of the function				
	and its derivative is in X when				
	these routines are called. It is				
	also available if necessary by				
	the following:				
			RCL	2	
			RCL	1	
			÷		argument
5	Calculate the roller center		A		x
	coordinates		R/S		y
6	Calculate the profile coordinates		B		x_c
		*	R/S		y_c
7	Calculate the grinder center				
	coordinates		C		x_g
		*	R/S		y_g
8	Steps 6 and 7 may be executed				
	in any order after A is pressed.				
	Repeat step 5 for all x ≤ L.				
9	To continue the cam design,				
	enter MD 1–13A, press NEXT,				
	and change duration, increment,				
	and/or lift as required. Then go				
	to step 3.		E		R_b'
10	For an entirely new case, go to				
	step 1.				

Example:

A 1 inch roller follower is to trace a path corresponding to the function $y = x^2$, from x = 0 inches to 10 inches on a linear cam. The cam will be ground by a 3 inch radius grinder. The follower should lift 2 inches over the total length. Calculate the cam data and roller and grinder center locations at increments of 1 inch. The base height of the cam is 1 inch.

Solution:

x (in)	y (in)	x_c (in)	y_c (in)	x_g (in)	y_g (in)
0.0000	2.0000	0.0000	1.0000	0.0000	4.0000
1.0000	2.0200	1.0400	1.0208	0.9201	4.0184
2.0000	2.0800	2.0797	1.0832	1.8405	4.0736
3.0000	2.1800	3.1191	1.1871	2.7617	4.1658
4.0000	2.3200	4.1580	1.3326	3.6840	4.2949
5.0000	2.5000	5.1961	1.5194	4.6078	4.4612
6.0000	2.7200	6.2334	1.7476	5.5333	4.6648
7.0000	2.9800	7.2696	2.0170	6.4607	4.9059
8.0000	3.2800	8.3048	2.3276	7.3904	5.1848
9.0000	3.6200	9.3387	2.6791	8.3226	5.5018
10.0000	4.0000	10.3714	3.0715	9.2572	5.8570

Keystrokes:

Enter MD1-13A

10 [A] 1 [B] 2 [C] 1 [D] 3 [D] 1 [D] ——→ 1.00

Enter MD1-18A

[GTO] [D]

Switch to W/PRGM ——→ 14

[f⁻¹] [√x] [RTN] [LBL] [E] 2 [×] [RTN]

Switch to RUN

[DSP] [•] 4

[A] ——→ 0.0000

[R/S] ——→ 2.0000

[B] ——→ 0.0000

[R/S] ——→ 1.0000

[C] ——→ 0.0000

[R/S] ——→ 4.0000

[A] ——→ 1.0000

[R/S] ——→ 2.0200

[B] ——→ 1.0400

[R/S] ——→ 1.0208

[C] ——→ 0.9201

R/S ⟶ 4.0184

⋮

A ⟶ 10.0000

R/S ⟶ 4.0000

B ⟶ 10.3714

R/S ⟶ 3.0715

C ⟶ 9.2572

R/S ⟶ 5.8570

To continue the cam design, the new function and its derivative must be properly referenced to the desired point. For example, if the follower is to return to its original position in 10 more units, by a motion such that the follower profile is symmetric about x = 10, the proper function is $f(x/L) = 1 - (x/L - 1)^2$.

The derivative is $-2(x/L - 1)/L$. MD1–18A calls the function and its derivative with the argument x/L, and the derivative portion automatically divides by L once, so the cam design continues as follows:

Keystrokes:

Enter MD1–13A

E 2 CHS C ⟶ –2.0000

Enter MD1–18A

GTO D

Switch to W/PRGM ⟶ 14

1 − ENTER↑ × 1 − CHS RTN

LBL E 1 − 2 × CHS RTN

Switch to RUN

A ⟶ 0.0000

R/S ⟶ 4.0000

B ⟶ –0.3714

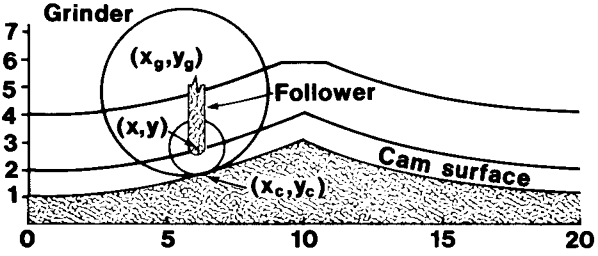
R/S ⟶ 3.0715

C ⟶ 0.7428

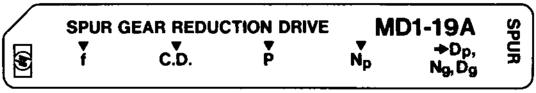
R/S ⟶ 5.8570

and so on. The computed values are with reference to x = 10 for their zero point.

Linear cam profile



SPUR GEAR REDUCTION DRIVE



For a spur gear meshing with a pinion, this program performs an interchangeable solution among the variables reduction (f), distance between the centers (C.D.), diametral pitch (P), and number of pinion teeth (N_p). Once these four basic variables have been determined, the program will also output values for the pitch diameters of the pinion and the gear (D_p and D_g) and the number of gear teeth (N_g).

The basic formula used in all solutions is:

$$f + 1 = \frac{2P \times C.D.}{N_p} \qquad (1)$$

The calculations for f, P, and C.D. are straightforward. The solution for N_p is more complicated since it must be an integer. Because of this constraint, there may not be a gear-pinion combination that will give exactly the desired reduction. In this case, the program finds the closest integer value for N_p by the formula

$$N_p = \text{INT}\left(\frac{2P \times C.D.}{f + 1} + 0.5\right)$$

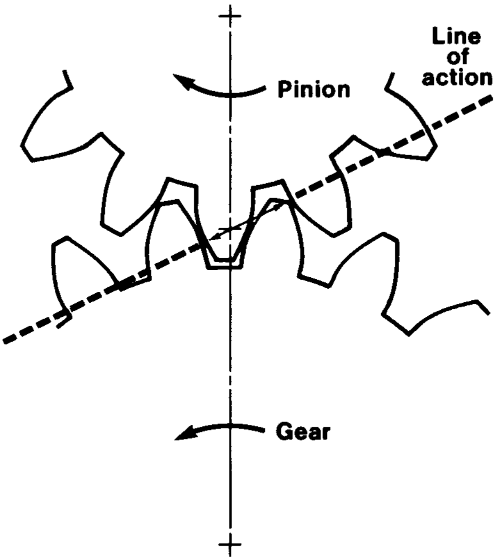
where INT represents the f INT function on the HP-65. Then a new value for the reduction, f′, is found by substituting this N_p into equation (1) above. The next step is to compute the number of gear teeth (also an integer) by

$$N_g = \text{INT}\,(f' N_p + 0.5).$$

Finally the true value of the reduction is found by

$$f = \frac{N_g}{N_p}$$

This modified value for f is stored in R_1 and may be recalled by the user if desired.



Remarks:

The program assumes that the reduction will be expressed as a decimal number greater than 1. For instance, a reduction of 9:2 should be input as $\frac{9}{2}$, or 4.5. If $f < 1$, the program will still work but the pinion values and gear values will be reversed.

Reference: Design of Machine Elements, M.F. Spotts, Prentice-Hall, 1971.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input three of the following				
	variables:				
	Reduction	f	A		f
	Center distance	C.D.	B		C.D.
	Diametral pitch	P	C		P
	Number of pinion teeth	N_p	D		N_p
3	Solve for the remaining				
	variables:				
	Reduction		A	R/S	f
	Center distance		B	R/S	C.D.
	Diametral pitch		C	R/S	P
	Number of pinion teeth		D	R/S	N_p
4	Display the following variables:				
	Pitch diameter of pinion		E		D_p
	Number of gear teeth		R/S		N_g
	Pitch diameter of gear		R/S		D_g
5	To display any of the basic				
	variables:				
	Reduction		RCL	1	f
	Center distance		RCL	2	
			2	÷	C.D.
	Diametral pitch		RCL	3	P
	Number of pinion teeth		RCL	4	N_p
6	To change any inputs, go to				
	step 2 and input the changed				
	variables.				

Example:

A spur gear reduction mechanism is to be designed to reduce a rotation from 1800 RPM to 650 RPM. The distance between the centers of the gear and pinion is constrained to be 9 inches. If the designer wishes to use teeth of diametral pitch 8, how many teeth should be on the pinion? On the gear? (38,106) What will the diameters of the gears be? (4.75 inches, 13.25 inches) What is the actual reduction in speed? (2.79)

Keystrokes:

1800 [ENTER↑] 650 [÷] [A] ——→ 2.77

9 [B] 8 [C] [D] [R/S] ——→ 38.00

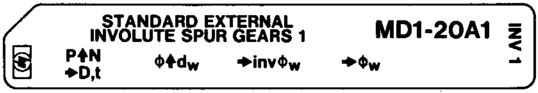
[E] ——→ 4.75

[R/S] ——→ 106.00

[R/S] ——→ 13.25

[RCL] 1 ——→ 2.79

STANDARD EXTERNAL INVOLUTE SPUR GEARS



This program uses two cards to compute various parameters for standard external involute spur gears. Given the diametral pitch P, number of teeth N, pressure angle ϕ, and pin diameter d_w, the first card of the program will compute the pitch diameter D, tooth thickness t, and the involute and corresponding flank angle inv ϕ_w and ϕ_w. The flank angle ϕ_w is calculated from the involute by a Newton's method iterative solution for the equation $f(\phi_w) = 0$,

where $$f(\phi_w) = \tan\phi_w - \phi_w - \text{inv}\,\phi_w.$$

In this solution, an initial guess is made for ϕ_w:

$$\phi_w^{(0)} = (3\ \text{inv}\,\phi_w)^{.3}$$

Newton's method then provides refinements of the initial guess by

$$\phi_w^{(n+1)} = \phi_w^{(n)} - \frac{f(\phi_w^{(n)})}{f'(\phi_w^{(n)})}$$

$$= \phi_w^{(n)} - \frac{\tan\phi_w^{(n)} - \phi_w^{(n)} - \text{inv}\,\phi_w}{\tan^2\phi_w^{(n)}}$$

The second card of the program computes various measurements over the pins, namely, the theoretical values of the measurement over pins, M; the radius to the center of the pin, q; and the measurement over one pin, R_w. In addition, given the value of the tooth thinning Δt, the program will return the measurement over pins with tooth thinning, M_t.

Equations:

$$D = \frac{N}{P}$$

$$t = \frac{\pi}{2P}$$

$$\text{inv}\ \phi_w\ (\text{radians}) = \frac{t}{D} + \tan\phi - \frac{\pi\phi}{180} + \frac{d_w}{D\cos\phi} - \frac{\pi}{N}$$

$$M = \begin{cases} d_w + 2q & (\text{N even}) \\ d_w + 2q\cos\left(\frac{90}{N}\right) & (\text{N odd}) \end{cases}$$

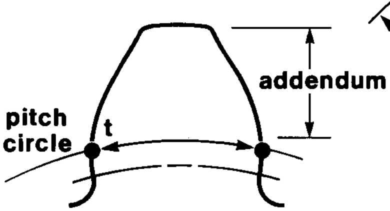
$$q = \frac{D\cos\phi}{2\cos\phi_w}$$

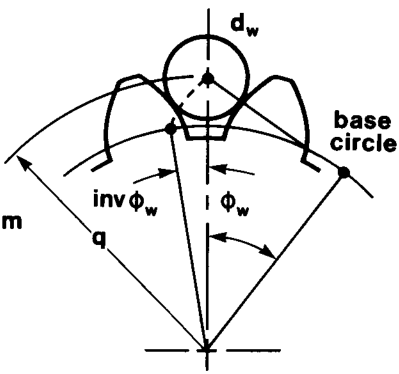
$$R_w = q + \frac{d_w}{2}$$

$$M_t = M - \Delta t\,\frac{\cos\phi}{\sin\phi_w}$$

Reference: Adapted from a program submitted to the HP-65 Users' Library by Mr. John Nemcovich, Los Angeles, CA.

Gear Handbook, D.W. Dudley, McGraw-Hill, 1962.





STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter MD 1–20A1				
2	Input the following:				
	Diametral pitch and	P	↑		P
	Number of teeth, and calcu-				
	late the pitch diameter and	N	A		D
	tooth thickness		R/S		t
3	Input the following:				
	Pressure angle	ϕ	↑		ϕ
	Pin diameter	d_w †	B		ϕ
4	Calculate the involute		C		inv ϕ_w (rad)
5	Compute the corresponding				
	flank angle		D		ϕ_w (dec. deg.)
6	Enter MD 1–20A2				
7	Calculate measurement over pins		A		M
	(theoretical)				
8	Input tooth thinning and				
	calculate measurement over pins	Δt	B		M_t
	with tooth thinning				
9	Compute radius to center of pin		C		q
10	Compute measurement over one				
	pin		D		R_w
11	To change tooth thinning go to				
	step 8. To change any other				
	input go to step 1.				
	†If d_w is not known, it may be				
	calculated from the pin con-	k	↑		k
	stant k and the pitch P:	P	÷		d_w
	$d_w = k/P$				
12	To compute ϕ_w directly from				
	inv ϕ_w: Enter MD 1–20A1				
	Store inv ϕ_w	Inv ϕ_w	STO	6	
	Compute ϕ_w		D		ϕ_w (dec. deg.)

Example:

A 27-tooth gear with pitch 8 is cut with a 20° pressure angle. The pin diameter is 0.24 inches, and tooth thinning is reckoned at 0.002 inches. Calculate the unknown parameters. (D = 3.3750 inches, t = 0.1963 inches; ϕ_w = 25.6215°; M = 3.7514 inches; M_t = 3.7470 inches; q = 1.7587 inches; R_w = 1.8787 inches).

Keystrokes:

Enter MD1-20A1

DSP [•] 4

8 [ENTER↑] 27 A ——→ 3.3750

R/S ——→ 0.1963

20 [ENTER↑] .24 B C ——→ 0.0324

D ——→ 25.6215

Enter MD1-20A2

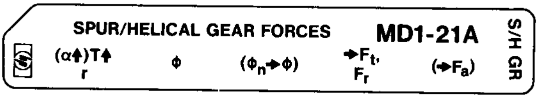
A ——→ 3.7514

.002 B ——→ 3.7470

C ——→ 1.7587

D ——→ 1.8787

SPUR/HELICAL GEAR FORCES



This program computes the various forces that act on spur and helical gears as a result of the gear torque. The inputs for spur or helical gears are the gear torque T, the pitch radius r of the gear, and the pressure angle ϕ. For helical gears, the helix angle α, measured from the axis of the gear, must also be input; the pressure angle may be input as either transverse (ϕ, measured perpendicular to the gear axis) or normal (ϕ_n, measured perpendicular to a tooth). In either case, the other pressure angle will also be calculated and stored.

Outputs of the program are the following gear forces:

for spur and helical gears, the tangential force F_t and the separating force F_r;

for helical gears only, the thrust force F_a.

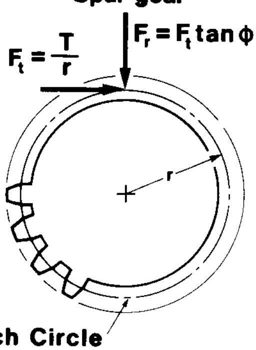
Equations:

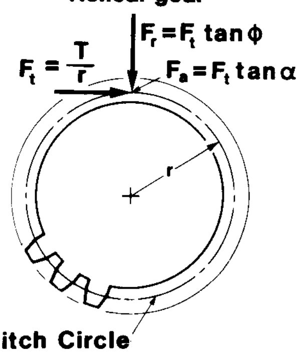
$$F_t = \frac{T}{r}$$

$$F_r = F_t \tan \phi$$

$$F_a = F_t \tan \alpha$$

$$\tan \phi = \frac{\tan \phi_n}{\cos \alpha}$$





Remarks:

The parentheses around certain variables on the magnetic card are used to denote inputs or outputs which apply to helical gears only. These variables (α, ϕ_n, F_a) may be ignored when solving spur gear problems.

Reference: Machine Design, Schaum's Outline Series, Hall, Holowenko, and Laughlin, McGraw-Hill, 1961.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2a	For spur gears, input the				
	following:				
	Gear torque	T	↑		T
	Pitch radius of gear	r	A		r
3a	Input pressure angle	ϕ	B		ϕ
4a	Calculate tangential force and				
	separating force		D		F_t
			R/S		F_r
5a	To change pressure angle, go to				
	step 3a. To change torque or				
	pitch radius, go to step 2a.				
2b	For helical gears, input the				
	following:				
	Helix angle	α	↑		α
	Gear torque	T	↑		T
	Pitch radius of gear	r	A		r
3b	Input one of the following two				
	variables:				
	Transverse pressure angle or	ϕ	B		ϕ
	Normal pressure angle	ϕ_n	C		ϕ
4b	Calculate tangential force and		D		F_t
	separating force		R/S		F_r
5b	Calculate thrust force		E		F_a
6b	To change pressure angle, go to				
	step 3b. To change any other				
	variable, go to step 2b.				

Example:

A helical gear with pitch radius 12 cm has a torque applied to it of 450,000 dynes-cm. The helix angle is 30°, and the normal pressure angle, measured perpendicular to a tooth, is 17.5°. Find the transverse pressure angle and the tangential, separating, and thrust forces. (20.01°; 37500.00 dynes, 13652.84 dynes, and 21650.64 dynes.)

Keystrokes:

30 [ENTER↑] 4.5 [EEX] 5 [ENTER↑]

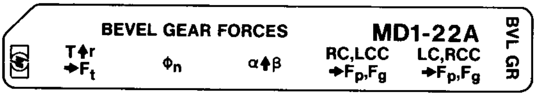
12 [A] 17.5 [C] ——→ 20.01

[D] ——→ 37500.00

[R/S] ——→ 13652.84

[E] ——→ 21650.64

BEVEL GEAR FORCES



This program computes the forces that act on straight or spiral bevel gears as a result of the torque. Inputs to the program are the torque T, the mean pitch radius r, the pressure angle ϕ_n, the pinion spiral angle α, and the pinion pitch cone angle β. For spiral bevel gears, ϕ_n must be the normal pressure angle, that is, measured in a plane normal to a tooth. For straight bevel gears, the spiral angle α must be input as zero.

The program outputs three mutually perpendicular components of force: the tangential force F_t, the pinion thrust force F_p acting parallel to the pinion axis, and the gear thrust force F_g acting parallel to the axis of the gear. Three sets of equations are used to calculate these forces.

For all bevel gears, $F_t = \frac{T}{r}$

For straight bevel gears,

$$F_p = F_t \tan \phi_n \sin \beta$$

$$F_g = F_t \tan \phi_n \cos \beta.$$

For spiral gears, the equations depend on the direction of the spiral and sense of rotation of the pinion. For a right-hand pinion spiral with clockwise pinion rotation or for a left-hand spiral with counter-clockwise rotation,

$$F_p = F_t \left(\frac{\tan \phi_n \sin \beta}{\cos \alpha} - \tan \alpha \cos \beta \right)$$

$$F_g = F_t \left(\frac{\tan \phi_n \cos \beta}{\cos \alpha} + \tan \alpha \sin \beta \right).$$

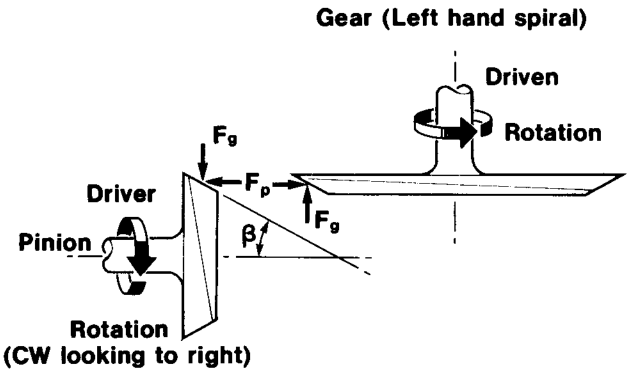
When running the program, these equations and those for straight bevel gears are selected by pressing the **D** key.

For a left-hand pinion spiral with clockwise pinion rotation or for a right-hand spiral with counterclockwise rotation,

$$F_p = F_t \left(\frac{\tan \phi_n \sin \beta}{\cos \alpha} + \tan \alpha \cos \beta \right)$$

$$F_g = F_t \left(\frac{\tan \phi_n \cos \beta}{\cos \alpha} - \tan \alpha \sin \beta \right)$$

These equations are selected by the **E** key of the program.



Remarks:

If the normal pressure angle ϕ_n is not known for a spiral bevel gear, but the pressure angle θ measured in a plane normal to the axis is known, then θ_n may be calculated by

$$\phi_n = \tan^{-1} (\tan \phi \cos \alpha).$$

The rotations of the pinion must be observed from the input end of the pinion shaft.

