HEWLETT-PACKARD

HP-67/HP-97

Users' Library Solutions

Control Systems

INTRODUCTION

In an effort to provide continued value to it's customers, Hewlett-Packard is introducing a unique service for the HP fully programmable calculator user. This service is designed to save you time and programming effort. As users are aware, Programmable Calculators are capable of delivering tremendous problem solving potential in terms of power and flexibility, but the real genie in the bottle is program solutions. HP's introduction of the first handheld programmable calculator in 1974 immediately led to a request for program **solutions** — hence the beginning of the HP-65 Users' Library. In order to save HP calculator customers time, users wrote their own programs and sent them to the Library for the benefit of other program users. In a short period of time over 5,000 programs were accepted and made available. This overwhelming response indicated the value of the program library and a Users' Library was then established for the HP-67/97 users.

To extend the value of the Users' Library, Hewlett-Packard is introducing a unique service—a service designed to save you time and money. The Users' Library has collected the best programs in the most popular categories from the HP-67/97 and HP-65 Libraries. These programs have been packaged into a series of low-cost books, resulting in substantial savings for our valued HP-67/97 users.

We feel this new software service will extend the capabilities of our programmable calculators and provide a great benefit to our HP-67/97 users.

A WORD ABOUT PROGRAM USAGE

Each program contained herein is reproduced on the standard forms used by the Users' Library. Magnetic cards are not included. The Program Description I page gives a basic description of the program. The Program Description II page provides a sample problem and the keystrokes used to solve it. The User Instructions page contains a description of the keystrokes used to solve problems in general and the options which are available to the user. The Program Listing I and Program Listing II pages list the program steps necessary to operate the calculator. The comments, listed next to the steps, describe the reason for a step or group of steps. Other pertinent information about data register contents, uses of labels and flags and the initial calculator status mode is also found on these pages. Following the directions in your HP-67 or HP-97 **Owners' Handbook and Programming Guide,** "Loading a Program" (page 134, HP-67; page 119, HP-97), key in the program from the Program Listing I and Program Listing II pages. A number at the top of the Program Listing indicates on which calculator the program was written (HP-67 or HP-97). If the calculator indicated differs from the calculator you will be using, consult Appendix E of your **Owner's Handbook** for the corresponding keycodes and keystrokes converting HP-67 to HP-97 keycodes and vice versa. No program conversion is necessary. The HP-67 and HP-97 are totally compatible, but some differences do occur in the keycodes used to represent some of the functions.

A program loaded into the HP-67 or HP-97 is not permanent—once the calculator is turned off, the program will not be retained. You can, however, permanently save any program by recording it on a blank magnetic card, several of which were provided in the Standard Pac that was shipped with your calculator. Consult your **Owner's Handbook** for full instructions. A few points to remember:

> The Set Status section indicates the status of flags, angular mode, and display setting. After keying in your program, review the status section and set the conditions as indicated before using or permanently recording the program.
>
> REMEMBER! To save the program permanently, **clip** the corners of the magnetic card once you have recorded the program. This simple step will protect the magnetic card and keep the program from being inadvertently erased.

As a part of HP's continuing effort to provide value to our customers, we hope you will enjoy our newest concept.

TABLE OF CONTENTS

Program Description I

Program Title Frequency Response of a Transfer Function

Contributor's Name Hewlett-Packard

Address 1000 N.E. Circle Blvd.

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables For transfer function of the form:

$$G(S) = \frac{K_1(\tau_2 S+1)}{S^{N_3}(\tau_4 S+1)(\tau_5 S+1)\left(\frac{S^2}{\omega_7^2} + \frac{2\zeta_6 S}{\omega_7} + 1\right)}$$

The program computes $\angle G(j\omega)$, $|G(j\omega|$ and log $|G(j\omega)|$ for any input frequency ω.

$\angle G(j\omega)$ is displayed upon completion of the calculation.

$|G(j\omega)|$ is stored in the stack (z and T) and in Register 8

Log$|G(j\omega)|$ is stored in the stack (y) and in register 9

Parameters $K_1, \tau_2, N_3, \tau_4, \tau_5, \zeta_6$ and ω_7 are stored in registers 1,2,3,4,5,6 and 7 respectively.

Operating Limits and Warnings

For type 0 systems enter N_3=0

τ_2, τ_4 and/or τ_5 can be entered as 0. If there is no quadratic term enter ζ_6 as 0 and ω_7 very large compared to $\frac{1}{\tau_5}$. Where τ_5 is the smallest (other than zero) first order term used.

Program Description II

Sketch(es)

Sample Problem(s) Find $\angle G(j\omega)$, $|G(j\omega)|$ and $\log|G(j\omega)|$ for

$$G(s) = \frac{12\ (s+.6)}{s(s+1)(s^2+6s+36)} = \frac{.2(1.67s+1)}{s(s+1)(\frac{s^2}{36}+\frac{2x.5}{6}s+1)}$$

For input frequencies of ω=.01,.1,1.0 and 10 rad/sec.

K_1 = .2
τ_2 = 1.67
N_3 = 1
τ_4 = 1
τ_5 = 0
ζ_6 = .5
ω_7 = 6

Solution(s)

ω(rad/sec)	$\angle G(j\omega)$degrees	$\lvert G(j\omega)\rvert$	Log$\lvert G(j\omega)\rvert$
.01	-89.71	20.00	1.30 (26.02dB)
.1	-87.18	2.02	.30 (6.10dB)
1.0	-85.64	.28	-.55 (-11.09dB)
10.0	-224.56	.01	-1.86 (-37.29dB)

Reference(s) Automatic Control Engineering, F.H. Raven, McGraw-Hill, N.Y., 1968
This program is a translation of the HP-65 Users' Library program #00834A submitted by Eugene Bahniuk.

User Instructions

FREQUENCY RESPONSE

Param. ω

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1.	Enter program				
2.	Initialize		A		1.00
3.	Enter the gain	k_1	R/S		2.00 7.00
	Enter Γ_2 when 2.00 is displayed	Γ_2, N_3	R/S		2.00→7.00
	Repeat parameter entries in order N_3, Γ_4, Γ_5	$\Gamma_4, \Gamma_5, \zeta_6$			
	ζ_6 and ω_7	ω_7			
4.	When 8.00 is displayed enter the frequency	ω			8.00
	(rad/sec)				
5.	Upon completion of the calculations $\angle G(j\omega)$				$\angle G(j\omega)$
	will be display				
6.	Amplitude ratio $\lvert G(j\omega)\rvert$ is stored in the				
	stack (z and T) and in register 8				
	To find $\lvert G(j\omega)\rvert$ REC 8		RCL	8	$\lvert G(j\omega)\rvert$
7.	Log $\lvert G(j\omega)\rvert$ is in stack y and in register 9		RCL	9	Log $\lvert G(j\omega)\rvert$
	To calculate decibels - REC 9, enter 20 and				
	multiply				
8.	For another frequency go to Step 4				
9.	To change transfer function parameters enter	K_1, Γ_2, N_3	A		1.00 thru
	all parameters or if only one parameter is to	$\Gamma_4 \Gamma_5 \zeta_6 \omega_7$	R/S		7.00
	be changed enter the changed parameter(s) in				
	the proper register(s) For Γ_4 in register 4				
	and so on.				
10.	For frequency response of the new transfer	ω	R/S		8.00
	function enter ω when 8.00 is displayed (if				
	only one parameter was changed first enter B)				

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	
002	1	01	
003	STOI	35 46	
004	*LBL9	21 09	Start of parameter entry display 1.00 and stop for entry of K_1 Store K_1
005	RCLI	36 46	
006	R/S	51	
007	STOi	35 45	
008	ISZI	16 26 46	
009	RCLI	36 46	Disply 2.00 and stop for entry of τ_2 etc.
010	9	09	
011	X>Y?	16-34	
012	GTO9	22 09	
013	RCL8	36 08	Compute $\angle G(j\omega)$, $\angle G(j\omega)$ and $\log\|G(j\omega)\|$
014	*LBLE	21 12	
015	STO8	35 08	
016	RCL6	36 06	
017	RCL7	36 07	
018	÷	-24	
019	2	02	This is $2\zeta_6\omega/\omega_7$
020	x	-35	
021	RCL8	36 08	
022	x	-35	
023	1	01	
024	RCL8	36 08	
025	RCL7	36 07	
026	÷	-24	
027	ENT↑	-21	Results in $1-\omega^2/\omega_7$
028	x	-35	
029	-	-45	
030	→P	34	
031	X⇄Y	-41	
032	RCL5	36 05	
033	RCL8	36 08	
034	x	-35	
035	1	01	
036	→P	34	
037	R↓	-31	
038	+	-55	
039	R↓	-31	
040	x	-35	
041	R↑	16-31	
042	RCL4	36 04	
043	RCL8	36 08	
044	x	-35	
045	1	01	
046	→P	34	
047	R↑	16-31	
048	x	-35	
049	R↓	-31	
050	+	-55	
051	R↑	16-31	
052	RCL8	36 08	
053	RCL3	36 03	
054	Y^x	31	
055	x	-35	
056	X⇄Y	-41	
057	RCL3	36 03	
058	9	09	
059	0	00	
060	x	-35	
061	+	-55	
062	CHS	-22	
063	RCL2	36 02	
064	RCL8	36 08	
065	x	-35	
066	RCL1	36 01	
067	x	-35	
068	RCL1	36 01	
069	→P	34	
070	R↑	16-31	Replaces ω with $\|G(j\omega)\|$
071	÷	-24	
072	STO8	35 08	
073	ENT↑	-21	Stores $\log\|G(j\omega)\|$
074	LOG	16 32	
075	STO9	35 09	
076	R↑	16-31	Computes $\angle G(j\omega)$
077	R↑	16-31	
078	+	-55	
079	RTN	24	
080	R/S	51	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	2

REGISTERS

0	1	2	3	4	5	6	7	8	9
	k_1	τ_2	N_3	τ_4	τ_5	ζ_6	ω_7	ω $\|G(j\omega)\|$	Log $\|G(j\omega)\|$
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Program Description I

Program Title BODE OF TRANSFER FUNCTION THAT HAS EACH POLE AND ZERO GIVEN

Contributor's Name Hewlett-Packard Company

Address 1000 N.E. Circle Boulevard

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables

Given a laplace transfer function:

$$F(s) = K\frac{(s+z_1+_jz_1')(s+z_2+_jz_2')\cdots(s+z_N+_jz_N')}{(s+p_1+_jp_1')(s+p_2+_jp_2')\cdots(s+z_M+_jz_M')}$$

$F(jw)$ = Magnitude $\angle\Theta$

where magnitue $= |K|\dfrac{\sqrt{(z_1'+\omega)^2+z_1^2}\ \sqrt{(z_2'+\omega)^2+z_2^2}\cdots\sqrt{(z_N'+\omega)^2+z_N^2}}{\sqrt{(p_1'+\omega)^2+p_1^2}\ \sqrt{(p_2'+\omega)^2+p_2^2}\cdots\sqrt{(p_M'+\omega)^2+p_M^2}}$

and $\Theta = \mathrm{Tan}^{-1}\dfrac{z_1'+\omega}{z_1} + \mathrm{Tan}^{-1}\dfrac{z_2'+\omega}{z_2} + \cdots + \mathrm{Tan}^{-1}\dfrac{z_N'+\omega}{z_N}$

$-\mathrm{Tan}^{-1}\dfrac{p_1'+\omega}{p_1} + \mathrm{Tan}^{-1}\dfrac{p_2'+\omega}{p_2} + \cdots + \mathrm{Tan}^{-1}\dfrac{p_M'+\omega}{p_M} + 2\dfrac{|K|-K}{K}\mathrm{Tan}^{-1}\,1$

also decibels = 20 $\log_{10}$ magnitude

N.B. $\mathrm{zero}_i = -(z_i+_jz_i')$

$\mathrm{pole}_i = -(p_i+_jp_i')$

Operating Limits and Warnings

K must be real and non-zero but may be negative.