Reference: Machine Design, Schaum's Outline Series, Hall, Hollowenko, and Laughlin, McGraw-Hill, 1961.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input gear torque and	T	↑		T
	mean pitch radius and				
	calculate tangential	r	A		F_t
	force				
3	Input the pressure angle (for	ϕ_n †	B		ϕ_n
	spiral gears, ϕ_n must be				
	normal pressure angle)				
4	Input the following:				
	Pinion spiral angle (zero for				
	straight gears)	α	↑		α
	Pinion pitch cone angle	β	C		β
5	For straight bevel gears				
	or				
	For right-hand spiral with				
	clockwise rotation				
	or				
	For left-hand spiral with				
	counter-clockwise rotation,				
	Compute pinion thrust force		D		F_p
	and gear thrust force		R/S		F_g
6	For left-hand spiral with clock-				
	wise rotation				
	or				
	For right-hand spiral with				
	counter-clockwise rotation,				
	Compute pinion thrust force		E		F_p
	and gear thrust force		R/S		F_g
7	For new case go to step 2.				

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
	†If the normal pressure angle ϕ_n		[ ] [ ]	
	is not known for a spiral gear,		[ ] [ ]	
	but the pressure angle ϕ mea-		[ ] [ ]	
	sured perpendicular to the axis		[ ] [ ]	
	is known, ϕ_n may be found:	ϕ	[f] [TAN]	
		α	[f] [COS]	
			[x] [f^{-1}]	
			[TAN] [ ]	ϕ_n

Example:

A left-hand spiral pinion with mean radius 1.73 inches is subjected to a torque of 745 in-lb. The pinion is cut with a normal pressure angle of 20°, a spiral angle of 35°, and a pitch cone of 18°. The rotation of the pinion is clockwise. Find the forces acting on the pinion. (F_t = 430.64 lb., F_p = 345.90 lb., F_g = 88.80 lb.)

Keystrokes:

745 [ENTER↑] 1.73 [A] ——→ 430.64

20 [B] 35 [ENTER↑] 18 [C] [E] ——→ 345.90

[R/S] ——→ 88.80

If a straight bevel gear with the same dimensions were used instead, what would the forces be? (F_t = 430.64 lb., F_p = 48.43 lb., F_g = 149.07 lb.)

Keystrokes:

745 [ENTER↑] 1.73 [A] ——→ 430.64

20 [B] 0 [ENTER↑] 18 [C] [D] ——→ 48.43

[R/S] ——→ 149.07

WORM GEAR FORCES

This program computes the forces acting on a worm and worm gear in mesh as a result of the input torque. Inputs to the program are the worm torque T, the mean pitch radius of the worm r_w, the coefficient of friction f, the normal pressure angle ϕ_n, measured in a plane normal to a tooth, and the lead L of the worm. From these variables the program computes the lead angle of the worm, λ; the tangential force on the worm, F_{wt}; the tangential force on the worm gear, F_{gt}; and the separating force F_r.

Equations:

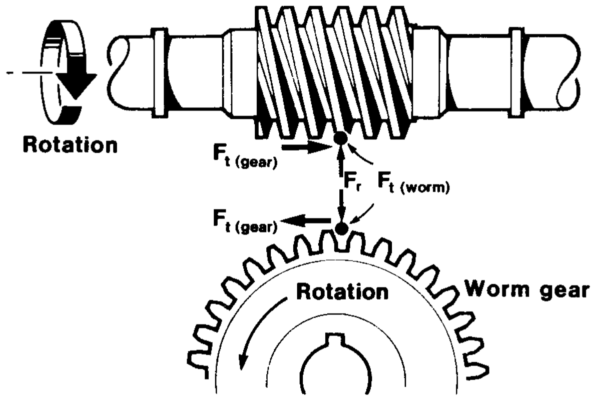
$$\lambda = \tan^{-1} \frac{L}{2\pi r_w}$$

$$F_{wt} = \frac{T}{r_w}$$

$$F_r = F_{wt} \left(\frac{\sin \phi_n}{\cos \phi_n \sin \lambda + f \cos \lambda} \right)$$

$$F_{gt} = F_{wt} \left(\frac{1 - \dfrac{f \tan \lambda}{\cos \phi_n}}{\tan \lambda + \dfrac{f}{\cos \phi_n}} \right)$$

Driver: Worm (Right hand)



Remarks:

The lead L may be found by L = P x N where P is the axial pitch of the worm and N is the number of threads of the worm (e.g., N = 2 for a double-thread worm).

If ϕ_n is not known but the pressure angle ϕ, measured in a plane containing the axis of the worm, is known, then ϕ_n may be found by

$$\phi_n = \tan^{-1} (\tan \phi \cos \lambda).$$

Reference: Machine Design, Schaum's Outline Series, Hall, Hollowenko, and Laughlin, McGraw-Hill, 1961.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input				
	Torque on the worm	T	↑		T
	Pitch radius of the worm	r_w	A		r_w
3	Input				
	Coefficient of friction	f	↑		f
	Pressure angle measured				
	normal to a tooth	ϕ_n	B		f
4	Input lead and calculate lead	L	C		λ
	angle				
5	Calculate				
	Tangential force on the				
	worm		D		F_{wt}
	Tangential force on the				
	worm gear		R/S		F_{gt}
6	Calculate separating force		E		F_r
7	For a new case, go to step 2				

Example:

A torque of 512 in-lb is applied to a worm having pitch diameter 2.92 inches and lead 2.20 inches. The normal pressure angle is 20°, and the coefficient of friction is 0.10. Find the lead angle and the forces on the worm and worm gear. (λ = 13.49; F_{wt} = 350.68 lb; F_{gt} = 986.99 lb; F_r = 379.10 lb.)

Keystrokes:

512 [ENTER↑] 2.92 [ENTER↑] 2 [÷] [A]

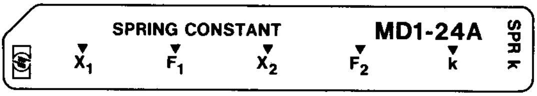
.1 [ENTER↑] 20 [B] 2.2 [C] ——→ 13.49

[D] ——→ 350.68

[R/S] ——→ 986.99

[E] ——→ 379.10

SPRING CONSTANT



This program calculates the value of any variable given the other four (X_1, F_1, X_2, F_2, k) in the spring equation. It may be used to solve any general linear equation of the form $y - y_0 = m(x - x_0)$. It is also useful for linear interpolation in tables. Computed values are automatically stored to provide an interchangeable solution.

X_1 = Spring length

F_1 = Force required to retain spring at length X_1

X_2 = Spring length

F_2 = Force required to retain spring at length X_2

k = Spring constant

Equations:

$$k = \frac{F_1 - F_2}{X_2 - X_1}$$

$$F_1 = F_2 + k\,(X_2 - X_1)$$

$$F_2 = F_1 + k\,(X_1 - X_2)$$

$$X_1 = \frac{F_2 - F_1}{k} + X_2$$

$$X_2 = \frac{F_1 - F_2}{k} + X_1$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input four of the following five				
	variables:	X_1	A		X_1
		F_1	B		F_1
		X_2	C		X_2
		F_2	D		F_2
		k	E		k
3	Solve for the remaining				
	variable:		A	R/S	X_1
			B	R/S	F_1
			C	R/S	X_2
			D	R/S	F_2
			E	R/S	k
4	Repeat any portion of steps 2				
	or 3 as required.				
5	For a new case, go to step 2.				

Example 1:

A compression spring is 4.0 inches long under no compressive forces. A force of 270 lbf compresses the spring to a length of 2.8 inches. The solid height of the spring is 2.5 inches. Find the spring constant and the force to fully compress the spring (225.00 lbf/in., 337.50 lbf.)

Keystrokes:

4 A 0 B 2.8 C 270 D E R/S ⟶ 225.00

2.5 C D R/S ⟶ 337.50

Example 2:

10.00%	10.25%	10.50%
215.93	222.60	229.31

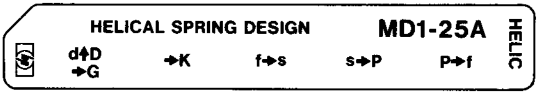
From the table shown, find the linear approximation to a value of 219.9749. (10.1516%)

Keystrokes:

10 A 215.93 B 10.25 C 222.60 D E R/S

219.9749 B A R/S DSP • 4 ⟶ 10.1516%

HELICAL SPRING DESIGN



This program interchangeably computes deflection, stress, and load for round-wire helical compression and extension springs. The Wahl factor K is computed so that both pure torsional stress and stress including curvature and shear may be handled. The energy stored per spring coil is also calculated.

d = Wire diameter

D = Mean coil diameter

K = Wahl factor

f = Deflection per coil

s = Pure torsional stress

P = Load on spring

u = Energy/coil

G = Torsional modulus of rigidity

Equations:

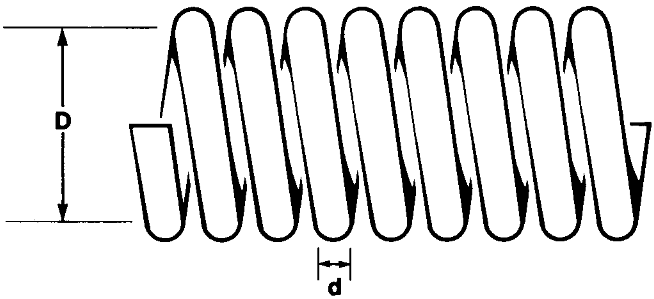
$$s = \frac{fGd}{\pi D^2}$$

$$P = \frac{\pi s d^3}{8D}$$

$$f = \frac{8PD^3}{Gd^4}$$

$$K = \frac{C - .25}{C - 1} + \frac{.615}{C} \quad \text{where } C = \frac{D}{d}$$

$$u = \frac{1}{2} Pf$$



Reference: Handbook of Mechanical Spring Design, Associated Spring Corporation, 1955.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input the wire diameter and	d	↑		d
	mean spring diameter	D	A		G
3	Calculate the Wahl factor		B		K
4	Input the deflection/coil and				
	compute the torsional stress	f	C		s
5	Input the torsional stress and				
	compute the load	s	D		P
6	Input the load and compute				
	the deflection/coil	P	E		f
	Optional: Display the energy/	*	R/S		u
	coil †				
7	Repeat steps, 4, 5, or 6 individ-				
	ually or in sequence as				
	required. Step 3 may be				
	executed after pressing C or				
	before D. To compute the				
	total stress from C:	Torsional stress	B	x	Total stress
	For the torsional stress for				
	input to D:	Total stress	B	÷	Torsional stress

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
8	For a new case, go to step 2.		[ ] [ ]	
	Note: The modulus of rigidity		[ ] [ ]	
	is assumed to be		[ ] [ ]	
	11500 000 and is auto-		[ ] [ ]	
	matically stored when		[ ] [ ]	
	A is pressed. G may be		[ ] [ ]	
	changed after A is press-		[ ] [ ]	
	ed by keying it in and		[ ] [ ]	
	storing it in R_3.	G	[STO] [3]	
	†f computed under E is stored		[ ] [ ]	
	in R_8 during calculation of u		[ ] [ ]	
	if the user wishes to recall f		[ ] [ ]	
	([RCL] 8) to the display.		[ ] [ ]	

Example 1:

A compression spring has a mean diameter of 2.0 inches and a wire diameter of 3/8 inches. Find the load necessary to deflect the spring 0.25 inches (88.83 lbs). Determine the stored energy resulting from this deflection (11.10 in-lb). Assume the spring has 10 active coils.

(For this solution we input the deflection per coil [.25/10] via C and calculate the load using the stress from C as an intermediate answer for input to D which gives the load. Similarly, the load is retained as the input for E to calculate the energy [energy/coil x #coils]).

Keystrokes:

3 [ENTER↑] 8 [÷] 2 A .25 [ENTER↑] 10 [÷] C D ⟶ 88.83

E R/S 10 [×] ⟶ 11.10

Example 2:

A spring is to compress 2.0 inches under a load of 100 pounds. The spring has inside diameter of 3.25 inches and wire diameter of 0.5 inches. Calculate the minimum number of active coils required (34 coils).

(For this problem we calculate the deflections/coil and divide this result into the total deflection, giving the total number of coils. 3.25 + .5 is the mean diameter of the spring.)

Keystrokes:

.5 [ENTER↑] 3.25 [ENTER↑] .5 [+]

[A] 100 [E] 2 [g] [x⇄y] [÷] ——————→ 34.07

Rounding 34.07 gives 34 coils.

Example 3:

An extension spring is initially loaded producing a stress of 5000 psi (includes curvature and shear stress). Determine the initial load and the total load to extend the spring 1 inch (4.08 lbs, 45.68 lbs). Find the energy from the total load (25.08 in-lbs). The spring is 0.125 inch round wire, has a mean diameter of 0.75 inch, and has 20 active coils.

(The deflection per coil is 1/20 = .05. The stress input must be divided by the Wahl factor to reduce it to pure torsional stress).

Keystrokes:

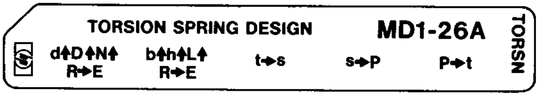
.125 [ENTER↑] .75 [A] 5000 [B] [÷] [D] [STO] 8 ——→ 4.08

.05 [C] [D] [RCL] 8 [+] ——————→ 45.68

[E] [R/S] 20 [×] ——————→ 25.08

(In the example above, R_8 is used for temporary storage of the initial load.)

TORSION SPRING DESIGN



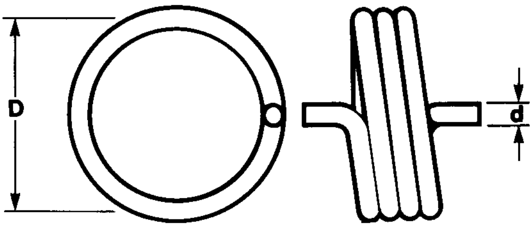
This program interchangeably computes deflection, stress, and load for round and flat wire torsion springs. The Wahl factor K is computed so that both pure torsional stress and stress including curvature and shear may be handled.

d = Round wire diameter
D = Mean diameter of spring
N = Number of active coils
R = Mean radius or lever arm
b = Flat wire width
h = Flat wire thickness
L = Length of active spring
E = Young's modulus
t = Number of turns or revolutions
s = Pure torsional stress
P = Load at distance R
K = Wahl factor

Equations:

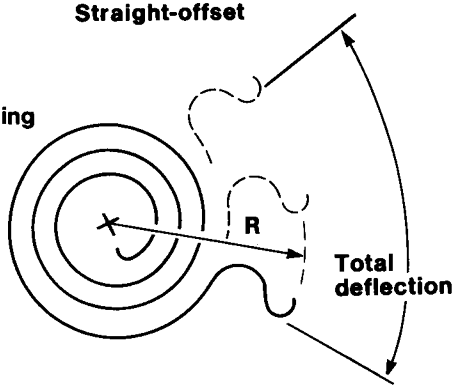
	Helical Round Wire	Flat Wire
s	$\frac{tdE}{DN}$	$\frac{\pi thE}{L}$
P	$\frac{\pi d^3 s}{32R}$	$\frac{bh^2 s}{6R}$
t	$\frac{32PRDN}{\pi d^4 E}$	$\frac{6PRL}{\pi bh^3 E}$

$$K = \frac{C - .25}{C - 1} + \frac{.615}{C} \qquad \text{where } C = \frac{D}{d}$$



Straight-offset

Flat wire spring



Reference: Handbook of Mechanical Spring Design, Associated Spring Corporation, 1955.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2a	Input the round wire spring				
	parameters	d	↑		d
		D	↑		D
		N	↑		N
	or	R	A		E
2b	Input the flat wire spring				
	parameters	b	↑		b
		h	↑		h
		L	↑		L
		R	B		E
3	Input the deflection and com-				
	pute the torsional stress	t	C		s
4	Input the torsional stress and				
	compute the load	s	D		P
5	Input the load and compute				
	the deflection	P	E		t

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
6	Repeat steps 3, 4, or 5 in		[ ]	[ ]	
	sequence as required. The		[ ]	[ ]	
	Wahl factor is available in		[ ]	[ ]	
	R_6 for helical torsion spring		[ ]	[ ]	
	stresses. To compute the		[ ]	[ ]	
	total stress from **C**	Torsional stress	RCL	6	
			X	[ ]	Total stress
	For the torsional stress for		[ ]	[ ]	
	input to **D**	Total stress	RCL	6	
			÷	[ ]	Torsional stress
7	For a new case, go to step 2a		[ ]	[ ]	
	or 2b.		[ ]	[ ]	
	Note: Young's modulus E is		[ ]	[ ]	
	assumed to be		[ ]	[ ]	
	30,000,000 and is auto-		[ ]	[ ]	
	matically stored when		[ ]	[ ]	
	A or **B** is pressed. E may		[ ]	[ ]	
	be changed after **A** or **B**		[ ]	[ ]	
	is pressed by keying it in		[ ]	[ ]	
	and storing it in R_7.	E	STO	7	

Example 1:

A helical torsion spring is manufactured from .125 inch steel wire, has a mean diameter of 2.50 inches and 40 active coils. A load is to act with a lever arm of 2.0 inches. Determine the load necessary to deflect the spring 1, 3, and 5 turns (3.60 lbs, 10.79 lbs, 17.98 lbs). Find the total stress at 5 turns (200666.94 psi).

Keystrokes:

.125 [ENTER↑] 2.5 [ENTER↑] 40 [ENTER↑]

2.0 **A** ——→ 30000000.00

1 **C** **D** ——→ 3.60

3 **C** **D** ——→ 10.79

5 **C** **D** ——→ 17.98

5 **C** [RCL] 6 [×] ——→ 200666.94 psi

Example 2 :

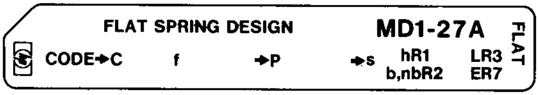
Find the deflection in degrees of a .02 inch stock flat wire spring 3/8 inches wide with 1.75 pounds load. The spring has 8 inches of active length and the load will act at a mean radius of 1.5 inches (160.43°).

Keystrokes:

3 [ENTER↑] 8 [÷] .02 [ENTER↑] 8 [ENTER↑] 1.5 [B]

1.75 [E] 360 [×] ──────────────► 160.43

FLAT SPRING DESIGN



This program computes the load and stress given deflection for eight cases of flat springs, including multiple leaf triangular plate springs.

h = Thickness of spring leaf

b = Width of spring leaf

L = Spring length

E = Young's modulus

n = Number of leaves for multiple leaf spring

f = Deflection

P = Load

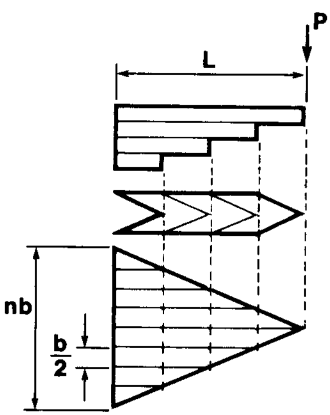
s = Stress

Equations :

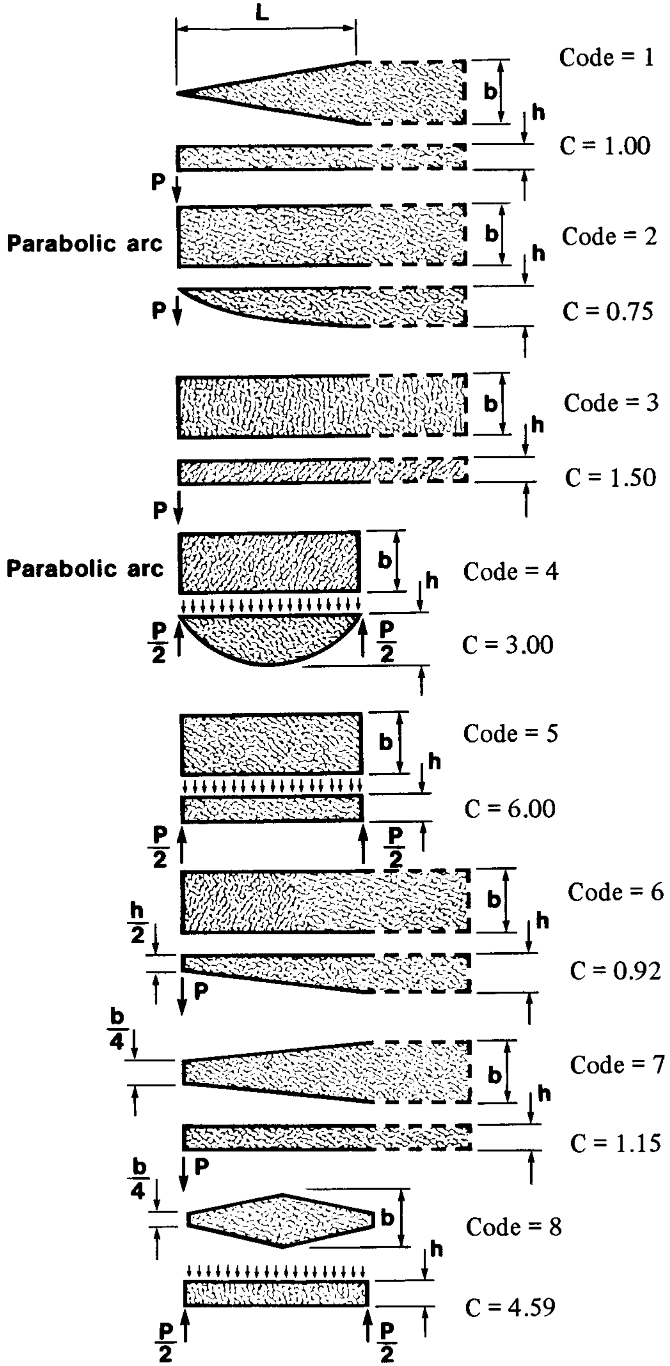
$$P = \frac{sbh^2}{6L}$$ for Codes 1, 2, 3, 6 and 7

$$P = \frac{4sbh^2}{6L}$$ for Codes 4, 5 and 8

$$s = \frac{ChfE}{L^2}$$



Code = 1   C = 1.00


L
b
h
Code = 1
C = 1.00
P
Parabolic arc
Code = 2
C = 0.75
Code = 3
C = 1.50
Parabolic arc
Code = 4
C = 3.00
P/2
Code = 5
C = 6.00
h/2
Code = 6
C = 0.92
b/4
Code = 7
C = 1.15
Code = 8
C = 4.59

Reference: Handbook for Mechanical Engineers, T. Baumeister, McGraw-Hill, 1967.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program		[ ]	[ ]	
2	Store the spring parameters	h	[STO]	[1]	h
		b	[STO]	[2]	b
		L	[STO]	[3]	L
		E	[STO]	[7]	E
	For multiple leaf triangular		[ ]	[ ]	
	plate springs, nb is stored		[ ]	[ ]	
	in R_2	nb	[STO]	[2]	nb
3	Input the spring code (1, 2,...,8)	Code	[A]	[ ]	C
4	Input the deflection	f	[B]	[ ]	f
5	Calculate the load		[C]	[ ]	P
6	Calculate the stress		[D]	[ ]	s
7	Repeat steps 4, 5, and 6 as		[ ]	[ ]	
	required.		[ ]	[ ]	
8	For a new case, go to step 2.		[ ]	[ ]	

Example 1 :

A cantilever spring is loaded 18 inches from the fulcrum point, and is made of 1/8" x 2" steel with E = 3 x 10^7 (Code = 3). Find the load necessary to deflect the spring 5.25 inches (26.37 lbs).