About 4 seconds of computing time is required for each pole and each zero, whereas 00361A takes half as long.

Program Description II

Sketch(es)

Sample Problem(s)

Find gain (in decibels and volts/volt) and phase shift in degrees

For $F(s) = 0.09091 \frac{s + 62890}{s + 5717}$ at 3333 Hz.

Solution(s)

3333 [A]	→ 0.
62890 [↑] 0 [B]	→ 1.
5717 [↑] 0 [C]	→ -1.
.09091 [R/S]	→ -1.
[D]	→-11.1 Decibels
[R/S]	→ 2.77590 (10^{-1}) Volts/Volt
[E]	→-56.3 Degrees

Reference(s) HP-65 Program 00361A

This program is a translation of the HP-65 Users' Library Program #02582A submitted by E. P. Sansing.

User Instructions

1 BODE, EACH POLE AND ZERO GIVEN 2

hz/rps	z_i, z_i'	p_i, p_i'	DB/mag	angle

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter program card			
2	(Optional) For dB = $10\log_{10}$ Magnitude:			
	Switch to run		GTO D	
	Switch to w/prgm		SST SST	31
			SST	02
			f DEL	062 1632
		1		01
	Switch to run			
3	(Optional) For phase angle not in degrees:			
	a. for θ in grads		f GRD	
	b. for θ in radians		f GRD	
4	Key in frequency			
	a. in Hertz or	Hz	A	0.
	b. in radians/second	rps	A R/S	1.
5	Key in z_i,	z_i	↑	
	Key in z_i'	z_i'	B	i.
6	Repeat step 5 for each i ≤ N			
7	Key in p_i	p_i	↑	
	Key in p_i'	p_i'	C	-i.
8	Repeat step 7 for each i ≤ M			
9	(Optional) key in k, otherwise the program			
	will default to k = + 1	k	R/S	
10	Display decibels		D	db
11	Display magnitude		R/S	unitless
12	Display phase angle		E	depends on 3
	For each new frequency, repeat steps 4			
	through 12.			

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	Frequency input
002	CLRG	16-53	Subroutine
003	STO6	35 06	
004	2	02	Convert Hertz to
005	×	-35	routine/second
006	Pi	16-24	
007	×	-35	
008	STO5	35 05	Store rads/sec k
009	1	01	will default to 1
010	STO1	35 01	unless step 9 used
011	RCL2	36 02	
012	FIX	-11	
013	DSP0	-63 00	
014	R/S	51	Display 0.
015	RCL6	36 06	If input was
016	STO5	35 05	rads/sec recall
017	RCL1	36 01	input store rads/
018	RTN	24	sec display 1.
019	*LBLB	21 12	Subroutine for
020	RCL3	36 03	zero inputs
021	1	01	Increment N counter
022	+	-55	
023	STO3	35 03	
024	STO7	35 07	
025	R↓	-31	
026	RCL5	36 05	
027	+	-55	
028	X⇄Y	-41	
029	→P	34	
030	GTO0	22 00	
031	*LBLC	21 13	Subroutine for pole
032	RCL4	36 04	inputs
033	1	01	Decrement -M pole
034	-	-45	inputs
035	STO4	35 04	
036	STO7	35 07	
037	R↓	-31	
038	RCL5	36 05	
039	+	-55	
040	CHS	-22	
041	X⇄Y	-41	
042	→P	34	
043	1/X	52	
044	*LBL0	21 00	Subroutine to
045	ST×1	35-35 01	update magnitude
046	R↓	-31	and angle
047	RCL2	36 02	
048	+	-55	
049	1	01	
050	→R	44	
051	→P	34	
052	R↓	-31	
053	STO2	35 02	Display N or -M
054	RCL7	36 07	
055	R/S	51	
056	0	00	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	X⇄Y	-41	
058	→P	34	
059	GTO0	22 00	
060	*LBLD	21 14	Subroutine to
061	RCL1	36 01	compute decibels 12
062	LOG	16 32	
063	2	02	
064	0	00	
065	x	-35	
066	DSP1	-63 01	
067	R/S	51	
068	RCL1	36 01	Display magnitude
069	DSP5	-63 05	
070	SCI	-12	
071	RTN	24	
072	*LBLE	21 15	Subroutine to call
073	RCL2	36 02	phase angle
074	DSP1	-63 01	
075	FIX	-11	
076	RTN	24	
077	R/S	51	

090

100

110

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n 2	

REGISTERS

0	1 magnitude M	2 phase ang. Θ	3 zero counts i < N	4 pole counts -i > -M	5 radians per second	6 first input, frequency	7 last updated (N or -M)	8	9
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Program Description I

Program Title BODE OF SECOND-ORDER OVER THIRD-ORDER TRANSFER FUNCTION

Contributor's Name Hewlett-Packard Company

Address 1000 N.E. Circle Boulevard

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables

$$F(s) = \frac{Qs^3 + Gs^2 + Hs + K}{Rs^4 + Ls^3 + Ms^2 + Ns + P}$$

where Q and R are options, limited to [-1, 0, +1]
G, H, L, L, M, N, and P may assume any real value

$$|magnitude| = \frac{\sqrt{(K-G\omega^2)^2 + (H\omega-Q\omega^2)^2}}{\sqrt{(P-M\omega^2+R\omega^4)^2 + (N\omega-L\omega^3)^2}}$$

where $\omega=2\pi F$

$$Decibels = 20 \log_{10} |magnitude|$$

$$Phase = Tan^{-1} \frac{H\omega-Q\omega^3}{K-G\omega^2} - Tan^{-1} \frac{N\omega-L\omega^3}{P-M\omega^2+R\omega^4}$$

in degrees (unless angular mode is set to radians or grads).

Operating Limits and Warnings Frequency, F, can not equal zero. Coefficient of s^3 in numerator is -1, 0, or+1. Coefficient of s^4 in denominator is -1, 0, or +1. Display of phase will be between -180° and +180° ($-\pi$ and $+\pi$ radians or -200 and +200 grads).

Program Description II

Sketch(es)

Sample Problem(s)

Find gain (in decibels and volts/volt) and phase shift in degrees

For $F(s) = \frac{8s^3-1}{3s^3+8}$ at DC and f=0.1 Hz

Option 3 (see page 4) is required but the coefficient of s^3 in the numerator can be only -1, 0, or +1.

Rewritten, $F(s) = \frac{s^3-0.125}{0.375s^3+1}$

G= 0	H= 0
k=-0.125	L= 0.375
M= 0	N= 0
p= 1	f=10^{-50} (zero is not allowed) and 0.1

Solution(s) Switch to Run: [GTO] 1 Switch to w/prgm: [g][DEL][RCL] 8[-]

Switch to Run: 0[↑] 0[↑] .125[CHS][A] →		0.00
.375 [↑] 0 [↑] 0 [↑] 1 [B] →		0.38
[EEX] 50 [CHS][D] →	F = 0 Hz	Gain = - 18.06 db
[R/S] →	F = 0 Hz	Gain = 0.13 volts/volt
[E] →	F = 0 Hz	Phase = 180.00 degrees
.1 [D] →	F = 0.1 Hz	Gain = - 11.16 db
[R/S] →	F = 0.1 Hz	Gain = 0.28 volts/volt
[E] →	F = 0.1 Hz	Phase = -111.43 degrees

Reference(s) This program is a translation of the HP-65 Users' Library Program #02272A submitted by Edward P. Sansing.

User Instructions

◀1	BODE OF $(Gs^2+Hs+K)/(Ls^3+Ms^2+Ns+P)$			2▶
Numer	denom		gain	phase

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Enter program			
2	Exercise option(s) if desired (see page 4)			
3	Select angular mode if grads or radians are to be computed			
4	Input numerator coefficients	G	↑	G
		H	↑	H
		K	A	G
5	Input denominator coefficients	L	↑	L
		M	↑	M
		N	↑	N
		P	B	L
6	Key in first frequency	f (or ω)	D	gain/DB
	(Optional)		R/S	Magnitude
7	Compute phase		E	Θ
	(Optional)		R/S	Θnumer
			g R↓	Θdenom
			RCL 8	ω/rad/sec
	(After a step 6 is done, it is not necessary to do steps 1, 2, 3, 4, 5, nor 7 before another step 6 is done.)			

User Instructions

BODE OF $(Gs^2+Hs+K)/(Ls^3+Ms^2+Ns+P)$

numer | denom | gain | phase

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
	OPTIONS			
	Any combination of the four may be used;			
	however, order of selection must be as follows:			
1	To use radians/second inputs instead of Hz.			
	Switch to Run		GTO D	
	Switch to w/prgm			2114
	Perform 4 times		SST f	35
			DEL	14
	Switch to Run			
2	For db=10 x $\log_{10}$|Magnitude|			
	Instead of 20 x $\log_{10}$|Magnitude|			
	Switch to Run		GTO 2	
	Switch to w/prgm			2102
	Single step 14 times		SST	02
			f DEL	1632
		1		01
	Switch to Run			
3	For s^3+Gs^2+Hs+K as numerator			
	Switch to Run		GTO 1	
	Switch to w/prgm		f DEL	-24
			RCL 8	36 08
	(For $-s^3$, use +)		-	-45
	Switch to Run			
4	For $s^4+Ls^3+Ms^2+Ns+P$ as denominator			
	Switch to Run		GTO 2	
	Switch to w/prgm		f DEL	-24
			f LST X	16 -63
	(For $-s^4$, use -)		+	-55
	Switch to Run			

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	Numerator coefficients
002	STO3	35 03	
003	R↓	-31	
004	STO2	35 02	
005	R↓	-31	
006	STO1	35 01	
007	RTN	24	
008	*LBLB	21 12	Denominator coefficients
009	STO7	35 07	
010	R↓	-31	
011	STO6	35 06	
012	R↓	-31	
013	STO5	35 05	
014	R↓	-31	
015	STO4	35 04	
016	RTN	24	
017	*LBLD	21 14	Convert degrees to radians
018	2	02	
019	x	-35	
020	Pi	16-24	
021	x	-35	
022	STO8	35 08	Compute |F(s)|
023	RCL2	36 02	
024	RCL8	36 08	
025	÷	-24	
026	*LBL1	21 01	
027	RCL3	36 03	
028	RCL8	36 08	
029	X²	53	
030	÷	-24	
031	RCL1	36 01	
032	-	-45	
033	→P	34	
034	STO9	35 09	
035	R↓	-31	
036	RCL6	36 06	
037	RCL8	36 08	
038	÷	-24	
039	RCL4	36 04	
040	RCL8	36 08	
041	x	-35	
042	-	-45	
043	RCL7	36 07	
044	RCL8	36 08	
045	X²	53	
046	÷	-24	
047	*LBL2	21 02	
048	RCL5	36 05	
049	-	-45	
050	RCL9	36 09	
051	R↓	-31	
052	→P	34	
053	R↓	-31	
054	R↓	-31	
055	STO9	35 09	
056	R↓	-31	
057	X⇄Y	-41	
058	÷	-24	
059	ENT↑	-21	
060	LOG	16 32	
061	2	02	
062	0	00	
063	x	-35	
064	R/S	51	
065	X⇄Y	-41	
066	RTN	24	
067	*LBLE	21 15	Compute Phase
068	R↑	16-31	
069	R↑	16-31	
070	RCL9	36 09	
071	-	-45	
072	CHS	-22	
073	LSTX	16-63	
074	X⇄Y	-41	
075	1	01	
076	→R	44	
077	→P	34	
078	R↓	-31	
079	R/S	51	
080	R↓	-31	
081	RTN	24	
082	R/S	51	
090			
100			
110			