Keystrokes:

1 [ENTER↑] 8 [÷] [STO] 1 ⟶ 0.13

2 [STO] 2 ⟶ 2.00

18 [STO] 3 ⟶ 18.00

3 [EEX] 7 [STO] 7 ⟶ 30000000.00

3 [A] 5.25 [B] [C] ⟶ 26.37

Example 2:

A triangular plate multi-leaf spring has a maximum allowable deflection of 2.0 inches. There are 5 leaves, the longest of which is 14.0 inches. The cross-sectional area of each leaf is .25" x 1.5". Assume E = 3 x 10^7 (Code = 1). Calculate the maximum load and stress (427.07 lbs, 76530.61 psi).

Keystrokes:

.25 [STO] 1 ——→ 0.25

1.5 [ENTER↑] 5 [×] [STO] 2 ——→ 7.50 (nb → R_2)

14 [STO] 3 ——→ 14.00

3 [EEX] 7 [STO] 7 ——→ 30000000.00

1 [A] 2 [B] [C] ——→ 427.07

[D] ——→ 76530.61

CONE AND PLATE CLUTCHES

This program computes the torque and horsepower capacity for cone and plate clutches assuming either uniform wear or uniform pressure.

F = Axial force, lb

N = Speed of rotation, RPM

f = Coefficient of friction

R_o = Outside radius of contact in inches

R_i = Inside radius of contact in inches

n = Number of surfaces in contact

α = Pitch cone angle

T = Torque capacity of clutch in in-lb

Hp = Horsepower capacity of clutch

Equations:

	Cone Clutches	Plate Clutches
Uniform wear	$T = \frac{Ff}{\sin\alpha}\left(\frac{R_o + R_i}{2}\right)$	$T = Ffn\left(\frac{R_o + R_i}{2}\right)$
Uniform pressure	$T = \frac{Ff}{\sin\alpha}\left[\frac{2}{3}\left(\frac{R_o^3 - R_i^3}{R_o^2 - R_i^2}\right)\right]$	$T = Ffn\left[\frac{2}{3}\left(\frac{R_o^3 - R_i^3}{R_o^2 - R_i^2}\right)\right]$

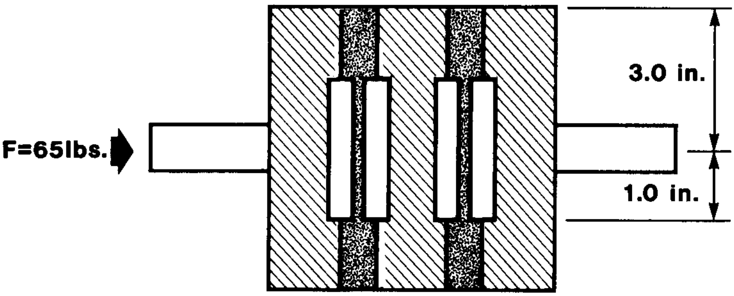
Hp = TN/63025.36

Reference: Machine Design, Schaum's Outline Series, Hall, Hollowenko, and Laughlin, 1961.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input the axial force	F	A		F
	Optional: input speed of				
	rotation	N (RPM)	A		N/63025.36
3	Input the coefficient of friction	f	B		f
4	Input the outside and inside				
	radius of				
	contact	R_o	↑		R_o
		R_i	C		R_o
5a	(For plate clutches)				
	Input the number of surfaces in				
	contact and compute torque				
	capacity assuming uniform wear	n	D		$T_{u.w.}$
	Optional: display horsepower				
	capacity for uniform wear	*	g	x⇄y	$Hp_{u.w.}$
	Compute torque capacity				
	assuming uniform pressure		R/S		$T_{u.p.}$
	Optional: display horsepower				
	capacity for uniform pressure	*	g	x⇄y	$Hp_{u.p.}$
5b	(For cone clutches)				
	Input the pitch cone angle and				
	compute torque capacity				
	assuming uniform wear	α	E		$T_{u.w.}$
	Optional: display horsepower				
	capacity for uniform wear	*	g	x⇄y	$Hp_{u.w.}$
	Compute torque capacity				
	assuming uniform pressure		R/S		$T_{u.p.}$
	Optional: display horsepower				
	capacity for uniform pressure	*	g	x⇄y	$Hp_{u.p.}$
6	Repeat portions of steps 2-5 as				
	required.				
7	For a new case, go to step 2.				

Example 1:

Find the torque and horsepower capacity of a multiple disk clutch with three steel and two bronze disks as shown below:



The coefficient of friction is .275. The clutch rotates at 500 RPM.

Solution:

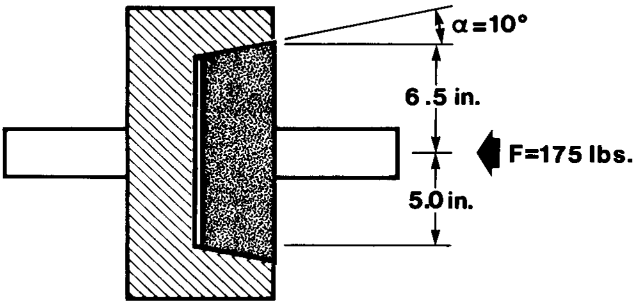
	Torque	Horsepower
Uniform wear	143.00 in-lb	1.13 hp
Uniform pressure	154.92 in-lb	1.23 hp

Keystrokes:

65 [A] 500 [A] .275 [B] 3 [ENTER↑] 1 [C] 4 [D] ⟶ 143.00
[g] [x⇄y] ⟶ 1.13
[R/S] ⟶ 154.92
[g] [x⇄y] ⟶ 1.23

Example 2:

Calculate the torque and horsepower capacity of the cone clutch shown below:



The coefficient of friction is .25. The clutch rotates at 1500 RPM.

Solution:

	Torque	Horsepower
Uniform wear	1448.69 in-lb	34.48 hp
Uniform pressure	1456.91 in-lb	34.67 hp

Keystrokes:

175 [A] 1500 [A] .25 [B] 6.5 [ENTER↑]

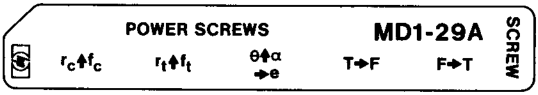
5 [C] 10 [E] ⟶ 1448.69

[g] [x⇄y] ⟶ 34.48

[R/S] ⟶ 1456.91

[g] [x⇄y] ⟶ 34.67

POWER SCREWS



This program computes the load that may be raised or lowered by some torque, or the torque necessary to raise or lower some load, by a power screw. It also computes the efficiency of the screw and the minimum thread coefficient of friction to prevent overhauling.

If the screw is used to lower a load, the helix angle α is input as negative. A negative torque computed under **E** implies the screw will overhaul without an opposing applied torque to lower the load. A negative load computed from a positive torque under **D** also implies the screw is overhauling.

r_t = Mean radius of thread

f_t = Coefficient of friction between screw and nut threads

α = Helix angle of thread at r_t

r_c = Collar radius

f_c = Coefficient of friction at collar

θ = Angle between a radial line from the axis and the line tangent to the thread face in an axial cross section.

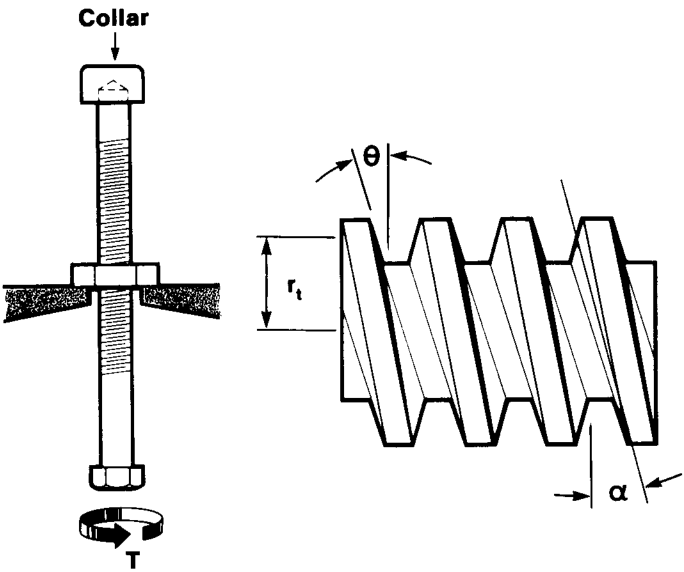
e = Screw efficiency

F = Load or force

T = Torque

f_t min = Minimum coefficient of friction before overhauling occurs for the given screw properties

α max = Maximum helix angle before overhauling occurs for the given screw properties



Equations:

To raise a load

$$T = F\left[r_t\left(\frac{\tan\alpha + f_t/g}{1 - f_t\tan\alpha/g}\right) + f_c\,r_c\right]$$

To lower a load

$$T = F\left[r_t\left(\frac{-\tan\alpha + f_t/g}{1 + f_t\tan\alpha/g}\right) + f_c\,r_c\right]$$

$$\alpha\,\max \doteq \tan^{-1}\left(\frac{f_t\,r_t/g + f_c\,r_c}{r_t - f_c\,r_c\,f_t/g}\right)$$

α max is an approximation since g appears in the equation. For small α, $g \doteq \cos\theta$ since $\lim_{\alpha\to 0}\cos\alpha = 1$.

$$f_t \min = \frac{(r_t \tan\alpha - f_c r_c)\, g}{r_t + f_c r_c \tan\alpha}$$

$$e = \frac{\tan\alpha}{\dfrac{\tan\alpha + f_t/g}{1 - f_t \tan\alpha/g} + \dfrac{f_c r_c}{r_t}}$$

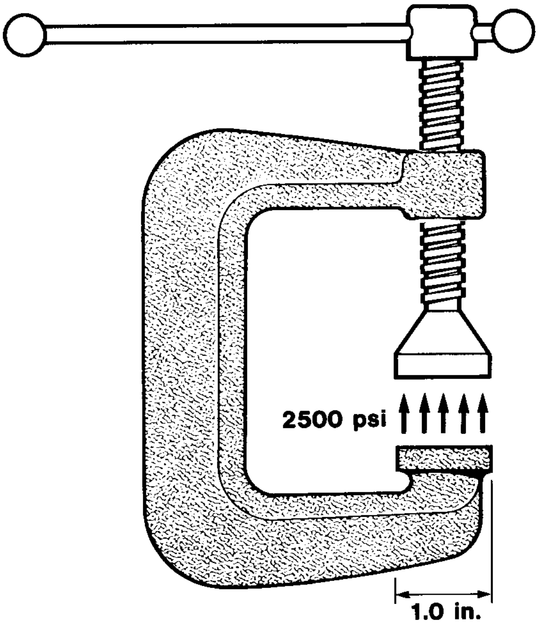
$$g = \cos(\tan^{-1}(\tan\theta \cos\alpha))$$

Reference: Machine Design, Schaum's Outline Series, Hall, Hollowenko, and Laughlin, McGraw-Hill, 1961.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input the screw parameters:				
	collar radius	r_c	↑		r_c
	collar coefficient of friction	f_c	A		$f_c r_c$
	thread mean radius	r_t	↑		r_t
	thread coefficient of friction	f_t	B		r_t
3	Input θ and the helix angle and				
	compute the screw efficiency	θ	↑		θ
		(±) α	C		e (%)
	Optional: display maximum				
	helix angle	*	g	R↓	α max
	Display minimum thread				
	coefficient of friction	*	g	R↓	f_t min
4	Input torque and compute load	T	D		F
5	Input load and compute torque	F	E		T
6	Repeat portions of steps 3 or 4				
	as required.				
7	For a new case, go to step 2.				

Example 1:

The C-clamp shown below exerts a force of 2500 psi to laminate three pieces of fibre board. The threads and collar have coefficients of friction of .15 and .12 respectively. The mean thread radius is .250 and there are 5 threads per inch. The collar has a flat surface with a diameter of 1.0 inches, and a mean radius of .225 inches. Assume θ = 14.5°. Determine the torque required to exert the required pressure. Check to insure there are no overhauling problems.



Solution:

T = 194.32 in-lb

The clamp will not overhaul.

Keystrokes:

$$\tan \alpha = \frac{\text{lead}}{2\pi r_t} = \frac{1/5}{2\pi(.25)} = .127324 \quad \alpha = 7.256083$$

.225 [ENTER↑] .12 [A] .25 [ENTER↑] .15 [B]

14.5 [ENTER↑] 7.256083 [C] [g] [R↓] ————→ 14.97

$\alpha < (\alpha \max)$ implies there is no problem with overhauling

[g] [R↓] [DSP] [•] 6 ——————→ .018464

$f_t > (f_t \min)$ implies there is no problem with overhauling.

(Each condition is sufficient to insure no overhauling problem. They are both given to indicate relative closeness of the boundary condition for overhauling.)

1.0 [ENTER↑] 2 [÷] [ENTER↑] [×] [g] [π] [×]
2500 [×] [DSP] [•] 2 ——————→ 1963.50 lb
(2500 psi x π (.5)^2 in^2)

[E] ——————→ 194.32 in-lb

Example 2:

A push-drill screwdriver is to be manufactured with $r_t = .75$, $r_c = .65$ inches, $f_t = f_c = .15$. In this situation, overhauling is a desired characteristic. Determine the minimum helix angle so overhauling will occur, and a helix angle that will allow a numerically larger torque output than the force input. Assuming this angle find the force required to deliver 60 in-lb to a driven screw. Let $\theta = 0°$. Disregard the force exerted by the return action of the spring.

Solution:

$\alpha \max = 15.94°$

$\alpha = 65°$

F = 58.01 lb

Keystrokes:

(To calculate (α max), we let α be small. In this case, let $\alpha = 0$. Repeating the following calculation with $\theta = 14.5°$ and $\alpha = 15°$, we get (α max) = 16.20° as the approximation.)

.65 [ENTER↑] .15 [A] .75 [ENTER↑] .15 [B]
0 [ENTER↑] 0 [C] [g] [R↓] ——————→ 15.94°

α is determined so that when **E** is pressed, $\left|\frac{T}{F}\right| \geqslant 1$. Try

0 [ENTER↑] 45 [CHS] **C** 1 **E** ⟶ –0.46

0 [ENTER↑] 60 [CHS] **C** 1 **E** ⟶ –0.84

0 [ENTER↑] 65 [CHS] **C** 1 **E** ⟶ –1.03

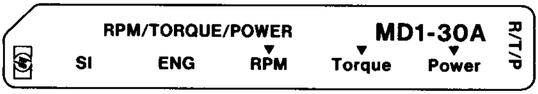
$|-1.03| > 1$, so 65° is a suitable helix angle.

(α is input with [CHS] for lowering loads).

Now determine the force to drive the screw:

60 **D** ⟶ –58.01

RPM/TORQUE/POWER



This program provides an interchangeable solution for RPM, torque, and power in both Système International (metric) and English units.

	SI	English
RPM	RPM	RPM
Torque	nt–m	ft-lb
Power	watts	hp

Equations:

RPM x Torque = Power

1 hp = 745.7 watts

1 ft-lb = 1.356 joules $\qquad$ 1 hp = $550 \frac{\text{ft-lb}}{\text{sec}}$

1 RPM = $\pi/30$ radians/sec

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Choose system of units:				
	Metric (SI)		A		
	or				
	English		B		
3	Input two of the following				
	variables:				
	RPM	RPM	C		RPM
	Torque	Torque	D		Torque
	Power	Power	E		Power
4	Compute the remaining				
	variable:				
	RPM		C	R/S	RPM
	Torque		D	R/S	Torque
	Optional: compute torque in		R/S		Torque
	other system				
	Power		E	R/S	Power
	Optional: compute power in				
	other sytem		R/S		Power
5	To change any input variable,				
	go to step 3.				
6	For a new case, go to step 2.				

Example 1:

Compute the torque from an engine developing 11 hp at 6500 RPM (8.89 ft-lb). Find the SI equivalent. (12.05 nt–m)

Keystrokes:

B 6500 C 11 E D R/S ⟶ 8.89

R/S ⟶ 12.05

Example 2:

A generator is turning at 1600 RPM with a torque of 20 nt–m. If it is 90% efficient, what is the power input in both systems? (3723.37 watts, 4.99 hp)

Keystrokes:

A 20 ENTER↑ .9 ÷ D 1600 C E R/S ⟶ 3723.37

R/S ⟶ 4.99

LINE-LINE INTERSECTION / GRID POINTS

This card calculates the point of intersection of two lines and the cartesian coordinates of points in other coordinate systems.

For both programs, the user specifies the angle from horizontal to lines in the problem. Slope may be converted to angle by the relation $\theta = \tan^{-1}$ (slope). Given two points (x_1, y_1) and (x_2, y_2) on the line, the angle is

$$\theta = \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right)$$

Line–Line Intersection

(x, y) = Coordinates of point of intersection

(x_1, y_1) = Coordinates of point on line one

(x_2, y_2) = Coordinates of point on line two

θ_1 = Angle from horizontal to line one

θ_2 = Angle from horizontal to line two

Grid Points

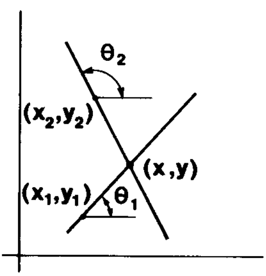
(x_0, y_0) = Coordinates of 0, 0 grid point

h_1, h_2 = Grid system unit vectors

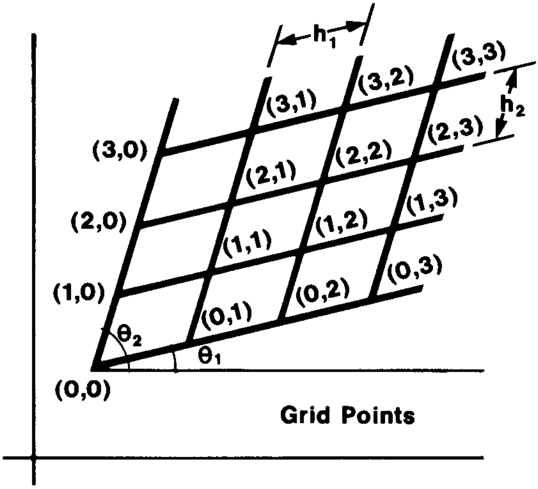
θ_1 = Angle to h_1 unit vector

θ_2 = Angle to h_2 unit vector

(x_{ij}, y_{ij}) = Coordinates of i, j grid point



Line-Line Intersection



Equations:

Line–Line Intersection

$$x = \frac{x_1 \tan\theta_1 - x_2 \tan\theta_2 + y_2 - y_1}{\tan\theta_1 - \tan\theta_2}$$

$$y = y_1 + (x - x_1)\tan\theta_1$$

Grid Points

$$x_{ij} = x_0 + j\Delta x_1 + i\Delta x_2$$

$$y_{ij} = y_0 + j\Delta y_1 + i\Delta y_2$$

$$\Delta x_1 = h_1 \cos\theta_1$$

$$\Delta y_1 = h_1 \sin\theta_1$$

$$\Delta x_2 = h_2 \cos\theta_2$$

$$\Delta y_2 = h_2 \sin\theta_2$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
	For line-line intersection (no				
	vertical lines)				
2a	Input coordinates of point on				
	line one and angle from hori-	x_1	↑		x_1
	zontal to the line	y_1	↑		y_1
		θ_1	A		
3a	Input coordinates of point on				
	line two and angle from hori-				
	zontal to the line and calculate	x_2	↑		x_2
	coordinates of the point of	y_2	↑		y_2
	intersection	θ_2	B		x
			R/S		y
	For line-line intersection (one				
	vertical line)				
2b	Input x coordinate of vertical				
	line, coordinates of point on	x	↑		x
	line one and angle from hori-	x_1	↑		x_1
	zontal to the line, and calculate	y_1	↑		y_1
	the y coordinate	θ_1	A		y
	For grid points				
2c	Input origin coordinates and	x_0	↑		x_0
	grid system unit vectors	y_0	↑		y_0
		h_1	↑		h_1
		h_2	C		x_0
3c	Input the angles from horizontal	θ_1	↑		θ_1
	to the unit vectors	θ_2	D		Δy_1
4c	Input the grid coordinates of	i	↑		i
	the point and calculate the (x, y)	j	E		x_{ij}
	coordinates		R/S		y_{ij}
5	For a new case, go to step 2				
	(a, b, c).				

Example 1:

Find the point of intersection of two lines passing through (10, 20), (40, 30) and (–10, 30), (50, 10). (15.00, 21.67)

Keystrokes:

$$\text{First, find } \theta_1 = \tan^{-1}\frac{30-20}{40-10} = \tan^{-1}\left(\frac{1}{3}\right)$$

$$\text{and } \theta_2 = \tan^{-1}\frac{10-30}{50+10} = \tan^{-1}\left(-\frac{1}{3}\right)$$

10 [ENTER↑] 20 [ENTER↑] 3 [g] [1/x] [f⁻¹] [TAN] [A]
10 [CHS] [ENTER↑] 30 [ENTER↑] 3 [CHS] [g]
[1/x] [f⁻¹] [TAN] [B] ──────► 15.00
[R/S] ──────► 21.67

Example 2:

Find the intersection of a line through (0, 0) with slope 2.8 and the line with equation x = 4.5. (4.5, 12.60)

Keystrokes:

4.5 [ENTER↑] 0 [ENTER↑] 0 [ENTER↑]
2.8 [f⁻¹] [TAN] [A] ──────► 12.60

Example 3:

For a grid with origin at (1, 1) and unit vectors 2 and 3 units long at 30° and 90°, respectively, find the cartesian coordinates for the following grid coordinates:

Grid Coordinates	Cartesian Coordinates
(0, 0)	(1.00, 1.00)
(1, 0)	(1.00, 4.00)
(2, 0)	(1.00, 7.00)
(0, 1)	(2.73, 2.00)
(0, 2)	(4.46, 3.00)
(1, 1)	(2.73, 5.00)
(1.5, 3)	(6.20, 8.50)

Keystrokes:

1 [ENTER↑] 1 [ENTER↑] 2 [ENTER↑] 3 [C] 30 [ENTER↑]

90 [D] 0 [ENTER↑] 0 [E] ⟶ 1.00

[R/S] ⟶ 1.00

1 [ENTER↑] 0 [E] ⟶ 1.00

[R/S] ⟶ 4.00

2 [ENTER↑] 0 [E] ⟶ 1.00

[R/S] ⟶ 7.00

0 [ENTER↑] 1 [E] ⟶ 2.73

[R/S] ⟶ 2.00

0 [ENTER↑] 2 [E] ⟶ 4.46

[R/S] ⟶ 3.00

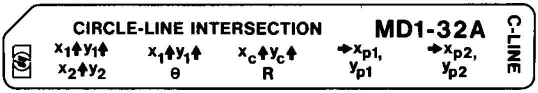
1 [ENTER↑] 1 [E] ⟶ 2.73

[R/S] ⟶ 5.00

1.5 [ENTER↑] 3 [E] ⟶ 6.20

[R/S] ⟶ 8.50

CIRCLE-LINE INTERSECTION



This program computes the points of intersection of a line and a circle, given the circle center coordinates and radius, and either two points on the line or one point and angle to the line from the horizontal axis.

θ = Angle from horizontal to line

α = Angle from horizontal to the line $\overline{C1}$

C = Length of line $\overline{C1}$

P = Length of line from (x_1, y_1) to points of intersection

R = Circle radius

(x_c, y_c) = Circle center coordinates

$(x_1, y_1), (x_2, y_2)$ = Coordinates of points on line

(x_p, y_p) = Coordinates of points of intersection

Equations:

$$\theta = \tan^{-1}\left[\frac{y_2 - y_1}{x_2 - x_1}\right]$$

$$\alpha = \tan^{-1}\left[\frac{y_c - y_1}{x_c - x_1}\right]$$

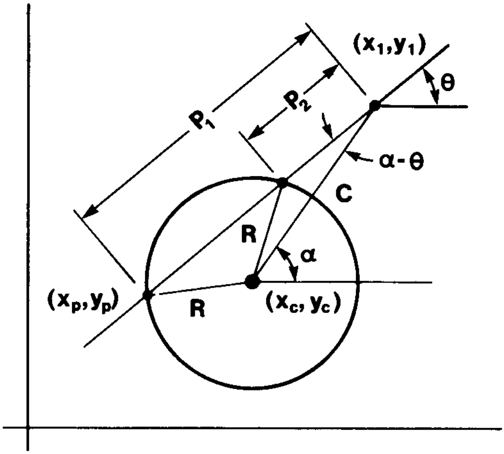
$$C = \sqrt{(x_c - x_1)^2 + (y_c - y_1)^2}$$

$$x_p = x_1 + P\cos\theta$$

$$y_p = y_1 + P\sin\theta$$

Remarks:

This program may generate blinking zeroes due to machine limitations for vertical lines tangent to the circle. Stop the blinking and press R/S to continue with the calculation.



STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2a	Input the coordinates of two	x_1	↑		x_1
	points on the line, or	y_1	↑		y_1
		x_2	↑		x_2
		y_2	A		θ
2b	Input the coordinates of a point	x_1	↑		x_1
	on the line and the angle to the	y_1	↑		y_1
	line from horizontal	θ	B		x_1
3	Input the circle center coordi-	x_c	↑		x_c
	nates and radius	y_c	↑		y_c
		R	C		α
4	Calculate the coordinates of the				
	points of intersection		D		x_{p1}
			R/S		y_{p1}
			E		x_{p2}
			R/S		y_{p2}
5	For a new case, go to step 2.				

Example 1:

Calculate the coordinates of the points on the circle shown below.

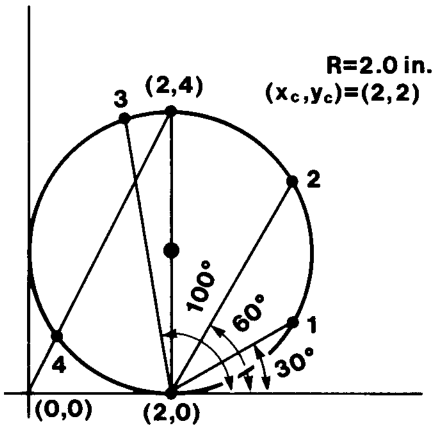
Solution:

1 (3.73, 1.00)

2 (3.73, 3.00)

3 (1.32, 3.88)

4 (0.40, 0.80)



Keystrokes:

2 [ENTER↑] 0 [ENTER↑] 30 [B] 2 [ENTER↑]

2 [ENTER↑] 2 [C] [D] ⟶ 3.73

[R/S] ⟶ 1.00

2 [ENTER↑] 0 [ENTER↑] 60 [B] 2 [ENTER↑]

2 [ENTER↑] 2 [C] [D] ⟶ 3.73

[R/S] ⟶ 3.00

2 [ENTER↑] 0 [ENTER↑] 100 [B] 2 [ENTER↑]

2 [ENTER↑] 2 [C] [D] ⟶ 1.32

[R/S] ⟶ 3.88

0 [ENTER↑] 0 [ENTER↑] 2 [ENTER↑] 4 [A]

2 [ENTER↑] 2 [ENTER↑] 2 [C] [D] ⟶ 2.00

[R/S] ⟶ 4.00

[E] ⟶ 0.40

[R/S] ⟶ 0.80

Example 2:

Find the points of intersection for a circle with center at (0, 0) and radius 50, and the line containing the points (20, 30) and (0, –10).

Solution:

(26.27, 42.54)   (–18.27, –46.54)

Keystrokes:

20 [ENTER↑] 30 [ENTER↑] 0 [ENTER↑] 10 [CHS] [A]

0 [ENTER↑] 0 [ENTER↑] 50 [C] [D] ——→ 26.27

[R/S] ——→ 42.54

[E] ——→ –18.27

[R/S] ——→ –46.54

CIRCLE-CIRCLE INTERSECTION

CIRCLE-CIRCLE INTERSECTION			MD1-33A	CIRCLS
$x_1 \uparrow y_1 \uparrow R_1$	$x_2 \uparrow y_2 \uparrow R_2$	$\rightarrow x_{p1}, y_{p1}$	$\rightarrow x_{p2}, y_{p2}$	

This program calculates the coordinates of the points of intersection for two circles, given the radius and center coordinates for each.

(x_1, y_1) = Center coordinates of circle one

R_1 = Radius of circle one

(x_2, y_2) = Center coordinates of circle two

R_2 = Radius of circle two

(x_p, y_p) = Coordinates of points of intersection

Equations:

$$x_{p1} = x_1 + R_1 \cos(\theta + \alpha)$$

$$y_{p1} = y_1 + R_1 \sin(\theta + \alpha)$$

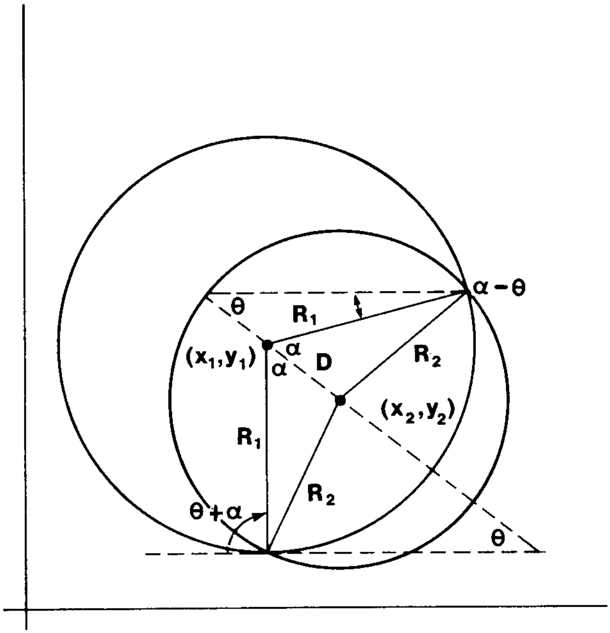
$$x_{p2} = x_1 + R_1 \cos(\theta - \alpha)$$

$$y_{p2} = y_1 + R_1 \sin(\theta - \alpha)$$

$$\theta = \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right)$$

$$\alpha = \cos^{-1}\left[\frac{D^2 + R_1^2 - R_2^2}{2DR_1}\right]$$

$$D = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$



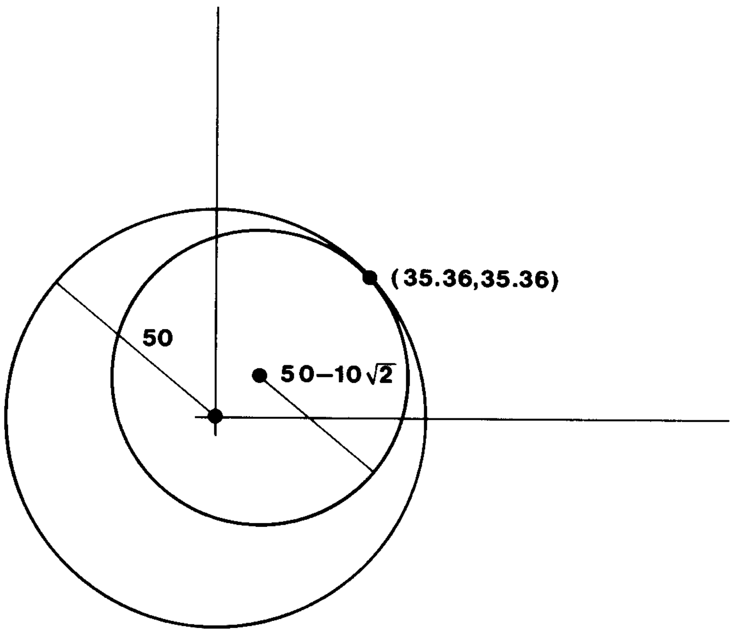
STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input the center coordinates	x_1	↑		x_1
	and radius of circle one.	y_1	↑		y_1
		R_1	A		x_1
3	Input the center coordinates	x_2	↑		x_2
	and radius of circle two	y_2	↑		y_2
		R_2	B		$\theta + \alpha$
4	Compute the coordinates of the		C		x_{p1}
	points of intersection	*	R/S		y_{p1}
			D		x_{p2}
		*	R/S		y_{p2}
5	For a new case, go to step 2.				

Example 1:

Find the point of intersection for circles at (0, 0) radius 50 and (10, 10) radius $50 - 10\sqrt{2}$. (35.36, 35.36)

Keystrokes:

0 [ENTER↑] 0 [ENTER↑] 50 [A] 10 [ENTER↑] 10 [ENTER↑]
5 [ENTER↑] 2 [f] [√x] [−] 10 [×] [B] [C] ⟶ 35.36
[R/S] ⟶ 35.36
[D] ⟶ 35.36
[R/S] ⟶ 35.36



Example 2:

Calculate the points of intersection for circles at (0, 0) radius 50 and (90, 30) radius 70.

Solution:

(21.64, 45.07) (44.36, - 23.07)

Keystrokes:

0 [ENTER↑] 0 [ENTER↑] 50 [A] 90 [ENTER↑]

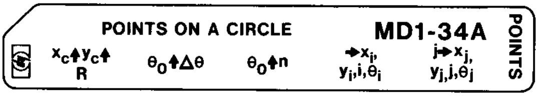
30 [ENTER↑] 70 [B] [C] ⟶ 21.64

[R/S] ⟶ 45.07

[D] ⟶ 44.36

[R/S] ⟶ –23.07

POINTS ON A CIRCLE



This program calculates coordinates on a circle at regular angular increments, or evenly spaced over the entire circle.

(x_i, y_i) = Coordinates of the i^{th} point

θ_0 = Initial angle

$\Delta\theta$ = Angular increment

(x_c, y_c) = Coordinates of circle center

R = Circle radius

n = Number of evenly spaced points

Equations:

$$x_i = x_c + R\cos(\theta_0 + (i-1)\Delta\theta)$$

$$y_i = y_c + R\sin(\theta_0 + (i-1)\Delta\theta)$$

$$\Delta\theta = \frac{360}{n} \text{ (for n evenly spaced points)}$$

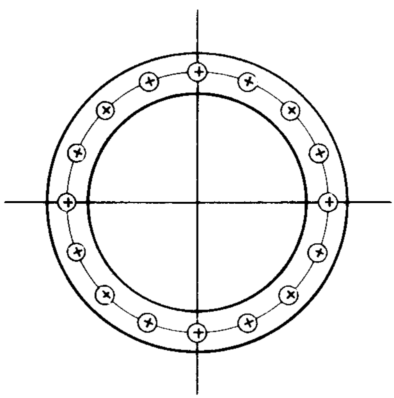
$$\theta_i = \theta_0 + (i-1)\Delta\theta$$

For n evenly spaced points, $x_{n+1} = x_1$, $x_{n+2} = x_2$, and so on.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input the circle center coordi-	x_c	↑		x_c
	nates and radius	y_c	↑		y_c
		R	A		0.00
3a	Input the initial angle and the	θ_0	↑		θ_0
	angular increment, or	$\Delta\theta$	B		θ_0
3b	Input the initial angle and	θ_0	↑		θ_0
	number of points on the circle	n	C		θ_0
4	Calculate the coordinates of		D		x_i
	point i, and the total angle		R/S		y_i
			R/S		i
			R/S		θ_i
5	Repeat step 4 for i = 1, 2, 3, ...				
6	Optional: Calculate the coordi-	j	E		x_j
	nates for a specified point j		R/S		y_j
			R/S		j
			R/S		θ_j
7	For a new case, go to step 2.				

Example 1:

Two sections of pipe are to be joined by a flange with 16 evenly spaced bolts 9.75 inches from the center of the pipe. Calculate the coordinates of the bolt holes to be drilled. Let $x_c = y_c = \theta_0 = 0$.



Solution:

i	x_i	y_i
1	9.75	0.00
2	9.01	3.73
3	6.89	6.89
4	3.73	9.01
5	0.00	9.75
6	–3.73	9.01
7	–6.89	6.89
8	–9.01	3.73
9	–9.75	0.00
10	–9.01	–3.73
11	–6.89	–6.89
12	–3.73	–9.01
13	0.00	–9.75
14	3.73	–9.01
15	6.89	–6.89
16	9.01	–3.73

Keystrokes:

0 [ENTER↑] 0 [ENTER↑] 9.75 [A] 0 [ENTER↑]

16 [C] [D] ⟶ 9.75

[R/S] ⟶ 0.00

[D] ⟶ 9.01

[R/S] ⟶ 3.73

[D] ⟶ 6.89

[R/S] ⟶ 6.89

⋮ ⋮

[D] ⟶ 6.89

[R/S] ⟶ –6.89

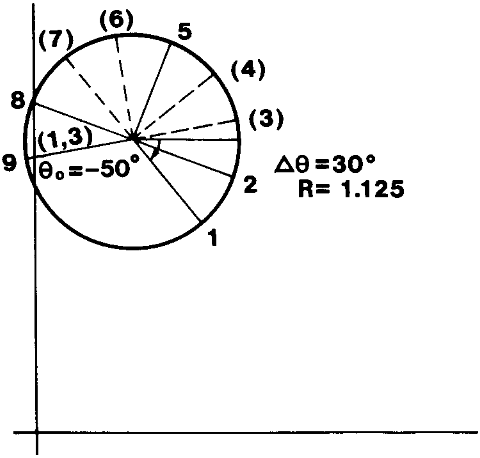
[D] ⟶ 9.01

[R/S] ⟶ –3.73

[R/S] ⟶ (16.00)

Example 2:

Find the coordinates of the points shown on the circle below.



Solution:

i	x_i	y_i
1	1.72	2.14
2	2.06	2.62
5	1.38	4.06
8	–0.06	3.38
9	–0.11	2.80

Keystrokes:

1 [ENTER↑] 3 [ENTER↑] 1.125 [A] 50 [CHS] [ENTER↑]

30 [B] [D] ——→ 1.72

[R/S] ——→ 2.14

[D] ——→ 2.06

[R/S] ——→ 2.62

5 [E] ——→ 1.38

[R/S] ——→ 4.06

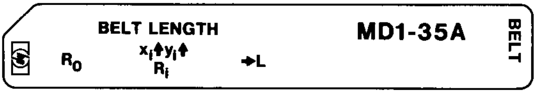
8 [E] ——→ –0.06

[R/S] ——→ 3.38

9 [E] ——→ –0.11

[R/S] ——→ 2.80

BELT LENGTH



This program computes the belt length around an arbitrary set of pulleys. It may also be used to compute the total length between any connected set of coordinates. The program assumes the coordinates of the first pulley to be (0, 0).