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n 2	

REGISTERS

0	1	2	3	4	5	6	7	8	9
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	B	C	D	E	I				

Program Description I

Program Title BODE OF 2ND - OVER 2ND - ORDER TIMES S**N TRANSFER FUNCTION

Contributor's Name Hewlett-Packard Company

Address 1000 N. E. Circle Boulevard

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables

$$F(s) = \frac{Qs^3 + Gs^2 + Hs + K}{s^N(Rs^3+Ls^2+Ms+P)}$$

where: Q and R are options, limited to [-1, 0, +1]
G, H, K, L, M, and P may assume any real value
N is a non-negative integer [0, 1, 2, ...]

$$|\text{Magnitude}| = \frac{\sqrt{(K-G\omega^2)^2 + (H\omega-Q\omega^3)^2}}{\omega^N \sqrt{(P-L\omega^2)^2 + (M\omega-R^3)^2}}$$

where: $\omega = 2\pi F$

$$\text{Decibels} = 20 \log_{10}|\text{Magnitude}|$$

$$\text{Phase} = \tan^{-1}\frac{H\omega-Q\omega^3}{K-G\omega^2} - N \sin^{-1} 1.0 - \tan^{-1}\frac{M\omega-R\omega^3}{P-L\omega^2}$$

in degrees (unless angular mode is set to radians or grads).

Operating Limits and Warnings Frequency, F, can not equal zero. Power, N, is a non-negative integer. Coefficient of s^3 in numerator or denominator is -1, 0, or +1 display of phase will be between -180° and +180° ($-\pi$ and $+\pi$ radians or -200 and +200 grads).

Program Description II

Sketch(es)

Sample Problem(s)

Find gain (in decibels and volts/volt) and phase shift in degrees

For $F(s) = \dfrac{8s^3 - 1}{s^2(s^2-2)}$ at F = 0.1 Hz and 1.0 Hz

Option 3 (see page 4) is required but the coefficient of s^3 can be only -1, 0, or +1

Rewritten, $F(s) = \dfrac{s^3 - 0.125}{s^2(0.125s^2-0.25)}$

So

G = 0	H = 0
K = -0.125	N = 2
L = 0.125	M = 0
P = -0.25	F = 0.1 and 1.0

Solution(s) Switch to Run: [GTO] 1   Switch to w/prgm: [g][DEL][g][DEL][RCL]8[F^{-1}][√][-]

Switch to Run: 0 [↑] 0 [↑] .125 [CHS][A] →			0.00
2 [↑] .125 [↑] 0 [↑] .25 [CHS][B] →			2.00
.1 [D] →		Gain =	7.42 db
[R/S] →	F = 0.1 Hz	Gain =	2.35 volts/volt
[E] →		Phase =	-116.74 degrees
1 [D] →		Gain =	1.67 db
[R/S] →	F = 1.0 Hz	Gain =	1.21 volts/volt
[E] →		Phase =	-90.03 degrees

Reference(s) This program is a translation of the HP-65 Users' Library Program #02273A submitted by Edward P. Sansing.

User Instructions

BODE OF $(GS^2+HS+k)/S^N(LS^2+MS+P)$

1 | NUMER | DENOM | | GAIN | PHASE | 2

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1.	Enter program				
2.	Exercise option(s)				
	If desired (see page 4).				
3.	Select angular mode if grads or radians are to be computed.				
4.	Input numerator coefficients	G	↑		G
		H	↑		H
		k	A		G
5.	Input denominator power of S	N	↑		N
	and coefficients	L	↑		L
		M	↑		M
		P	B		N
6.	Key in first frequency	F (or ω)	D		GAIN/dB
	(Optional)		R/S		Magnitude
7.	Compute phase		E		θ
	(Optional)		RCL	8	ω /RAD/SEC
	(After a step 6 is done, it is not necessary to do steps 1,2,3,4,5, nor 7 before another step 6 is done.)				

User Instructions

BODE OF $(GS^2+HS+K)/S^N(LS^2+MS+P)$

NUMER	DENOM		GAIN	PHASE

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
	OPTIONS				
	Any combination of the four may be used; however, order of selection must be as follows:				
1.	To use radians/sec. inputs instead of Hz				
	Switch to run		GTO	D	
	Switch to W/PRGM				21 14
	Perform 4 times		{ SST	f	35
			{ DEL		14
	Switch to run				
2.	For dB-10 x $\log_{10}$ Magnitude				
	Instead of 20 x $\log_{10}$ Magnitude				
	Switch to run		GTO	1	
	Switch to W/PRGM				23 01
	Single step 16 times		SST		02
			f	DEL	16 32
	'	1			01
	Switch to run				
3.	For $S^3 + GS^2 + HS + k$ as numerator				
	Switch to run		GTO	1	
	Switch to W/PRGM		RCL	8	34 08
				$\sqrt{x}$	
				x^2	53
	(for -5^3, use +)			-	-45
	Switch to RUN				
4.	For $S^N(S^3+LS^2+MS+P)$				
	As denominator switch to run		GTO	2	
	Switch to W/PRGM				23 02
			RCL	8	34 08
			x^2		53
	(for $-S^3$, use +)			-	-45
	Switch to RUN				