(x_i, y_i, R_i) = x, y coordinates and radius of pulley i

R_0 = Radius of first pulley

C.D. = Center to center distance of consecutive pulleys

L = Total length of belt

Equations:

$$L_{12} = \sqrt{C.D._{12}{}^2 - (R_2 - R_1)^2}$$

$$\text{Arc Length}_2 = R_2\,(\pi - \alpha - \beta - \gamma_2)$$

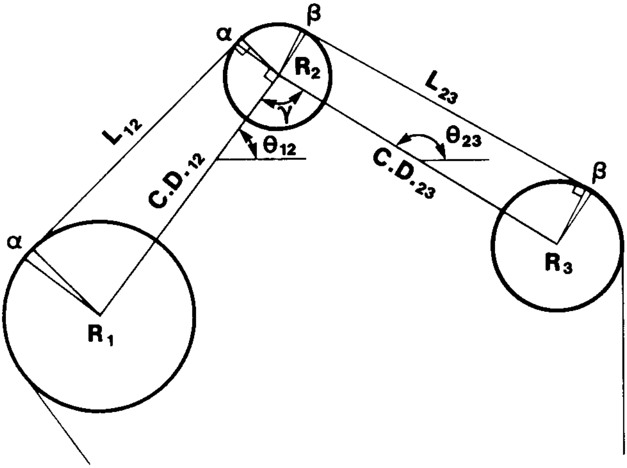
$$\alpha = \tan^{-1}\left(\frac{R_1 - R_2}{L_{12}}\right)$$

$$\beta = \tan^{-1}\left(\frac{R_3 - R_2}{L_{23}}\right)$$

$$\gamma = \theta_{12} - \theta_{23}$$

$$\theta_{12} = \tan^{-1}\frac{y_2 - y_1}{x_2 - x_1}$$

$$\theta_{23} = \tan^{-1}\frac{y_3 - y_2}{x_3 - x_2}$$



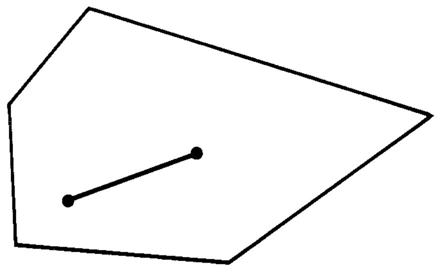
STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Set the calculator to radians				
	mode		g	RAD	
3	Input the initial pulley radius	R_0	A		R_0
4	Input the next pulley	x_i	↑		x_i
	coordinates and radius	y_i	↑		y_i
		R_i	B		R_i
5	Repeat step 4 for all pulleys.				
	(The last pulley to be input is				
	the origin pulley [0 ENTER↑				
	0 ENTER↑ R_0 B]).				
6	Compute the belt length		C		L
7	For a new case, go to step 3.				

Remarks:

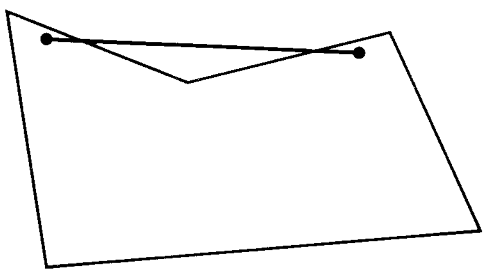
The calculator is set and left in radians mode.

This program generates accurate results for any convex polygon, i.e. a line between any two points within the region bounded by the center-to-center line segments is entirely contained within the region.

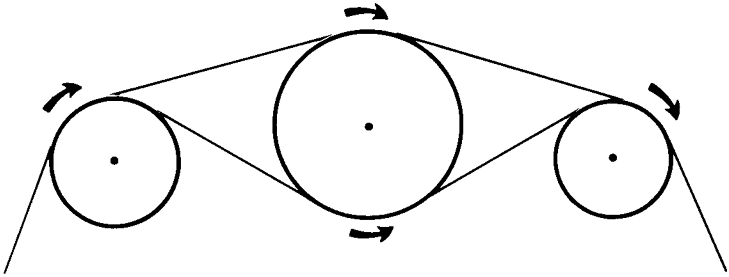
Convex



Concave

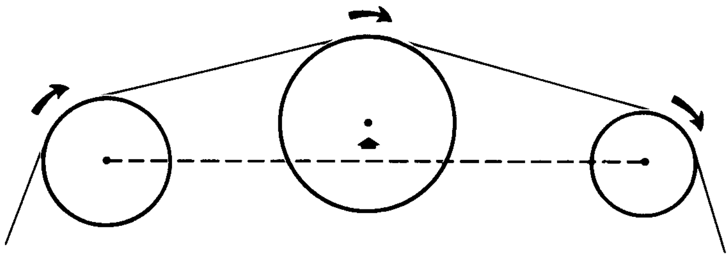


In some cases, there are two physically possible directions for the belt to take:



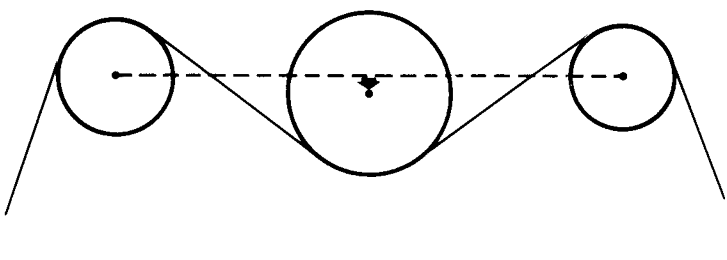
The program chooses the upper side if the middle pulley center lies above the line connecting the previous and following pulleys.

Case 1



The program chooses the lower side if the middle pulley center lies below the line connecting the previous and following pulleys.

Case 2



The program generates inaccurate answers in the second case. Note the figure bounded by the center-to-center line segments for the second case is not convex.

Example 1:

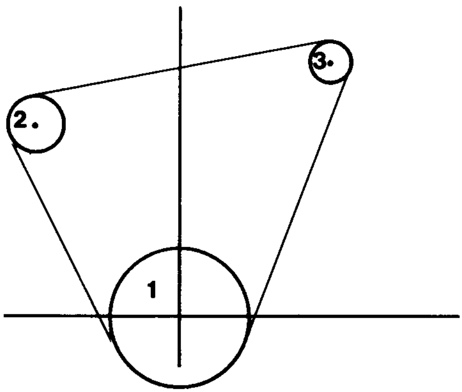
Assume three pulleys are positioned as shown below with the following coordinates and radii:

Pulley 1 (0, 0, 4 inches)

Pulley 2 (–8, 15, 1.5 inches)

Pulley 3 (9, 16, 1 inches).

Find the belt length around the three pulleys. (66.53 inches)



Keystrokes:

g RAD 4 A ⟶ 4.00

8 CHS ENTER↑ 15 ENTER↑ 1.5 B ⟶ 1.50

9 ENTER↑ 16 ENTER↑ 1 B ⟶ 1.00

0 ENTER↑ 0 ENTER↑ 4 B ⟶ 4.00

C ⟶ 66.53

Example 2:

Find the length of line connecting the points (0, 0), (1.5, 7), (3.2, –6), (0, 0.5), (0, 0). (28.01). Let the radius of each "pulley" be 0.

Keystrokes:

[g] [RAD] 0 [A] ——→ 0.00
1.5 [ENTER↑] 7 [ENTER↑] 0 [B] ——→ 0.00
3.2 [ENTER↑] 6 [CHS] [ENTER↑] 0 [B] ——→ 0.00
0 [ENTER↑] .5 [ENTER↑] 0 [B] ——→ 0.00
0 [ENTER↑] 0 [ENTER↑] 0 [B] ——→ 0.00
[C] ——→ 28.01

REGISTER ALLOCATION
MACHINE DESIGN PAC 1

CARD	#S	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9
ACC t	MD1-1A	$x(\theta)$	$v_0(\omega_0)$	t	$a(\alpha)$	$v(\omega)$				
ACC v	MD1-2A	$x(\theta)$	$v_0(\omega_0)$	t	$a(\alpha)$	$v(\omega)$				
K.E.	MD1-3A	K.E.	W(m)	v	2(met)64.3(Eng)					
VIBR 1	MD1-4A1	k	m	x_0	$\dot{x}_0$	$-c/2m$	$R(1),A_{cr}(2),r_1(3)$	$\delta(1),B_{cr}(2),r_2(3)$	$c,\omega(1),A_{ov}(3)$	$Used,B_{ov}(3)$
VIBR 2	MD1-4A2	k	m	Used	$t,\omega t-\delta$	$-c/2m$	$R(1),A_{cr}(2),r_1(3)$	$\delta(1),B_{cr}(2),r_2(3)$	$\omega(1),A_{ov}(3)$	$Used(1),B_{ov}(3)$
FCOSωt	MD1-5A	k	m	c	F_0	ω	δ	Δ	t	Used
OSCLTR	MD1-6A	k	m	c	$x_{n+½}^{(2)}$	$x_n^{(1)}$	$x_n^{(2)}$	h	t	
SERIES	MD1-7A	C_1	C_2	C_3	C_4	C_5	C_6	k	J,j	N
SHAFT	MD1-8A	$\Sigma W_i y_i$	$\Sigma W_i y_i^2$	Σy_{ij}	W_i	x_i	$\min(x_i,x_j)$	$\max(x_i,x_j)$	ℓ	6EIℓ,Used
FRDSTN	MD1-9A1	x_1,d_1	x_2,d_2	x_3,d_3	θ_1,a_1	a_2	θ_3,a_3	ϕ_1,b_1	ϕ_3,b_2	Used,b_3
3x3 EQ	MD1-9A2	$d_1 \rightarrow R_1$	$d_2 \rightarrow R_2$	$d_3 \rightarrow R_3$	a_1	$a_2,a_2/a_1$	$a_3,a_3/a_1$	b_1	b_2,Used	b_3,Used
LINK	MD1-9A3	R_1	R_2	R_3	a	b	c	d		
4BR PV	MD1-10A1	$d(-c),\dot{\theta}$	$c(d),d\phi/d\theta(d\alpha/d\theta)$	θ	a	b	c	d	$e,\phi(\alpha)$	Used
4BR A	MD1-10A2	$\dot{\theta},\ddot{\theta}$	$d\phi/d\theta(d\alpha/d\theta)$	θ	a	b	c	d	$\phi(\alpha)$	Used
SLDR x	MD1-11A	R	L	E	ω	θ	ϕ	$\cos\phi$	Used	Used
SLDR θ	MD1-12A	R	L	E	ω	θ	ϕ	$\phi max,\Delta\phi$	$d^2\phi/d\theta^2$	Used
CAMS	MD1-13A	β,L	–Inc	h	R_b	R_g-R_r	R_r		Inc	
HCAM R	MD1-14A	β	θ	h	R_b	R_g-R_r	Used	Used	Inc	Used
HCAM F	MD1-15A	β	θ	h	R_b	R_g	Used	Used	Inc	Used

RCAM f	MD1-16A	β	θ	h	R_b	R_g-R_r	Used	Used	Inc	Used
FCAM f	MD1-17A	β	θ	h	R_b	R_g	Used	Used	Inc	Used
LCAM f	MD1-18A	L	x	h	R_b	R_g-R_r	R_r	y	Inc	Used
SPUR	MD1-19A	f	2 C.D.	P	N_p	D_p	N_g	D_g		
INV 1	MD1-20A1	N	P	d_w	ϕ	D	inv ϕ_w	ϕ_w	t	Used
INV 2	MD1-20A2	N	P	d_w	ϕ	D,q	inv ϕ_w	ϕ_w	M	Used
S/H GR	MD1-21A	T	r	α	ϕ	ϕ_n	F_t	F_r	F_a	Used
BVL GR	MD1-22A	F_t	ϕ_n	α	β	Used	Used	Used	Used	Used
WM GR	MD1-23A	F_{wt}	ϕ_n	f	λ	Used,F_{gt}	Used,F_r	r_w		Used
SPR k	MD1-24A	X_1	F_1	X_2	F_2	k				
HELIC	MD1-25A	d	D	G	C	f	s	P		
TORSN	MD1-26A	d,h	$32R/\pi$,6R/b	DN,L/π	d^3,h^2	D,C	K	E		
FLAT	MD1-27A	h	b	L	C	1.25	f	E	Code	Used
CLUTCH	MD1-28A	F	f	R_i	R_o	n,csc α	$(R_i+R_o)/2$	N/63025.36		Used
SCREW	MD1-29A	r_t	f_t	$f_c r_c$	g	α	tan α	e	f_t/g	Used
R/T/P	MD1-30A	Used	RPM	Torque	Power	Used	Used			
GRID	MD1-31A	x_1,x_0	$y_1,\Delta x_1$	tan $\theta_1,\Delta x_2$	tan θ_2,y_0	Δy_1	Δy_2	h_1	h_2	Used
C-LINE	MD1-32A	x_1	y_1	θ	α	C	R	P_1	P_2	Used
CIRCLS	MD1-33A	x_1	y_1	R_1	x_2	y_2	R_2	$\theta+\alpha$	$\theta-\alpha$	Used
POINTS	MD1-34A	x_c	y_c	R	$\Delta\theta$	θ_o	θ_i	i(j)	−i	Used
BELT	MD1-35A	R_{i-1}	x_i	y_i	R_i	θ_o	θ_i	α	Σ Length	Used

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CONSTANT ACCELERATION–TIME

KEYS	CODE
STO 1	33 01
R/S	84
RCL 2	34 02
RCL 4	34 04
2	02
÷	81
RCL 3	34 03
x	71
+	61
RCL 3	34 03
x	71
STO 1	33 01
R/S	84
LBL	23
B	12
STO 2	33 02
R/S	84
RCL 1	34 01
RCL 3	34 03
÷	81
RCL 4	34 04
RCL 3	34 03
x	71
2	02
÷	81
–	51
STO 2	33 02
R/S	84
LBL	23
C	13
STO 3	33 03
R/S	84
E	15
RCL 2	34 02
–	51

KEYS	CODE
RCL 4	34 04
÷	81
STO 3	33 03
R/S	84
LBL	23
D	14
STO 4	33 04
R/S	84
RCL 1	34 01
RCL 2	34 02
RCL 3	34 03
x	71
–	51
RCL 3	34 03
↑	41
x	71
2	02
÷	81
÷	81
STO 4	33 04
R/S	84
LBL	23
E	15
RCL 2	34 02
↑	41
x	71
RCL 1	34 01
RCL 4	34 04
2	02
x	71
x	71
+	61
f	31
$\sqrt{x}$	09
STO 5	33 05

KEYS	CODE
RTN	24
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1 x (θ)	R_4 a (α)	R_7
R_2 v_0 (ω_0)	R_5 v (ω)	R_8
R_3 t	R_6	R_9

CONSTANT ACCELERATION–VELOCITY

KEYS	CODE
STO 1	33 01
R/S	84
RCL 5	34 05
↑	41
x	71
RCL 2	34 02
↑	41
x	71
–	51
RCL 4	34 04
÷	81
2	02
÷	81
STO 1	33 01
R/S	84
LBL	23
B	12
STO 2	33 02
R/S	84
RCL 5	34 05
↑	41
x	71
RCL 1	34 01
RCL 4	34 04
x	71
2	02
x	71
–	51
f	31
$\sqrt{x}$	09
STO 2	33 02
R/S	84
LBL	23
C	13
STO 5	33 05

KEYS	CODE
R/S	84
RCL 2	34 02
↑	41
x	71
RCL 1	34 01
RCL 4	34 04
x	71
2	02
x	71
+	61
f	31
$\sqrt{x}$	09
STO 5	33 05
R/S	84
LBL	23
D	14
STO 4	33 04
R/S	84
RCL 5	34 05
↑	41
x	71
RCL 2	34 02
↑	41
x	71
–	51
RCL 1	34 01
÷	81
2	02
÷	81
STO 4	33 04
R/S	84
LBL	23
E	15
RCL 2	34 02
↑	41

KEYS	CODE
x	71
RCL 1	34 01
RCL 4	34 04
x	71
2	02
x	71
+	61
f	31
$\sqrt{x}$	09
RCL 2	34 02
–	51
RCL 4	34 04
÷	81
STO 3	33 03
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1 x (θ)	R_4 a (α)	R_7
R_2 v_0 (ω)	R_5 v (ω)	R_8
R_3 t	R_6	R_9

KINETIC ENERGY

KEYS	CODE
2	02
STO 4	33 04
R/S	84
LBL	23
B	12
6	06
4	04
•	83
3	03
4	04
7	07
9	09
6	06
STO 4	33 04
R/S	84
LBL	23
C	13
STO 1	33 01
R/S	84
RCL 2	34 02
RCL 3	34 03
↑	41
x	71
x	71
RCL 4	34 04
÷	81
STO 1	33 01
R/S	84
RCL 1	34 01
1	01
9	09
8	08
EEX	43
4	04
÷	81

KEYS	CODE
R/S	84
LBL	23
D	14
STO 2	33 02
R/S	84
RCL 1	34 01
RCL 4	34 04
x	71
RCL 3	34 03
↑	41
x	71
÷	81
STO 2	33 02
R/S	84
LBL	23
E	15
STO 3	33 03
R/S	84
RCL 1	34 01
RCL 4	34 04
x	71
RCL 2	34 02
÷	81
f	31
$\sqrt{x}$	09
STO 3	33 03
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

KEYS	CODE
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	34 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1 K. E.	R_4 2(met) 64.3(Eng)	R_7
R_2 W(m)	R_5	R_8
R_3 v	R_6	R_9

FREE VIBRATIONS SET-UP

KEYS	CODE
g	35
RAD	42
STO 4	33 04
g x⇄y	35 07
STO 3	33 03
R/S	84
LBL	23
B	12
STO 1	33 01
g R↓	35 08
STO 8	33 08
g R↓	35 08
STO 2	33 02
RCL 8	34 08
2	02
÷	81
RCL 2	34 02
÷	81
CHS	42
STO 5	33 05
C	13
RCL 8	34 08
g x>y	35 24
GTO	22
3	03
CLX	44
RCL 4	34 04
RCL 3	34 03
STO 6	33 06
RCL 5	34 05
x	71
–	51
STO 7	33 07
g R↑	35 08
RCL 8	34 08

KEYS	CODE
g x=y	35 23
2	02
R/S	84
RCL 7	34 07
D	14
STO 8	33 08
÷	81
RCL 3	34 03
f	31
R→P	01
STO 6	33 06
g x⇄y	35 07
STO 7	33 07
1	01
R/S	84
LBL	23
3	03
RCL 5	34 05
D	14
–	51
STO 6	33 06
RCL 5	34 05
g LST X	35 00
+	61
STO 7	33 07
–	51
RCL 3	34 03
RCL 3	34 03
RCL 6	34 06
x	71
RCL 4	34 04
–	51
g R↑	35 09
÷	81
STO	33

KEYS	CODE
9	09
–	51
STO 8	33 08
3	03
R/S	84
LBL	23
C	13
RCL 1	34 01
RCL 2	34 02
x	71
f	31
$\sqrt{x}$	09
2	02
x	71
RTN	24
LBL	23
D	14
RCL 5	34 05
↑	41
x	71
RCL 1	34 01
RCL 2	34 02
÷	81
–	51
g	35
ABS	06
f	31
$\sqrt{x}$	09
RTN	24
g NOP	35 01

R_1 k	R_4 $\dot{x}_0$	R_7 $\delta(1), B_{cr}(2), r_2(3)$
R_2 m	R_5 $-c/2m$	R_8 $c, \omega(1), A_{ov}(3)$
R_3 x_0	R_6 $R(1), A_{cr}(2), r_1(3)$	R_9 Used, $B_{ov}(3)$

FREE VIBRATIONS SOLUTION

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 5	34 05	↑	41	RCL 7	34 07
x	71	↑	41	RCL 3	34 03
2	02	R/S	84	x	71
x	71	RCL 5	34 05	+	61
g x⇄y	35 07	x	71	R/S	84
RCL 1	34 01	RCL 4	34 04	GTO	22
x	71	f	31	0	00
RCL 2	34 02	SIN	04	LBL	23
÷	81	RCL 3	34 03	C	13
–	51	x	71	STO 4	33 04
R/S	84	RCL 8	34 08	RCL 6	34 06
LBL	23	x	71	E	15
E	15	RCL 6	34 06	RCL 8	34 08
RCL 4	34 04	x	71	x	71
x	71	–	51	STO 3	33 03
f^{-1}	32	R/S	84	RCL 7	34 07
LN	07	GTO	22	E	15
RTN	24	0	00	RCL	34
LBL	23	LBL	23	9	09
A	11	B	12	x	71
STO 4	33 04	STO 4	33 04	+	61
RCL 5	34 05	RCL 5	34 05	R/S	84
E	15	E	15	g LST X	35 00
STO 3	33 03	STO 3	33 03	RCL 7	34 07
RCL 4	34 04	RCL 7	34 07	x	71
RCL 8	34 08	RCL 4	34 04	RCL 3	34 03
x	71	x	71	RCL 6	34 06
RCL 7	34 07	RCL 6	34 06	x	71
–	51	+	61	+	61
STO 4	33 04	x	71	R/S	84
f	31	↑	41		
COS	05	↑	41		
x	71	R/S	84		
RCL 6	34 06	RCL 5	34 05		
x	71	x	71		

R_1	k	R_4	t, $\omega t - \delta$	R_7	δ(1), B_{cr}(2), r_2(3)
R_2	m	R_5	$-c/2m$	R_8	ω(1), A_{ov}(3)
R_3	Used	R_6	R(1), A_{cr}(2), r_1(3)	R_9	Used (1), B_{ov} (3)

VIBRATION FORCED BY F_0COS ωt

KEYS	CODE
STO 1	33 01
g R↓	35 08
STO 3	33 03
g R↓	35 08
STO 2	33 02
RCL 1	34 01
RCL 2	34 02
÷	81
RCL 3	34 03
RCL 2	34 02
÷	81
↑	41
x	71
2	02
÷	81
–	51
f	31
√x	09
R/S	84
LBL	23
B	12
STO 4	33 04
g x⇄y	35 07
STO 5	33 05
R/S	84
LBL	23
C	13
g	35
RAD	42
RCL 3	34 03
RCL 5	34 05
x	71
RCL 1	34 01
RCL 2	34 02
÷	81

KEYS	CODE
RCL 5	34 05
↑	41
x	71
–	51
RCL 2	34 02
x	71
f	31
R→P	01
STO 7	33 07
g x⇄y	35 07
STO 6	33 06
RCL 4	34 04
RCL 7	34 07
÷	81
R/S	84
RCL 6	34 06
R/S	84
LBL	23
D	14
g	35
RAD	42
STO 8	33 08
RCL 5	34 05
x	71
RCL 6	34 06
–	51
↑	41
f	31
COS	05
RCL 4	34 04
x	71
RCL 7	34 07
÷	81
R/S	84
g x⇄y	35 07

KEYS	CODE
f	31
TAN	06
RCL 5	34 05
x	71
CHS	42
g x⇄y	35 07
x	71
R/S	84
g LST X	35 00
RCL 1	34 01
x	71
g x⇄y	35 07
RCL 3	34 03
x	71
+	61
RCL 5	34 05
RCL 8	34 08
x	71
f	31
COS	05
RCL 4	34 04
x	71
–	51
RCL 2	34 02
÷	81
CHS	42
g	35
DEG	41
R/S	84
g NOP	35 01

R_1	k	R_4	F_0	R_7	Δ
R_2	m	R_5	ω	R_8	t
R_3	c	R_6	δ	R_9	Used

FORCED OSCILLATOR WITH ARBITRARY FUNCTION

KEYS	CODE
RCL 8	34 08
E	15
RCL 6	34 06
RCL 3	34 03
x	71
–	51
RCL 1	34 01
RCL 5	34 05
x	71
–	51
RCL 2	34 02
÷	81
RCL 7	34 07
x	71
2	02
÷	81
RCL 6	34 06
+	61
STO 4	33 04
RCL 8	34 08
RCL 7	34 07
2	02
÷	81
+	61
E	15
RCL 4	34 04
RCL 3	34 03
x	71
–	51
RCL 6	34 06
RCL 7	34 07
x	71
2	02
÷	81
RCL 5	34 05

KEYS	CODE
+	61
RCL 1	34 01
x	71
–	51
RCL 2	34 02
÷	81
RCL 7	34 07
x	71
RCL 6	34 06
+	61
STO 6	33 06
RCL 4	34 04
RCL 7	34 07
x	71
RCL 5	34 05
+	61
STO 5	33 05
RCL 8	34 08
RCL 7	34 07
+	61
STO 8	33 08
R/S	84
RCL 5	34 05
R/S	84
RCL 6	34 06
R/S	84
RCL 8	34 08
E	15
RCL 3	34 03
RCL 6	34 06
x	71
–	51
RCL 1	34 01
RCL 5	34 05
x	71

KEYS	CODE
–	51
RCL 2	34 02
÷	81
R/S	84
LBL	23
E	15
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	k	R_4	$x_{n+½}^{(2)}$	R_7	h
R_2	m	R_5	$x_n^{(1)}$	R_8	t
R_3	c	R_6	$x_n^{(2)}$	R_9	

FOURIER SERIES

KEYS	CODE
f	31
REG	43
STO	33
9	09
R/S	84
LBL	23
B	12
CHS	42
STO 8	33 08
1	01
STO 7	33 07
R/S	84
LBL	23
C	13
g	35
RAD	42
2	02
RCL	34
9	09
÷	81
x	71
RCL 7	34 07
g LST X	35 00
x	71
g	35
π	02
x	71
↑	41
E	15
STO	33
+	61
1	01
f	31
TF 1	61
GTO	22

KEYS	CODE
2	02
E	15
STO	33
+	61
2	02
E	15
STO	33
+	61
3	03
E	15
STO	33
+	61
4	04
E	15
STO	33
+	61
5	05
E	15
STO	33
+	61
6	06
LBL	23
2	02
6	06
f	31
TF 1	61
CLX	44
1	01
STO	33
+	61
8	08
RCL 7	34 07
1	01
+	61
STO 7	33 07

KEYS	CODE
g	35
DEG	41
R/S	84
LBL	23
E	15
g R↓	35 08
↑	41
↑	41
RCL 8	34 08
CHS	42
g	35
DSZ	83
x	71
RCL	34
9	09
g R↓	35 08
LBL	23
1	01
f	31
COS	05
g R↑	35 09
STO	33
9	09
CLX	44
+	61
g R↑	35 09
x	71
RTN	24
g NOP	35 01
g NOP	35 01

R_1	C_1	R_4	C_4	R_7	k
R_2	C_2	R_5	C_5	R_8	J, j
R_3	C_3	R_6	C_6	R_9	N

CRITICAL SHAFT SPEED

KEYS	CODE
f	31
REG	43
STO 8	33 08
x	71
x	71
6	06
x	71
STO	33
9	09
R/S	84
LBL	23
B	12
STO 5	33 05
g x⇄y	35 07
STO 4	33 04
0	00
STO 3	33 03
g R↓	35 08
g x⇄y	35 07
LBL	23
C	13
RCL 5	34 05
RCL	34
9	09
g R↓	35 08
g x>y	35 24
g x⇄y	35 07
g NOP	35 01
STO 6	33 06
g x⇄y	35 07
STO 7	33 07
g R↑	35 09
STO	33
9	09
g R↓	35 08

KEYS	CODE
↑	41
x	71
g x⇄y	35 07
↑	41
x	71
+	61
RCL 8	34 08
RCL 7	34 07
x	71
2	02
x	71
–	51
x	71
RCL 6	34 06
x	71
RCL 7	34 07
RCL 8	34 08
–	51
x	71
RCL	34
9	09
÷	81
RCL 3	34 03
+	61
STO 3	33 03
RCL 4	34 04
g x⇄y	35 07
R/S	84
LBL	23
D	14
↑	41
g R↓	35 08
x	71
STO	33
+	61

KEYS	CODE
1	01
g R↑	35 09
x	71
STO	33
+	61
2	02
R/S	84
LBL	23
E	15
RCL 1	34 01
x	71
RCL 2	34 02
÷	81
f	31
$\sqrt{x}$	09
g	35
π	02
÷	81
2	02
÷	81
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1 $\Sigma W_i y_i$	R_4 W_i	R_7 $\max(x_i, x_j)$
R_2 $\Sigma W_i {y_i}^2$	R_5 x_i	R_8 ℓ
R_3 Σy_{ij}	R_6 $\min(x_i, x_j)$	R_9 6EIℓ, Used

FREUDENSTEIN'S EQUATIONS

KEYS	CODE
RCL 2	34 02
B	12
RCL 1	34 01
B	12
STO 5	33 05
–	51
RCL 3	34 03
B	12
RCL 5	34 05
–	51
÷	81
RCL 8	34 08
RCL 7	34 07
–	51
x	71
RCL 7	34 07
+	61
RCL 2	34 02
RCL 1	34 01
–	51
RCL 3	34 03
RCL 1	34 01
–	51
÷	81
RCL 6	34 06
RCL 4	34 04
–	51
x	71
RCL 4	34 04
+	61
C	13
STO 5	33 05
g x⇄y	35 07
STO 1	33 01
g LST X	35 00

KEYS	CODE
–	51
C	13
STO 2	33 02
RCL 1	34 01
RCL 4	34 04
RCL 7	34 07
–	51
C	13
STO 1	33 01
RCL 6	34 06
RCL 8	34 08
–	51
C	13
STO 3	33 03
RCL 4	34 04
C	13
STO 4	33 04
g R↑	35 09
RCL 6	34 06
C	13
STO 6	33 06
RCL 7	34 07
C	13
CHS	42
STO 7	33 07
RCL 8	34 08
g R↑	35 09
C	13
CHS	42
STO 8	33 08
g x⇄y	35 07
C	13
CHS	42
STO	33
9	09

KEYS	CODE
R/S	84
LBL	23
C	13
f	31
COS	05
RTN	24
LBL	23
B	12
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	x_1, d_1	R_4	θ_1, a_1	R_7	ϕ_1, b_1
R_2	x_2, d_2	R_5	a_2	R_8	ϕ_3, b_2
R_3	x_3, d_3	R_6	θ_3, a_3	R_9	Used, b_3

3 X 3 SIMULTANEOUS EQUATIONS

KEYS	CODE
LBL	23
A	11
RCL 4	34 04
g	35
1/x	04
STO 4	33 04
STO	33
x	71
6	06
STO	33
x	71
5	05
RCL 5	34 05
RCL 7	34 07
x	71
RCL 8	34 08
–	51
STO 8	33 08
RCL 6	34 06
1	01
–	51
x	71
RCL 6	34 06
RCL 7	34 07
x	71
RCL	34
9	09
–	51
STO	33
9	09
RCL 5	34 05
1	01
–	51
x	71
–	51

KEYS	CODE
g	35
1/x	04
↑	41
↑	41
RCL 5	34 05
RCL 1	34 01
x	71
RCL 2	34 02
–	51
STO 2	33 02
RCL	34
9	09
x	71
CHS	42
RCL 6	34 06
RCL 1	34 01
x	71
RCL 3	34 03
–	51
STO 3	33 03
RCL 8	34 08
x	71
+	61
x	71
STO	33
9	09
CLX	44
RCL 6	34 06
1	01
–	51
RCL 2	34 02
x	71
RCL 5	34 05
1	01
–	51

KEYS	CODE
RCL 3	34 03
x	71
–	51
x	71
STO 2	33 02
RCL	34
9	09
STO 3	33 03
RCL 1	34 01
g x⇄y	35 07
–	51
RCL 4	34 04
x	71
RCL 2	34 02
RCL 7	34 07
x	71
RCL 4	34 04
x	71
–	51
STO 1	33 01
RTN	24
LBL	23
B	12
RCL 2	34 02
RTN	24
LBL	23
C	13
RCL 3	34 03
RTN	24
g NOP	35 01

R_1 $d_1 \to R_1$	**R_4** a_1	**R_7** b_1
R_2 $d_2 \to R_2$	**R_5** a_2, a_2/a_1	**R_8** b_2, Used
R_3 $d_3 \to R_3$	**R_6** a_3, a_3/a_1	**R_9** b_3, Used

LINK LENGTHS AND RATIOS

KEYS	CODE
STO 7	33 07
g R↓	35 08
STO 6	33 06
g R↓	35 08
STO 5	33 05
g R↓	35 08
STO 4	33 04
RCL 7	34 07
÷	81
STO 1	33 01
RCL 4	34 04
RCL 5	34 05
÷	81
STO 2	33 02
E	15
g x⇄y	35 07
RCL 6	34 06
↑	41
x	71
–	51
g x⇄y	35 07
÷	81
STO 3	33 03
RCL 7	34 07
R/S	84
LBL	23
B	12
RCL 1	34 01
R/S	84
RCL 2	34 02
R/S	84
RCL 3	34 03
R/S	84
LBL	23
C	13

KEYS	CODE
STO 3	33 03
g R↓	35 08
STO 2	33 02
g R↓	35 08
STO 1	33 01
RCL 3	34 03
R/S	84
LBL	23
D	14
STO 4	33 04
RCL 1	34 01
÷	81
STO 7	33 07
RCL 4	34 04
RCL 2	34 02
÷	81
STO 5	33 05
E	15
RCL 3	34 03
x	71
–	51
f	31
$\sqrt{x}$	09
STO 6	33 06
RCL 5	34 05
R/S	84
RCL 6	34 06
R/S	84
RCL 7	34 07
R/S	84
LBL	23
E	15
RCL 4	34 04
↑	41
x	71

KEYS	CODE
RCL 5	34 05
↑	41
x	71
+	61
RCL 7	34 07
↑	41
x	71
+	61
RCL 5	34 05
2	02
x	71
RCL 7	34 07
x	71
RTN	24
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1 R_1	R_4 a	R_7 d
R_2 R_2	R_5 b	R_8
R_3 R_3	R_6 c	R_9

POSITION AND VELOCITY OF FOUR BAR SYSTEM

KEYS	CODE
STO 1	33 01
RCL 2	34 02
x	71
R/S	84
LBL	23
A	11
STO 7	33 07
g R↓	35 08
STO 6	33 06
g R↓	35 08
STO 5	33 05
g R↓	35 08
STO 4	33 04
R/S	84
LBL	23
B	12
RCL 6	34 06
RCL 7	34 07
GTO	22
1	01
LBL	23
D	14
RCL 7	34 07
RCL 6	34 06
CHS	42
LBL	23
1	01
STO 1	33 01
g R↓	35 08
STO 2	33 02
g R↓	35 08
STO 3	33 03
1	01
f^{-1}	32
R→P	01

KEYS	CODE
RCL 4	34 04
x	71
g x⇄y	35 07
RCL 4	34 04
x	71
g x⇄y	35 07
RCL 5	34 05
+	61
f	31
R→P	01
STO 8	33 08
RCL 1	34 01
f	31
R→P	01
f^{-1}	32
$\sqrt{x}$	09
RCL 2	34 02
f^{-1}	32
$\sqrt{x}$	09
−	51
RCL 1	34 01
÷	81
RCL 8	34 08
÷	81
2	02
÷	81
f^{-1}	32
COS	05
RCL 5	34 05
RCL 8	34 08
÷	81
RCL 3	34 03
f	31
SIN	04
x	71

KEYS	CODE
f^{-1}	32
SIN	04
+	61
STO 8	33 08
f	31
SIN	04
RCL 4	34 04
RCL 5	34 05
÷	81
x	71
RCL 3	34 03
f	31
SIN	04
RCL 4	34 04
RCL 1	34 01
÷	81
x	71
RCL 3	34 03
RCL 8	34 08
−	51
f	31
SIN	04
−	51
g x⇄y	35 07
g LST X	35 00
−	51
÷	81
STO 2	33 02
RCL 8	34 08
R/S	84

R_1 d (−c), $\dot{\theta}$	R_4 a	R_7 d
R_2 c(d), $d\phi/d\theta$ ($d\alpha/d\theta$)	R_5 b	R_8 e, $\phi(\alpha)$
R_3 θ	R_6 c	R_9 Used

ACCELERATION OF FOUR BAR SYSTEM

KEYS	CODE	KEYS	CODE	KEYS	CODE
f	31	x	71	g	35
SF 1	51	RCL 3	34 03	π	02
GTO	22	RCL 8	34 08	x	71
1	01	–	51	RCL 1	34 01
LBL	23	f	31	RCL 2	34 02
B	12	COS	05	x	71
f^{-1}	32	x	71	+	61
SF 1	51	RCL 4	34 04	R/S	84
LBL	23	RCL 5	34 05	g NOP	35 01
1	01	÷	81	g NOP	35 01
RCL 3	34 03	RCL 8	34 08	g NOP	35 01
RCL 8	34 08	f	31	g NOP	35 01
–	51	COS	05	g NOP	35 01
f	31	x	71	g NOP	35 01
SIN	04	RCL 2	34 02	g NOP	35 01
RCL 4	34 04	f^{-1}	32	g NOP	35 01
RCL 5	34 05	$\sqrt{x}$	09	g NOP	35 01
÷	81	x	71	g NOP	35 01
RCL 8	34 08	+	61	g NOP	35 01
f	31	RCL 4	34 04	g NOP	35 01
SIN	04	RCL 6	34 06	g NOP	35 01
x	71	CHS	42	g NOP	35 01
–	51	f	31	g NOP	35 01
RCL 1	34 01	TF 1	61	g NOP	35 01
↑	41	CLX	44	g NOP	35 01
x	71	RCL 7	34 07	g NOP	35 01
g x⇄y	35 07	÷	81	g NOP	35 01
÷	81	RCL 3	34 03	g NOP	35 01
g x⇄y	35 07	f	31	g NOP	35 01
STO 1	33 01	COS	05	g NOP	35 01
CLX	44	x	71		
1	01	–	51		
RCL 2	34 02	x	71		
–	51	2	02		
↑	41	x	71		

R_1 $\dot{\theta}, \ddot{\theta}$	R_4 a	R_7 d
R_2 $d\phi/d\theta\,(d\alpha/d\theta)$	R_5 b	R_8 $\phi(\alpha)$
R_3 θ	R_6 c	R_9 Used

LINEAR PROGRESSION OF SLIDER CRANK

KEYS	CODE
STO 1	33 01
g R↓	35 08
STO 2	33 02
g R↓	35 08
STO 3	33 03
g R↓	35 08
g	35
π	02
x	71
3	03
0	00
÷	81
STO 4	33 04
R/S	84
LBL	23
B	12
STO 5	33 05
f	31
SIN	04
RCL 1	34 01
x	71
RCL 3	34 03
+	61
RCL 2	34 02
÷	81
f^{-1}	32
SIN	04
STO 6	33 06
f	31
COS	05
STO 7	33 07
RCL 2	34 02
x	71
RCL 5	34 05
f	31

KEYS	CODE
COS	05
RCL 1	34 01
x	71
+	61
R/S	84
RCL 3	34 03
RCL 2	34 02
RCL 1	34 01
LBL	23
1	01
+	61
STO 8	33 08
÷	81
f^{-1}	32
SIN	04
f	31
COS	05
RCL 8	34 08
x	71
R/S	84
RCL 3	34 03
RCL 2	34 02
RCL 1	34 01
CHS	42
GTO	22
1	01
LBL	23
C	13
RCL 6	34 06
RCL 5	34 05
+	61
RCL 1	34 01
CHS	42
f^{-1}	32
R→P	01

KEYS	CODE
STO 8	33 08
CLX	44
RCL 4	34 04
x	71
RCL 7	34 07
÷	81
R/S	84
LBL	23
D	14
RCL 8	34 08
RCL 5	34 05
f	31
COS	05
RCL 7	34 07
÷	81
RCL 1	34 01
x	71
↑	41
x	71
RCL 2	34 02
÷	81
–	51
RCL 4	34 04
↑	41
x	71
x	71
RCL 7	34 07
÷	81
R/S	84
g NOP	35 01

R_1	R	R_4	ω	R_7	$\cos\phi$
R_2	L	R_5	θ	R_8	Used
R_3	E	R_6	ϕ	R_9	Used

ANGULAR PROGRESSION OF SLIDER CRANK

KEYS	CODE
STO 1	33 01
g R↓	35 08
STO 2	33 02
g R↓	35 08
STO 3	33 03
g R↓	35 08
g	35
π	02
x	71
3	03
0	00
÷	81
STO 4	33 04
R/S	84
LBL	23
B	12
STO 5	33 05
E	15
STO 6	33 06
R/S	84
9	09
0	00
E	15
STO 7	33 07
R/S	84
2	02
7	07
0	00
E	15
STO	33
–	51
7	07
R/S	84
RCL 7	34 07
R/S	84

KEYS	CODE
LBL	23
E	15
f	31
SIN	04
RCL 1	34 01
x	71
RCL 3	34 03
+	61
RCL 2	34 02
÷	81
f^{-1}	32
SIN	04
RTN	24
LBL	23
C	13
RCL 5	34 05
f	31
COS	05
RCL 1	34 01
x	71
RCL 6	34 06
f	31
COS	05
RCL 2	34 02
x	71
÷	81
STO 8	33 08
RCL 4	34 04
x	71
R/S	84
LBL	23
D	14
RCL 6	34 06
f	31
TAN	06

KEYS	CODE
RCL 8	34 08
↑	41
x	71
x	71
RCL 5	34 05
f	31
SIN	04
RCL 1	34 01
x	71
RCL 6	34 06
f	31
COS	05
÷	81
RCL 2	34 02
÷	81
–	51
RCL 4	34 04
↑	41
x	71
x	71
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	R	R_4	ω	R_7	ϕmax, $\Delta\phi$
R_2	L	R_5	θ	R_8	$d^2\phi/d\theta^2$
R_3	E	R_6	ϕ	R_9	Used