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	
002	STO3	35 03	
003	R↓	-31	
004	STO2	35 02	Store numerator coefficients
005	R↓	-31	
006	STO1	35 01	
007	RTN	24	
008	*LBLB	21 12	
009	STO7	35 07	
010	R↓	-31	
011	STO6	35 06	
012	R↓	-31	Store denominator coefficients & power
013	STO5	35 05	
014	R↓	-31	
015	STO4	35 04	
016	RTN	24	
017	*LBLD	21 14	Compute gain
018	2	02	
019	×	-35	
020	Pi	16-24	These four program steps are deleted for inputting radians/second
021	×	-35	
022	STO8	35 08	
023	RCL6	36 06	
024	*LBL2	21 02	
025	RCL7	36 07	
026	RCL8	36 08	
027	÷	-24	
028	RCL5	36 05	
029	RCL8	36 08	
030	×	-35	
031	-	-45	
032	→P	34	
033	RCL8	36 08	
034	RCL4	36 04	
035	Y^x	31	
036	×	-35	Denominator magnitude
037	1	01	
038	SIN^{-1}	16 41	
039	RCL4	36 04	
040	×	-35	
041	X⇄Y	-41	
042	R↓	-31	
043	+	-55	
044	R↑	16-31	
045	STO9	35 09	
046	R↓	-31	
047	RCL3	36 03	
048	RCL8	36 08	
049	÷	-24	
050	RCL1	36 01	
051	RCL8	36 08	
052	×	-35	
053	-	-45	
054	RCL2	36 02	
055	*LBL1	21 01	
056	X⇄Y	-41	
057	RCL9	36 09	
058	R↓	-31	
059	→P	34	
060	R↑	16-31	
061	÷	-24	
062	R↓	-31	
063	-	-45	
064	CHS	-22	
065	R↑	16-31	
066	ENT↑	-21	
067	LOG	16 32	Total phase magnitude
068	2	02	
069	0	00	
070	×	-35	
071	R/S	51	
072	X⇄Y	-41	
073	RTN	24	
074	*LBLE	21 15	
075	R↑	16-31	
076	1	01	Compute phase
077	→R	44	
078	→P	34	
079	R↓	-31	
080	RTN	24	
081	R/S	51	
090			
100			
110			

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	2

REGISTERS

0	1	2	3	4	5	6	7	8	9
G, coeff of S^2	G, coeff of S^2	H, coeff of s^1	k, coeff of s^0	N, power of S	L, coeff of S^2	M, coeff. of S1	p, coeff of S0	ω RAD/SEC	DENOM MAGNIT
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Program Description I

Program Title Pole-Zero to Group Delay

Contributor's Name Hewlett-Packard

Address 1000 N.E. Circle Blvd.

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables Given a transmission function in the S-Plane:

$$\frac{V_0}{E_i} = \frac{k[s-(\sigma_{z1} + j\Omega_{z1})]\,[s-(\sigma_{z2} + j\Omega_{z2})] \cdots [s-(\sigma_{zn} + j\Omega_{zn})]}{[s-(\sigma_{p1} + j\Omega_{p1})]\,[s-(\sigma_{p2} + j\Omega_{p2})] \cdots [s-(\sigma_{pm} + j\Omega_{pm})]}$$

in which poles & zeros are of the form: $\sigma + j\Omega$

This program evaluates the expression for time response:

$$T = \sum_{k=1}^{m} d_{pk} - \sum_{k=1}^{n} d_{zk} \quad \text{where } d_k = \frac{\sigma_k}{\sigma_k^2 + (\omega - \Omega_k)^2} \quad \text{for}$$

either poles or zeros. A negative quantity for T indicates delay so that for positive values of time delay

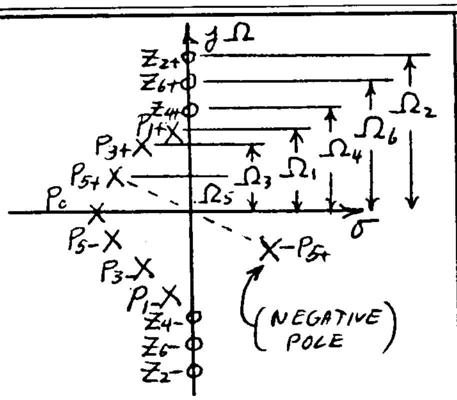
$$TD = -T = \sum_{k=1}^{n} d_{zk} - \sum_{k=1}^{m} d_{pk}$$

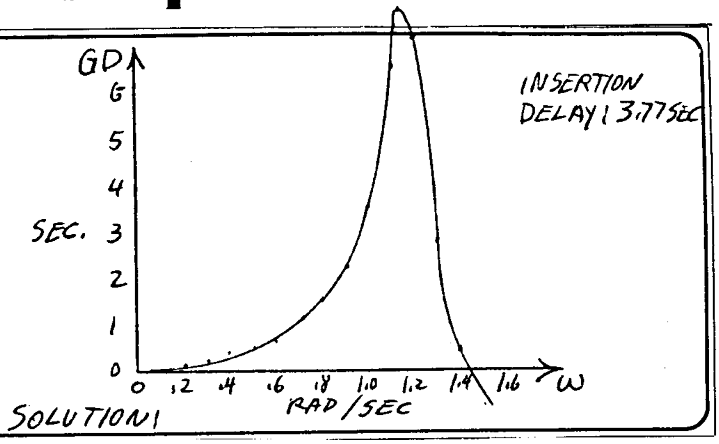
Group delay: $GD = TD - TD_0$ where is the time delay at reference frequency ω_0.
As $\omega_0 \to 0, TD_0 \to$ insertion delay.

Operating Limits and Warnings

Program Description II

Sketch(es)





Sample Problem(s) A 7 pole Caver - Chebyshev filter normalized to R = 1Ω and ω_0 = 1 rad/sec has pole & zero coordinates as follows:

σ_0	σ_1	σ_3	σ_5	Ω_1	Ω_2	Ω_3	Ω_4	Ω_5	Ω_6
-.78683	-.12406	-.3904	-.65874	1.16504	4.3544	.99847	2.0445	.60818	2.4903

Tabulate the group delay referred to ω=.001 from ω=.1 to ω= 1.5 and generate a normalized group delay curve.

SOLUTION: Note that all zeros lie on the jΩ axis resulting in no contribution to delay. Register loading is shown below. Pole zero data is called up with the following sequence written in step 2 of the instructions. Results are tabulated below and graphed at top of page.