CAM DATA STORAGE

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 1	33 01	RCL 3	34 03	g NOP	35 01
R/S	84	RCL 4	34 04	g NOP	35 01
LBL	23	+	61	g NOP	35 01
B	12	STO 4	33 04	g NOP	35 01
STO 8	33 08	R/S	84	g NOP	35 01
CHS	42	g NOP	35 01	g NOP	35 01
STO 2	33 02	g NOP	35 01	g NOP	35 01
CHS	42	g NOP	35 01	g NOP	35 01
R/S	84	g NOP	35 01	g NOP	35 01
LBL	23	g NOP	35 01	g NOP	35 01
C	13	g NOP	35 01	g NOP	35 01
STO 3	33 03	g NOP	35 01	g NOP	35 01
R/S	84	g NOP	35 01	g NOP	35 01
LBL	23	g NOP	35 01	g NOP	35 01
D	14	g NOP	35 01	g NOP	35 01
STO 4	33 04	g NOP	35 01	g NOP	35 01
R/S	84	g NOP	35 01	g NOP	35 01
LBL	23	g NOP	35 01	g NOP	35 01
D	14	g NOP	35 01	g NOP	35 01
STO 5	33 05	g NOP	35 01	g NOP	35 01
R/S	84	g NOP	35 01	g NOP	35 01
LBL	23	g NOP	35 01	g NOP	35 01
D	14	g NOP	35 01	g NOP	35 01
STO 6	33 06	g NOP	35 01	g NOP	35 01
RCL 5	34 05	g NOP	35 01	g NOP	35 01
g x⇄y	35 07	g NOP	35 01	g NOP	35 01
–	51	g NOP	35 01	g NOP	35 01
STO 5	33 05	g NOP	35 01	g NOP	35 01
RCL 6	34 06	g NOP	35 01	g NOP	35 01
R/S	84	g NOP	35 01	g NOP	35 01
LBL	23	g NOP	35 01		
E	15	g NOP	35 01		
RCL 8	34 08	g NOP	35 01		
CHS	42	g NOP	35 01		
STO 2	33 02	g NOP	35 01		

R_1	β, L	R_4	R_b	R_7	
R_2	–Inc	R_5	$R_g - R_r$	R_8	Inc
R_3	h	R_6	R_r	R_9	

HARMONIC CAM DESIGN–RADIAL ROLLER FOLLOWER

KEYS	CODE
RCL 2	34 02
RCL 8	34 08
+	61
STO 2	33 02
R/S	84
LBL	23
B	12
1	01
RCL 2	34 02
1	01
8	08
0	00
x	71
RCL 1	34 01
÷	81
STO 6	33 06
f	31
COS	05
–	51
RCL 3	34 03
x	71
2	02
÷	81
STO 7	33 07
R/S	84
LBL	23
C	13
RCL 6	34 06
1	01
f^{-1}	32
R→P	01
g	35
π	02
RCL 1	34 01
÷	81

KEYS	CODE
STO 6	33 06
RCL 3	34 03
x	71
2	02
÷	81
x	71
g x⇄y	35 07
g LST X	35 00
x	71
g x⇄y	35 07
RCL 6	34 06
x	71
g x⇄y	35 07
STO 6	33 06
R/S	84
g x⇄y	35 07
R/S	84
LBL	23
D	14
RCL 6	34 06
1	01
8	08
0	00
x	71
g	35
π	02
÷	81
RCL 4	34 04
RCL 7	34 07
+	61
STO 7	33 07
÷	81
f^{-1}	32
TAN	06
STO 6	33 06

KEYS	CODE
R/S	84
LBL	23
E	15
RCL 6	34 06
1	01
f^{-1}	32
R→P	01
RCL 5	34 05
x	71
g x⇄y	35 07
RCL 5	34 05
x	71
g x⇄y	35 07
RCL 7	34 07
+	61
f	31
R→P	01
STO 7	33 07
R/S	84
RCL 6	34 06
f	31
SIN	04
RCL 5	34 05
x	71
RCL 7	34 07
÷	81
f^{-1}	32
SIN	04
R/S	84
g NOP	35 01

R_1	β	R_4	R_b	R_7	Used
R_2	θ	R_5	$R_g - R_r$	R_8	Inc
R_3	h	R_6	Used	R_9	Used

HARMONIC CAM DESIGN—FLAT FACED FOLLOWER

KEYS	CODE
RCL 2	34 02
RCL 8	34 08
+	61
STO 2	33 02
R/S	84
LBL	23
B	12
1	01
RCL 2	34 02
1	01
8	08
0	00
x	71
RCL 1	34 01
÷	81
STO 6	33 06
f	31
COS	05
—	51
RCL 3	34 03
x	71
2	02
÷	81
STO 7	33 07
R/S	84
LBL	23
C	13
RCL 6	34 06
1	01
f^{-1}	32
R→P	01
g	35
π	02
RCL 1	34 01
÷	81

KEYS	CODE
STO 6	33 06
RCL 3	34 03
x	71
2	02
÷	81
x	71
g x⇄y	35 07
g LST X	35 00
x	71
g x⇄y	35 07
RCL 6	34 06
x	71
g x⇄y	35 07
STO 6	33 06
R/S	84
g x⇄y	35 07
R/S	84
LBL	23
D	14
RCL 6	34 06
1	01
8	08
0	00
x	71
g	35
π	02
÷	81
RCL 4	34 04
RCL 7	34 07
+	61
÷	81
g LST X	35 00
RCL 6	34 06
f	31
R→P	01

KEYS	CODE
STO 7	33 07
g R↓	35 08
g R↓	35 08
f^{-1}	32
TAN	06
STO 6	33 06
R/S	84
LBL	23
E	15
RCL 6	34 06
RCL 5	34 05
f^{-1}	32
R→P	01
RCL 7	34 07
+	61
f	31
R→P	01
R/S	84
g LST X	35 00
g x⇄y	35 07
÷	81
f^{-1}	32
COS	05
RCL 6	34 06
—	51
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	β	R_4	R_b	R_7	Used
R_2	θ	R_5	R_g	R_8	Inc
R_3	h	R_6	Used	R_9	Used

ROLLER FOLLOWER CAM FUNCTION GENERATOR

KEYS	CODE
RCL 2	34 02
RCL 8	34 08
+	61
STO 2	33 02
R/S	84
LBL	23
B	12
RCL 2	34 02
RCL 1	34 01
÷	81
STO 6	33 06
D	14
RCL 3	34 03
x	71
STO 7	33 07
R/S	84
LBL	23
C	13
RCL 4	34 04
RCL 7	34 07
+	61
STO 7	33 07
RCL 6	34 06
E	15
RCL 1	34 01
÷	81
RCL 3	34 03
x	71
1	01
8	08
0	00
x	71
g	35
π	02
÷	81

KEYS	CODE
RCL 7	34 07
÷	81
f^{-1}	32
TAN	06
STO 6	33 06
RCL 5	34 05
f^{-1}	32
R→P	01
RCL 7	34 07
+	61
f	31
R→P	01
STO 7	33 07
R/S	84
RCL 6	34 06
f	31
SIN	04
RCL 5	34 05
x	71
RCL 7	34 07
÷	81
f^{-1}	32
SIN	04
R/S	84
LBL	23
D	14
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

KEYS	CODE
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	β	R_4	R_b	R_7	Used
R_2	θ	R_5	$R_g - R_r$	R_8	Inc
R_3	h	R_6	Used	R_9	Used

FLAT FACED FOLLOWER CAM FUNCTION GENERATOR

KEYS	CODE
RCL 2	34 02
RCL 8	34 08
+	61
STO 2	33 02
R/S	84
LBL	23
B	12
RCL 2	34 02
RCL 1	34 01
÷	81
STO 6	33 06
D	14
RCL 3	34 03
x	71
STO 7	33 07
R/S	84
LBL	23
C	13
RCL 4	34 04
RCL 7	34 07
+	61
STO 7	33 07
RCL 6	34 06
E	15
RCL 1	34 01
÷	81
RCL 3	34 03
x	71
1	01
8	08
0	00
x	71
g	35
π	02
÷	81

KEYS	CODE
STO 6	33 06
RCL 7	34 07
÷	81
f^{-1}	32
TAN	06
RCL 6	34 06
RCL 7	34 07
f	31
R→P	01
STO 7	33 07
g R↓	35 08
g R↓	35 08
STO 6	33 06
RCL 5	34 05
f^{-1}	32
R→P	01
RCL 7	34 07
+	61
f	31
R→P	01
STO 7	33 07
R/S	84
g LST X	35 00
RCL 7	34 07
÷	81
f^{-1}	32
COS	05
RCL 6	34 06
–	51
R/S	84
LBL	23
D	14
g NOP	35 01
g NOP	35 01
g NOP	35 01

KEYS	CODE
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	β	R_4	R_b	R_7	Used
R_2	θ	R_5	R_g	R_8	Inc
R_3	h	R_6	Used	R_9	Used

LINEAR CAM FUNCTION GENERATOR

KEYS	CODE
RCL 2	34 02
RCL 8	34 08
+	61
STO 2	33 02
RCL 1	34 01
÷	81
D	14
RCL 3	34 03
x	71
RCL 4	34 04
+	61
RCL 6	34 06
+	61
STO 7	33 07
RCL 2	34 02
R/S	84
RCL 7	34 07
R/S	84
LBL	23
B	12
RCL 2	34 02
RCL 1	34 01
÷	81
E	15
RCL 1	34 01
÷	81
RCL 3	34 03
x	71
f^{-1}	32
TAN	06
RCL 6	34 06
f^{-1}	32
R→P	01
RCL 7	34 07
g x⇄y	35 07

KEYS	CODE
−	51
g x⇄y	35 07
RCL 2	34 02
+	61
R/S	84
g x⇄y	35 07
R/S	84
LBL	23
C	13
RCL 2	34 02
RCL 1	34 01
÷	81
E	15
RCL 1	34 01
÷	81
RCL 3	34 03
x	71
f^{-1}	32
TAN	06
RCL 5	34 05
f^{-1}	32
R→P	01
RCL 7	34 07
+	61
g x⇄y	35 07
RCL 2	34 02
g x⇄y	35 07
−	51
R/S	84
g x⇄y	35 07
R/S	84
LBL	23
D	14
g NOP	35 01
g NOP	35 01

KEYS	CODE
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1 L	R_4 R_b	R_7 y
R_2 x	R_5 $R_g - R_r$	R_8 Inc
R_3 h	R_6 R_r	R_9 Used

SPUR GEAR REDUCTION DRIVE

KEYS	CODE
STO 1	33 01
R/S	84
RCL 2	34 02
RCL 3	34 03
x	71
RCL 4	34 04
÷	81
1	01
–	51
STO 1	33 01
R/S	84
LBL	23
B	12
2	02
x	71
STO 2	33 02
R/S	84
RCL 1	34 01
1	01
+	61
RCL 4	34 04
x	71
RCL 3	34 03
÷	81
STO 2	33 02
2	02
÷	81
R/S	84
LBL	23
C	13
STO 3	33 03
R/S	84
RCL 4	34 04
RCL 1	34 01
1	01

KEYS	CODE
+	61
x	71
RCL 2	34 02
÷	81
STO 3	33 03
R/S	84
LBL	23
D	14
STO 4	33 04
R/S	84
RCL 2	34 02
RCL 3	34 03
x	71
RCL 1	34 01
1	01
+	61
÷	81
•	83
5	05
+	61
f	31
INT	83
STO 4	33 04
CHS	42
RCL 2	34 02
RCL 3	34 03
x	71
+	61
•	83
5	05
+	61
f	31
INT	83
RCL 4	34 04
÷	81

KEYS	CODE
STO 1	33 01
RCL 4	34 04
R/S	84
LBL	23
E	15
RCL 4	34 04
RCL 3	34 03
÷	81
STO 5	33 05
R/S	84
RCL 4	34 04
RCL 1	34 01
x	71
STO 6	33 06
R/S	84
RCL 5	34 05
RCL 1	34 01
x	71
STO 7	33 07
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	f	R_4	N_p	R_7	D_g
R_2	2 C.D.	R_5	D_p	R_8	
R_3	P	R_6	N_g	R_9	

STANDARD EXTERNAL INVOLUTE SPUR GEARS 1

KEYS	CODE
STO 1	33 01
g $x \rightleftarrows y$	35 07
STO 2	33 02
÷	81
STO 5	33 05
R/S	84
g	35
π	02
2	02
÷	81
RCL 2	34 02
÷	81
STO 8	33 08
R/S	84
LBL	23
B	12
STO 3	33 03
g $x \rightleftarrows y$	35 07
STO 4	33 04
R/S	84
LBL	23
C	13
RCL 8	34 08
RCL 5	34 05
÷	81
RCL 4	34 04
f	31
TAN	06
+	61
RCL 4	34 04
g	35
π	02
x	71
1	01
8	08

KEYS	CODE
0	00
÷	81
–	51
RCL 3	34 03
RCL 5	34 05
÷	81
RCL 4	34 04
f	31
COS	05
÷	81
+	61
g	35
π	02
RCL 1	34 01
÷	81
–	51
STO 6	33 06
R/S	84
LBL	23
D	14
g	35
RAD	42
RCL 6	34 06
3	03
x	71
•	83
3	03
g	35
y^x	05
STO 7	33 07
LBL	23
1	01
RCL 6	34 06
RCL 7	34 07
+	61

KEYS	CODE
RCL 7	34 07
f	31
TAN	06
–	51
g LST X	35 00
↑	41
x	71
÷	81
STO	33
+	61
7	07
RCL 7	34 07
÷	81
g	35
ABS	06
EEX	43
CHS	42
6	06
g $x \leq y$	35 22
GTO	22
1	01
RCL 7	34 07
f	31
SIN	04
g	35
DEG	41
f^{-1}	32
SIN	04
STO 7	33 07
R/S	84

R_1	N	R_4	ϕ	R_7	ϕ_w
R_2	P	R_5	D	R_8	t
R_3	d_w	R_6	inv ϕ_w	R_9	Used

STANDARD EXTERNAL INVOLUTE SPUR GEARS 2

KEYS	CODE	KEYS	CODE	KEYS	CODE
RCL 5	34 05	GTO	22	+	61
2	02	2	02	R/S	84
÷	81	LBL	23	g NOP	35 01
RCL 4	34 04	1	01	g NOP	35 01
f	31	g R↓	35 08	g NOP	35 01
COS	05	g R↓	35 08	g NOP	35 01
x	71	+	61	g NOP	35 01
RCL 7	34 07	LBL	23	g NOP	35 01
f	31	2	02	g NOP	35 01
COS	05	STO 8	33 08	g NOP	35 01
÷	81	R/S	84	g NOP	35 01
STO 5	33 05	LBL	23	g NOP	35 01
2	02	B	12	g NOP	35 01
x	71	RCL 4	34 04	g NOP	35 01
RCL 3	34 03	f	31	g NOP	35 01
RCL 1	34 01	COS	05	g NOP	35 01
2	02	x	71	g NOP	35 01
÷	81	RCL 7	34 07	g NOP	35 01
f^{-1}	32	f	31	g NOP	35 01
INT	83	SIN	04	g NOP	35 01
0	00	÷	81	g NOP	35 01
g x=y	35 23	CHS	42	g NOP	35 01
GTO	22	RCL 8	34 08	g NOP	35 01
1	01	+	61	g NOP	35 01
g R↓	35 08	R/S	84	g NOP	35 01
g R↓	35 08	LBL	23	g NOP	35 01
g x⇄y	35 07	C	13	g NOP	35 01
9	09	RCL 5	34 05	g NOP	35 01
0	00	R/S	84	g NOP	35 01
RCL 1	34 01	LBL	23	g NOP	35 01
÷	81	D	14		
f	31	RCL 3	34 03		
COS	05	2	02		
x	71	÷	81		
+	61	RCL 5	34 05		

R_1 N	R_4 ϕ	R_7 ϕ_w
R_2 P	R_5 D, q	R_8 M
R_3 d_w	R_6 inv ϕ_w	R_9 Used

SPUR/HELICAL GEAR FORCES

KEYS	CODE
STO 2	33 02
g R↓	35 08
STO 1	33 01
g R↓	35 08
STO 3	33 03
RCL 2	34 02
R/S	84
LBL	23
B	12
STO 4	33 04
f	31
TAN	06
RCL 3	34 03
f	31
COS	05
x	71
f^{-1}	32
TAN	06
STO 5	33 05
RCL 4	34 04
R/S	84
LBL	23
C	13
STO 5	33 05
f	31
TAN	06
RCL 3	34 03
f	31
COS	05
÷	81
f^{-1}	32
TAN	06
STO 4	33 04
R/S	84
LBL	23

KEYS	CODE
D	14
RCL 1	34 01
RCL 2	34 02
÷	81
STO 6	33 06
R/S	84
RCL 4	34 04
f	31
TAN	06
RCL 6	34 06
x	71
STO 7	33 07
R/S	84
LBL	23
E	15
RCL 6	34 06
RCL 3	34 03
f	31
TAN	06
x	71
STO 8	33 08
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

KEYS	CODE
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	T	R_4	ϕ	R_7	F_r
R_2	r	R_5	ϕ_n	R_8	F_a
R_3	α	R_6	F_t	R_9	Used

BEVEL GEAR FORCES

KEYS	CODE	KEYS	CODE	KEYS	CODE
÷	81	TAN	06	x	71
STO 1	33 01	x	71	R/S	84
R/S	84	STO 6	33 06	g NOP	35 01
LBL	23	g x⇄y	35 07	g NOP	35 01
B	12	g LST X	35 00	g NOP	35 01
STO 2	33 02	x	71	g NOP	35 01
R/S	84	STO 8	33 08	g NOP	35 01
LBL	23	RCL 4	34 04	g NOP	35 01
C	13	R/S	84	g NOP	35 01
STO 4	33 04	LBL	23	g NOP	35 01
g x⇄y	35 07	D	14	g NOP	35 01
STO 3	33 03	RCL 5	34 05	g NOP	35 01
g x⇄y	35 07	RCL 6	34 06	g NOP	35 01
1	01	–	51	g NOP	35 01
f^{-1}	32	RCL 1	34 01	g NOP	35 01
R→P	01	x	71	g NOP	35 01
RCL 2	34 02	R/S	84	g NOP	35 01
f	31	RCL 7	34 07	g NOP	35 01
TAN	06	RCL 8	34 08	g NOP	35 01
RCL 3	34 03	+	61	g NOP	35 01
f	31	RCL 1	34 01	g NOP	35 01
COS	05	x	71	g NOP	35 01
÷	81	R/S	84	g NOP	35 01
x	71	LBL	23	g NOP	35 01
STO 7	33 07	E	15	g NOP	35 01
g x⇄y	35 07	RCL 5	34 05	g NOP	35 01
g LST X	35 00	RCL 6	34 06	g NOP	35 01
x	71	+	61	g NOP	35 01
STO 5	33 05	RCL 1	34 01	g NOP	35 01
RCL 4	34 04	x	71	g NOP	35 01
1	01	R/S	84		
f^{-1}	32	RCL 7	34 07		
R→P	01	RCL 8	34 08		
RCL 3	34 03	–	51		
f	31	RCL 1	34 01		

R_1	F_t	R_4	β	R_7	Used
R_2	ϕ_n	R_5	Used	R_8	Used
R_3	α	R_6	Used	R_9	Used

WORM GEAR FORCES

KEYS	CODE
÷	81
STO 1	33 01
g LST X	35 00
STO 7	33 07
R/S	84
LBL	23
B	12
STO 2	33 02
g R↓	35 08
STO 3	33 03
R/S	84
LBL	23
C	13
RCL 7	34 07
2	02
x	71
÷	81
g	35
π	02
÷	81
STO 5	33 05
f^{-1}	32
TAN	06
STO 4	33 04
R/S	84
LBL	23
D	14
RCL 1	34 01
R/S	84
1	01
RCL 3	34 03
RCL 5	34 05
x	71
RCL 2	34 02
f	31

KEYS	CODE
COS	05
STO 6	33 06
÷	81
–	51
RCL 3	34 03
RCL 6	34 06
÷	81
RCL 5	34 05
+	61
÷	81
RCL 1	34 01
x	71
STO 5	33 05
R/S	84
LBL	23
E	15
RCL 2	34 02
f	31
SIN	04
RCL 4	34 04
f	31
SIN	04
RCL 2	34 02
f	31
COS	05
x	71
RCL 4	34 04
f	31
COS	05
RCL 3	34 03
x	71
+	61
÷	81
RCL 1	34 01
x	71

KEYS	CODE
STO 6	33 06
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	F_{wt}	R_4	λ	R_7	r_w
R_2	ϕ_n	R_5	Used, F_{gt}	R_8	
R_3	f	R_6	Used, F_r	R_9	Used

SPRING CONSTANT

KEYS	CODE
STO 1	33 01
R/S	84
RCL 3	34 03
RCL 4	34 04
RCL 2	34 02
–	51
RCL 5	34 05
÷	81
+	61
STO 1	33 01
R/S	84
LBL	23
B	12
STO 2	33 02
R/S	84
RCL 4	34 04
RCL 5	34 05
RCL 3	34 03
RCL 1	34 01
–	51
x	71
+	61
STO 2	33 02
R/S	84
LBL	23
C	13
STO 3	33 03
R/S	84
RCL 1	34 01
RCL 2	34 02
RCL 4	34 04
–	51
RCL 5	34 05
÷	81
+	61

KEYS	CODE
STO 3	33 03
R/S	84
LBL	23
D	14
STO 4	33 04
R/S	84
RCL 2	34 02
RCL 5	34 05
RCL 1	34 01
RCL 3	34 03
–	51
x	71
+	61
STO 4	33 04
R/S	84
LBL	23
E	15
STO 5	33 05
R/S	84
RCL 2	34 02
RCL 4	34 04
–	51
RCL 3	34 03
RCL 1	34 01
–	51
÷	81
STO 5	33 05
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

KEYS	CODE
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	X_1	R_4	F_2	R_7	
R_2	F_1	R_5	k	R_8	
R_3	X_2	R_6		R_9	

HELICAL SPRING DESIGN

KEYS	CODE
STO 2	33 02
g x⇄y	35 07
STO 1	33 01
1	01
1	01
5	05
EEX	43
5	05
STO 3	33 03
B	12
RCL 3	34 03
R/S	84
LBL	23
B	12
RCL 2	34 02
RCL 1	34 01
÷	81
STO 4	33 04
•	83
2	02
5	05
–	51
RCL 4	34 04
1	01
–	51
÷	81
•	83
6	06
1	01
5	05
RCL 4	34 04
÷	81
+	61
RTN	24
LBL	23

KEYS	CODE
C	13
STO 5	33 05
RCL 3	34 03
x	71
RCL 4	34 04
÷	81
RCL 2	34 02
÷	81
g	35
π	02
÷	81
R/S	84
LBL	23
D	14
STO 6	33 06
g	35
π	02
x	71
RCL 4	34 04
÷	81
RCL 1	34 01
↑	41
x	71
x	71
8	08
÷	81
R/S	84
LBL	23
E	15
STO 7	33 07
8	08
x	71
RCL 4	34 04
3	03
g	35

KEYS	CODE
y^x	05
x	71
RCL 1	34 01
÷	81
RCL 3	34 03
÷	81
R/S	84
STO 8	33 08
RCL 7	34 07
x	71
2	02
÷	81
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1 d	R_4 C	R_7 P
R_2 D	R_5 f	R_8
R_3 G	R_6 s	R_9

TORSION SPRING DESIGN

KEYS	CODE
g R↓	35 08
g x⇄y	35 07
STO 5	33 05
x	71
STO 3	33 03
g R↓	35 08
STO 1	33 01
3	03
g	35
y^x	05
STO 4	33 04
g R↓	35 08
3	03
2	02
x	71
g	35
π	02
÷	81
STO 2	33 02
RCL 5	34 05
RCL 1	34 01
÷	81
STO 5	33 05
•	83
2	02
5	05
–	51
RCL 5	34 05
1	01
–	51
÷	81
•	83
6	06
1	01
5	05

KEYS	CODE
RCL 5	34 05
÷	81
+	61
STO 6	33 06
GTO	22
1	01
LBL	23
B	12
g R↑	35 09
÷	81
6	06
x	71
STO 2	33 02
g R↓	35 08
g	35
π	02
÷	81
STO 3	33 03
g R↓	35 08
STO 1	33 01
↑	41
x	71
STO 4	33 04
LBL	23
1	01
3	03
EEX	43
7	07
STO 7	33 07
R/S	84
LBL	23
C	13
RCL 1	34 01
x	71
RCL 3	34 03

KEYS	CODE
÷	81
RCL 7	34 07
x	71
R/S	84
LBL	23
D	14
RCL 2	34 02
÷	81
RCL 4	34 04
x	71
R/S	84
LBL	23
E	15
RCL 4	34 04
÷	81
RCL 1	34 01
÷	81
RCL 3	34 03
x	71
RCL 7	34 07
÷	81
RCL 2	34 02
x	71
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	d, h	R_4	d^3, h^2	R_7	E
R_2	32R/π, 6R/b	R_5	D, C	R_8	
R_3	DN, L/π	R_6	K	R_9	

FLAT SPRING DESIGN

KEYS	CODE
1	01
•	83
0	00
9	09
÷	81
STO 4	33 04
R/S	84
LBL	23
D	14
RCL 1	34 01
RCL 7	34 07
x	71
RCL 4	34 04
x	71
RCL 3	34 03
↑	41
x	71
÷	81
RCL 6	34 06
x	71
RTN	24
LBL	23
C	13
D	14
RCL 2	34 02
x	71
RCL 1	34 01
↑	41
x	71
x	71
6	06
÷	81
RCL 3	34 03
÷	81
8	08

KEYS	CODE
RCL 8	34 08
–	51
5	05
RCL 8	34 08
–	51
x	71
4	04
RCL 8	34 08
–	51
x	71
0	00
g x≠y	35 21
g R↑	35 09
R/S	84
g R↑	35 09
4	04
x	71
R/S	84
LBL	23
B	12
STO 6	33 06
R/S	84
LBL	23
A	11
STO 8	33 08
1	01
•	83
2	02
5	05
STO 5	33 05
g x⇄y	35 07
6	06
g x≤y	35 22
GTO	22
2	02

KEYS	CODE
g x⇄y	35 07
1	01
g x⇄y	35 07
g x=y	35 23
STO 4	33 04
R/S	84
4	04
–	51
2	02
g x⇄y	35 07
g	35
y^x	05
3	03
x	71
STO 4	33 04
R/S	84
LBL	23
2	02
g x⇄y	35 07
g x=y	35 23
1	01
GTO	22
7	07
g x⇄y	35 07
g x=y	35 23
RCL 5	34 05
GTO	22
5	05
g NOP	35 01
g NOP	35 01

R_1	h	R_4	C	R_7	E
R_2	b	R_5	1.25	R_8	Code
R_3	L	R_6	f	R_9	Used

CONE AND PLATE CLUTCHES

KEYS	CODE
STO 2	33 02
R/S	84
LBL	23
A	11
STO 1	33 01
1	01
STO 7	33 07
g x⇄y	35 07
R/S	84
LBL	23
A	11
6	06
3	03
0	00
2	02
5	05
•	83
3	03
6	06
÷	81
STO 7	33 07
R/S	84
LBL	23
C	13
STO 3	33 03
g x⇄y	35 07
STO 4	33 04
R/S	84
LBL	23
E	15
f	31
SIN	04
g	35
$^1/x$	04
LBL	23

KEYS	CODE
D	14
STO 5	33 05
RCL 3	34 03
RCL 4	34 04
+	61
2	02
÷	81
STO 6	33 06
LBL	23
1	01
RCL 5	34 05
x	71
RCL 1	34 01
x	71
RCL 2	34 02
x	71
RCL 7	34 07
g x⇄y	35 07
x	71
g LST X	35 00
R/S	84
RCL 4	34 04
↑	41
x	71
RCL 3	34 03
RCL 4	34 04
x	71
+	61
RCL 3	34 03
↑	41
x	71
+	61
RCL 6	34 06
÷	81
3	03

KEYS	CODE
÷	81
GTO	22
1	01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1 F	R_4 R_o	R_7 N/63025.36
R_2 f	R_5 n, csc α	R_8
R_3 R_i	R_6 $(R_i + R_o)/2$	R_9 Used

POWER SCREWS

KEYS	CODE
x	71
STO 3	33 03
R/S	84
LBL	23
B	12
STO 2	33 02
g R↓	35 08
STO 1	33 01
R/S	84
LBL	23
C	13
STO 5	33 05
f	31
COS	05
g x⇄y	35 07
f	31
TAN	06
x	71
f^{-1}	32
TAN	06
f	31
COS	05
STO 4	33 04
EEX	43
2	02
RCL 5	34 05
g	35
ABS	06
f	31
TAN	06
STO 6	33 06
x	71
E	15
RCL 1	34 01
x	71

KEYS	CODE
STO 7	33 07
RCL 1	34 01
RCL 6	34 06
x	71
RCL 3	34 03
–	51
RCL 4	34 04
x	71
RCL 6	34 06
RCL 3	34 03
x	71
RCL 1	34 01
+	61
÷	81
RCL 1	34 01
RCL 8	34 08
x	71
RCL 3	34 03
+	61
RCL 3	34 03
RCL 8	34 08
x	71
RCL 1	34 01
g x⇄y	35 07
–	51
÷	81
f^{-1}	32
TAN	06
RCL 7	34 07
RCL 5	34 05
f	31
TAN	06
STO 6	33 06
g R↓	35 08
R/S	84

KEYS	CODE
LBL	23
E	15
D	14
g LST X	35 00
↑	41
x	71
x	71
RTN	24
LBL	23
D	14
RCL 6	34 06
RCL 2	34 02
RCL 4	34 04
÷	81
STO 8	33 08
+	61
g LST X	35 00
RCL 6	34 06
x	71
1	01
g x⇄y	35 07
–	51
÷	81
RCL 1	34 01
x	71
RCL 3	34 03
+	61
÷	81
RTN	24
g NOP	35 01

R_1	r_t	R_4	g	R_7	e
R_2	f_t	R_5	α	R_8	f_t/g
R_3	$f_c r_c$	R_6	tan α	R_9	Used

RPM/TORQUE/POWER

KEYS	CODE
A	11
g	35
$^{1}/x$	04
STO 6	33 06
g x⇄y	35 07
g	35
$^{1}/x$	04
STO 5	33 05
÷	81
x	71
STO 1	33 01
R/S	84
LBL	23
A	11
3	03
0	00
g	35
π	02
÷	81
STO 1	33 01
7	07
4	04
5	05
•	83
7	07
STO 5	33 05
1	01
•	83
3	03
5	05
6	06
STO 6	33 06
RTN	24
LBL	23
C	13

KEYS	CODE
STO 2	33 02
R/S	84
RCL 4	34 04
RCL 3	34 03
÷	81
RCL 1	34 01
x	71
STO 2	33 02
R/S	84
RCL 2	34 02
R/S	84
LBL	23
D	14
STO 3	33 03
R/S	84
RCL 4	34 04
RCL 2	34 02
÷	81
RCL 1	34 01
x	71
STO 3	33 03
R/S	84
RCL 3	34 03
RCL 6	34 06
÷	81
R/S	84
LBL	23
E	15
STO 4	33 04
R/S	84
RCL 2	34 02
RCL 3	34 03
x	71
RCL 1	34 01
÷	81

KEYS	CODE
STO 4	33 04
R/S	84
RCL 4	34 04
RCL 5	34 05
÷	81
R/S	84
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01
g NOP	35 01

R_1	Used	R_4	Power	R_7	
R_2	RPM	R_5	Used	R_8	
R_3	Torque	R_6	Used	R_9	

LINE-LINE INTERSECTION/ GRID POINTS

KEYS	CODE
f	31
TAN	06
STO 3	33 03
g R↓	35 08
STO 2	33 02
g R↓	35 08
STO 1	33 01
–	51
x	71
+	61
R/S	84
LBL	23
B	12
f	31
TAN	06
STO 4	33 04
g x⇄y	35 07
g R↓	35 08
x	71
g R↑	35 09
–	51
RCL 2	34 02
+	61
RCL 1	34 01
RCL 3	34 03
x	71
–	51
RCL 4	34 04
RCL 3	34 03
–	51
÷	81
STO 4	33 04
R/S	84
RCL 4	34 04
RCL 1	34 01

KEYS	CODE
–	51
RCL 3	34 03
x	71
RCL 2	34 02
+	61
R/S	84
LBL	23
C	13
STO 8	33 08
g R↓	35 08
STO 7	33 07
g R↓	35 08
STO 4	33 04
g R↓	35 08
STO 1	33 01
R/S	84
LBL	23
D	14
1	01
f^{-1}	32
R→P	01
RCL 8	34 08
x	71
STO 3	33 03
g R↓	35 08
RCL 8	34 08
x	71
STO 6	33 06
g R↓	35 08
1	01
f^{-1}	32
R→P	01
RCL 7	34 07
x	71
STO 2	33 02

KEYS	CODE
g R↓	35 08
RCL 7	34 07
x	71
STO 5	33 05
R/S	84
LBL	23
E	15
STO 8	33 08
RCL 2	34 02
x	71
RCL 1	34 01
+	61
g x⇄y	35 07
STO 7	33 07
RCL 3	34 03
x	71
+	61
R/S	84
RCL 8	34 08
RCL 5	34 05
x	71
RCL 4	34 04
+	61
RCL 7	34 07
RCL 6	34 06
x	71
+	61
R/S	84
g NOP	35 01
g NOP	35 01

R_1	x_1, x_0	R_4	$\tan\theta_2$, y_0	R_7	h_1
R_2	y_1, Δx_1	R_5	Δy_1	R_8	h_2
R_3	$\tan\theta_1$, Δx_2	R_6	Δy_2	R_9	Used

CIRCLE-LINE INTERSECTION

KEYS	CODE
g x⇄y	35 07
g R↑	35 09
STO 1	33 01
–	51
g R↓	35 08
g x⇄y	35 07
STO 2	33 02
–	51
g R↑	35 09
0	00
g x=y	35 23
GTO	22
2	02
g R↓	35 08
÷	81
f^{-1}	32
TAN	06
STO 3	33 03
R/S	84
LBL	23
2	02
9	09
0	00
STO 3	33 03
R/S	84
LBL	23
B	12
STO 3	33 03
g R↓	35 08
STO 2	33 02
g R↓	35 08
STO 1	33 01
R/S	84
LBL	23
C	13

KEYS	CODE
STO 6	33 06
g R↓	35 08
RCL 2	34 02
–	51
g x⇄y	35 07
RCL 1	34 01
–	51
f	31
R→P	01
STO 5	33 05
g x⇄y	35 07
STO 4	33 04
R/S	84
LBL	23
D	14
RCL 3	34 03
RCL 4	34 04
–	51
f	31
COS	05
RCL 5	34 05
x	71
STO 8	33 08
↑	41
↑	41
x	71
RCL 5	34 05
↑	41
x	71
–	51
RCL 6	34 06
↑	41
x	71
+	61
f	31

KEYS	CODE
√x	09
STO	33
–	51
8	08
+	61
STO 7	33 07
LBL	23
1	01
RCL 3	34 03
f	31
COS	05
x	71
RCL 1	34 01
+	61
RTN	24
RCL 7	34 07
RCL 3	34 03
f	31
SIN	04
x	71
RCL 2	34 02
+	61
R/S	84
LBL	23
E	15
D	14
RCL 8	34 08
STO 7	33 07
GTO	22
1	01

R_1	x_1	R_4	α	R_7	P_1
R_2	y_1	R_5	C	R_8	P_2
R_3	θ	R_6	R	R_9	Used

CIRCLE-CIRCLE INTERSECTION

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 3	33 03	RCL 7	34 07	RCL 2	34 02
g R↓	35 08	2	02	+	61
STO 2	33 02	x	71	R/S	84
g R↓	35 08	RCL 3	34 03	g NOP	35 01
STO 1	33 01	x	71	g NOP	35 01
R/S	84	÷	81	g NOP	35 01
LBL	23	f^{-1}	32	g NOP	35 01
B	12	COS	05	g NOP	35 01
STO 6	33 06	STO	33	g NOP	35 01
g R↓	35 08	–	51	g NOP	35 01
STO 5	33 05	8	08	g NOP	35 01
g R↓	35 08	+	61	g NOP	35 01
STO 4	33 04	STO 7	33 07	g NOP	35 01
RCL 5	34 05	R/S	84	g NOP	35 01
RCL 2	34 02	LBL	23	g NOP	35 01
–	51	C	13	g NOP	35 01
RCL 4	34 04	RCL 7	34 07	g NOP	35 01
RCL 1	34 01	GTO	22	g NOP	35 01
–	51	1	01	g NOP	35 01
f	31	LBL	23	g NOP	35 01
R→P	01	D	14	g NOP	35 01
STO 7	33 07	RCL 8	34 08	g NOP	35 01
g x⇄y	35 07	LBL	23	g NOP	35 01
STO 8	33 08	1	01	g NOP	35 01
g x⇄y	35 07	1	01	g NOP	35 01
↑	41	f^{-1}	32	g NOP	35 01
x	71	R→P	01	g NOP	35 01
RCL 3	34 03	RCL 3	34 03	g NOP	35 01
↑	41	x	71	g NOP	35 01
x	71	RCL 1	34 01	g NOP	35 01
+	61	+	61		
RCL 6	34 06	R/S	84		
↑	41	g x⇄y	35 07		
x	71	RCL 3	34 03		
–	51	x	71		

R_1	x_1	R_4	x_2	R_7	$\theta + \alpha$
R_2	y_1	R_5	y_2	R_8	$\theta - \alpha$
R_3	R_1	R_6	R_2	R_9	Used

POINTS ON A CIRCLE

KEYS	CODE	KEYS	CODE	KEYS	CODE
STO 3	33 03	RCL 5	34 05	g NOP	35 01
g R↓	35 08	+	61	g NOP	35 01
STO 2	33 02	STO 6	33 06	g NOP	35 01
g R↓	35 08	f	31	g NOP	35 01
STO 1	33 01	COS	05	g NOP	35 01
0	00	RCL 3	34 03	g NOP	35 01
STO 8	33 08	x	71	g NOP	35 01
R/S	84	RCL 1	34 01	g NOP	35 01
LBL	23	+	61	g NOP	35 01
C	13	R/S	84	g NOP	35 01
3	03	RCL 6	34 06	g NOP	35 01
6	06	f	31	g NOP	35 01
0	00	SIN	04	g NOP	35 01
g x⇄y	35 07	RCL 3	34 03	g NOP	35 01
÷	81	x	71	g NOP	35 01
LBL	23	RCL 2	34 02	g NOP	35 01
B	12	+	61	g NOP	35 01
STO 4	33 04	R/S	84	g NOP	35 01
g x⇄y	35 07	RCL 7	34 07	g NOP	35 01
STO 5	33 05	R/S	84	g NOP	35 01
R/S	84	RCL 6	34 06	g NOP	35 01
LBL	23	R/S	84	g NOP	35 01
D	14	g NOP	35 01	g NOP	35 01
g	35	g NOP	35 01	g NOP	35 01
DSZ	83	g NOP	35 01	g NOP	35 01
RCL 8	34 08	g NOP	35 01	g NOP	35 01
g	35	g NOP	35 01	g NOP	35 01
ABS	06	g NOP	35 01	g NOP	35 01
LBL	23	g NOP	35 01	g NOP	35 01
E	15	g NOP	35 01	g NOP	35 01
STO 7	33 07	g NOP	35 01		
1	01	g NOP	35 01		
−	51	g NOP	35 01		
RCL 4	34 04	g NOP	35 01		
x	71	g NOP	35 01		

R_1	x_c	R_4	$\Delta\theta$	R_7	i (j)
R_2	y_c	R_5	θ_o	R_8	–i
R_3	R	R_6	θ_i	R_9	Used

BELT LENGTH

KEYS	CODE
f	31
REG	43
STO 1	33 01
f	31
SF1	51
R/S	84
LBL	23
B	12
STO 4	33 04
CLX	44
RCL 3	34 03
g x⇄y	35 07
STO 3	33 03
g x⇄y	35 07
–	51
g x⇄y	35 07
RCL 2	34 02
g x⇄y	35 07
STO 2	33 02
g x⇄y	35 07
–	51
f	31
R→P	01
↑	41
x	71
g x⇄y	35 07
↑	41
CLX	44
g x>y	35 24
3	03
6	06
0	00
f^{-1}	32
→D.MS	03
+	61

KEYS	CODE
f	31
TF1	61
STO 5	33 05
STO 6	33 06
RCL 6	34 06
g x⇄y	35 07
STO 6	33 06
E	15
g x⇄y	35 07
RCL 1	34 01
RCL 4	34 04
–	51
↑	41
x	71
–	51
f	31
$\sqrt{x}$	09
STO	33
+	61
8	08
RCL 1	34 01
RCL 4	34 04
–	51
g x⇄y	35 07
÷	81
f^{-1}	32
TAN	06
STO 7	33 07
+	61
RCL 1	34 01
x	71
STO	33
+	61
8	08
RCL 4	34 04

KEYS	CODE
STO 1	33 01
f^{-1}	32
SF1	51
R/S	84
LBL	23
E	15
–	51
1	01
f^{-1}	32
R→P	01
f	31
R→P	01
x	71
g	35
ABS	06
RCL 7	34 07
–	51
RTN	24
LBL	23
C	13
RCL 6	34 06
RCL 5	34 05
E	15
RCL 1	34 01
x	71
STO	33
+	61
8	08
RCL 8	34 08
R/S	84

R_1	R_{i-1}	R_4	R_i	R_7	α
R_2	x_i	R_5	θ_o	R_8	Σ Length
R_3	y_i	R_6	θ_i	R_9	Used

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