Solution(s)

REGISTER:	In W. PRGM MODE:
$R4=-\sigma_1=0.12406$	$-P_0$: .787↑0C
$R5=\Omega_1=1.16504$	$-P_{1+}$: RCL 4 RCL 5 CHS C
$R6=-\sigma_3=0.3904$	$-P_{1-}$: RCL 4 RCL 5 C
$R7=\Omega_3=0.99847$	$-P_{3+}$: RCL 6 RCL 7 CHS C
$R8=-\sigma_5=0.65874$	$-P_{3-}$: RCL 6 RCL 7 C
	$-P_{5+}$: RCL 8 .608 CHS C
	$-P_{5-}$: RCL 8 .608 C
	TOTAL: 34 steps

ω RAD/SEC	TD/GD SEC	ω RAD/SEC	GD SEC
.001	TD=3.770	.8	1.544
.1	GD=0.015	.9	2.282
.2	0.064	1.0	3.647
.3	0.150	1.1	6.663
.4	0.281	1.2	7.220
.5	0.462	1.3	2.842
.6	0.708	1.4	0.390
.7	1.052	1.5	-0.808

Reference(s)

Handbook of Filter Synthesis - A. Zverev 1967 p. 149.

This program is a translation of the HP-65 program #04775A submitted by Charles R. Olson.

User Instructions

POLE-ZERO TO GROUP DELAY

W.PRGM.

GD | TD_0 | $\sigma_p \uparrow \Omega_p$ | $\sigma_z \uparrow \Omega_z$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1.	Enter program & initialize		GTO	0	
2.	Switch to W. PRGM mode. Enter 3 digit:				
	a) real component of negative * of 1st pole	$-\sigma_{p1}$ RAD/SEC	↑		11
	b) imag. comp. of neg. of 1st pole	$-\Omega_{p1}$ RAD/SEC	C		REGISTERS
	c) repeat (a) & (b) for each pole				AND 183
	d) real comp. of neg. of 1st zero	$-\sigma_{z1}$ RAD/SEC	↑		STEPS
	e) imag. comp. of neg of 1st zero	$-\Omega_{z1}$ RAD/SEC	D		AVAIL.
3.	Record on auxil. card. switch to RUN				
4.	Enter ω for GD=0	ω_0 RAD/SEC			
5.	Calculate time delay at REF FREQ.		B		
6.	Enter ω	ω RAD/SEC			
7.	Calculate group delay		A		GD SEC
8.	Repeat (6) & (7) for each freq.				

NOTES: * 1) Since poles & zeros often lie in the left half plane, entering negative vectors results in positive values saving many CHS steps.

2) Any pole or zero with real comp. equal to zero may be omitted in step 2

3) Use registers 4-8 and A-I to store coordinates of critical poles & zeroes. Use RCL ( ) in step 2 instead of 3 digit data and enter ↑.

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBL0	21 00	
002	RCL2	36 02	
003	F1?	16 23 01	
004	GTO3	22 03	
005	RCL3	36 03	
006	-	-45	
007	R/S	51	
008	*LBLA	21 11	
009	CF1	16 22 01	
010	STO1	35 01	
011	0	00	
012	STO2	35 02	
013	GTO0	22 00	
014	*LBLB	21 12	
015	SF1	16 21 01	
016	STO1	35 01	
017	0	00	
018	STO2	35 02	
019	GTO0	22 00	
020	*LBLC	21 13	
021	RCL1	36 01	
022	+	-55	
023	X⇄Y	-41	
024	→P	34	M
025	LSTX	16-63	
026	X⇄Y	-41	
027	X²	53	
028	÷	-24	
029	ST+2	35-55 02	d_p subtracted from
030	RTN	24	R2
031	*LBLD	21 14	
032	RCL1	36 01	
033	+	-55	
034	X⇄Y	-41	
035	→P	34	
036	LSTX	16-63	
037	X⇄Y	-41	
038	X²	53	
039	÷	-24	
040	ST-2	35-45 02	d_z added to R2
041	RTN	24	
042	*LBL3	21 03	
043	STO3	35 03	
044	R/S	51	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	3

REGISTERS

0	1	2	3	4	5	6	7	8	9
	ω	TD	TD_0						Used

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Program Description I

Program Title ROUTH TEST FOR CONTINUOUS AND DISCRETE TIME SYSTEM STABILITY

Contributor's Name JAMES V. WISEMAN JR.

Address 3926 CANYON Rd

City LAFAYETTE State CALIF Zip Code 94549

Program Description, Equations, Variables DESIGNED TO TEST THE LOCATION OF THE ROOTS OF A CHARACTERISTIC EQUATION IN THE FORM:

$a_0 p^n + a_1 p^{n-1} + \ldots a_{n-1} p + a_n = 0$ p IS 's' OR 'z' DEPENDING ON SYSTEM AT HAND

ROUTH TEST FOR RHP ROOTS: REPEATED $n+1$ TIMES: $k = a_0/a_1$, LOOP FOR $i = 1,3,5\ldots$ $\{a_{i-1} = a_i;\ a_i = a_{i+1} - k a_{i+2}\}$

#RHP ROOTS = Σ(#TIMES $k<0$)

AXIS SHIFT FOR GIVEN OFFSET d: ($p \leftarrow p' + d$)

$$\begin{bmatrix} a_1 = a_1 + a_0 d \\ a_2 = a_2 + a_1 d \\ \vdots \\ a_n = a_n + a_{n-1} d \end{bmatrix} \begin{bmatrix} a_1 = a_1 + a_0 d \\ a_2 = a_2 + a_1 d \\ \vdots \\ a_{n-1} = a_{n-1} + a_{n-2} d \end{bmatrix} \cdots \begin{bmatrix} a_1 = a_1 + a_0 d \\ a_2 = a_2 + a_1 d \end{bmatrix} \begin{bmatrix} a_1 = a_1 + a_0 d \end{bmatrix}$$

$z = (s+1)/(s-1)$ SUBISTUTION: WHERE: $k_j^i = \dfrac{(-1)^j\, i!}{(i-j)!\, j!}$

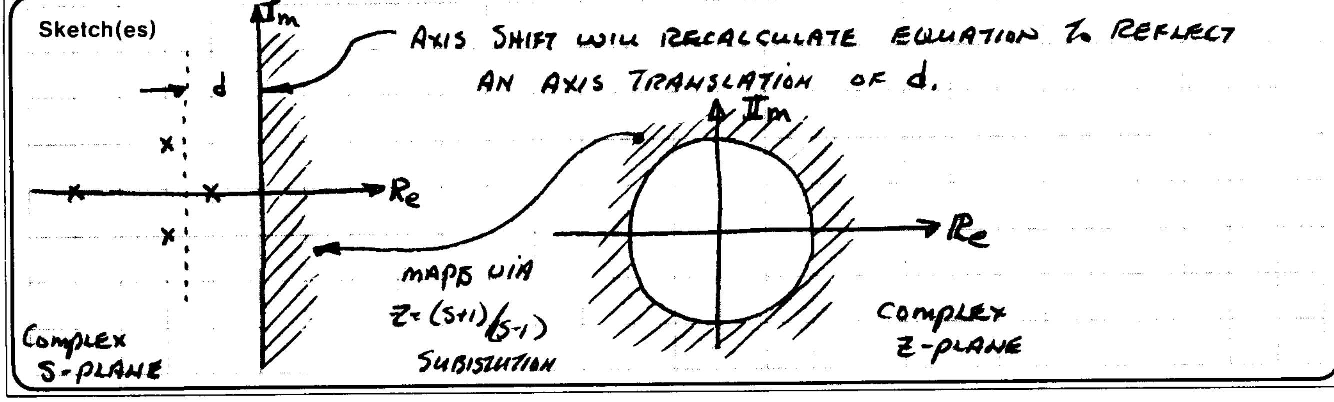
$$\begin{bmatrix} a_0' = a_0 + k_0^1 a_1 \\ a_1' = a_0 + k_1^1 a_1 \end{bmatrix} \begin{bmatrix} a_0' = a_0 + k_0^2 a_2 \\ a_1' = a_0 + a_1 + k_1^2 a_2 \\ a_2' = a_1 + k_2^2 a_2 \end{bmatrix} \cdots \begin{bmatrix} a_0 = a_0 + k_0^n a_n \\ a_1' = a_0 + a_1 + k_1^n a_n \\ a_2' = a_1 + a_2 + k_2^n a_n \\ \vdots \\ a_n = a_{n-1} + k_n^n a_n \end{bmatrix}$$

Operating Limits and Warnings

1) LIMITED BY CALCULATOR REGISTERS TO 20th ORDER #'s
2) ROUTH TEST WITH VARIOUS ROOTS ALONG IMAGINARY AXIS MAY INDICATE INSTABILITY. SHIFT AXIS SLIGHTLY TO CHECK ACTUAL LOCATION OF ROOTS.

Program Description II

Sketch(es)



Sample Problem(s)

1) DOES $s^4+2s^3+s^2+4s+4$ REPRESENT A STABLE CONTINUOUS TIME SYSTEM?
   a) ENTER POLY. BY PRESSING 'fe'. IN RESPONSE TO THE FLASHING '0' KEY IN a_0 (1), IN RESPONSE TO THE FLASHING '1' KEY IN a_1 (2) ETC ETC UNTIL a_4 (4) IS ENTERED IN RESPONSE TO THE FLASHING '4'. STORE POLY. BY PRESSING 'fd' (IGNORE FLASHING '5').
   b) EXECUTE ROUTH TEST BY PRESSING 'A'. CALCULATOR WILL PAUSE DISPLAYING 1ST COLUMN OF ROUTH ARRAY: 1, 2, -1, 12, 4 AND FLASH (OR PRINT) THE NUMBER OF RHP ROOTS: 2. <u>UNSTABLE</u>
2) RECALCULATE $p^4+9p^3+29p^2+41p+20$ TO REFLECT AN AXIS SHIFT OF $d=-1.5$ (SEE ABOVE SKETCH)
   a) ENTER POLY. AS IN PROB. #1 PART (a
   b) KEY-IN -1.5 PRESS 'C'. AT END OF CALCULATION, PRINT OUT NEW POLYNOMIAL BY 'E': $p^4+3p^3+2p^2+1.25p-1.5625$
3) DOES $z^4+.3z^3+.1z^2+.05z+.001$ REPRESENT A STABLE DISCRETE TIME SYSTEM?
   a) ENTER POLY. AS IN PROB #1 PART (a
   b) MAKE $z=(s+1)/(s-1)$ SUBISTUTION BY 'fc'. RESULTS CAN BE FOUND BY 'E' TO BE: $1.451s^4+4.496s^3+5.806s^2+3.496s+.751$
   c) EXECUTE ROUTH TEST BY PRESSING 'A'. AS IN PROB #1 PART (b CALCULATOR WILL PAUSE AT 1.451, 4.496, 4.678, 2.774 & 0.751 STOPPING WITH "0." IN THE DISPLAY, THE # RHP ∴ <u>STABLE</u>

Reference(s)

1) Y. TAKAHASHI, M. RABINS, AND D. AUSLANDER, <u>CONTROL</u>, ADDISON-WESLEY, READING, MASS., 1970

2) JURY, E.I., <u>THEORY AND APPLICATION OF THE Z TRANSFORM METHOD</u>., NEW YORK: WILEY 1964

3) J. WISEMAN, <u>RECURSIVE ALGORITHMS FOR ROUTH TEST IN CONT. & DISCRETE TIME</u> <u>TRANSACTIONS OF ASME, JDSMC</u> TO BE PUBLISHED.

User Instructions

ROUTH TEST — POLYNOMIAL OPERATIONS

ROUTH TEST	ABORT	$S \leftarrow S'+X$	RESTORE	WRITE
		$Z = \frac{(S+1)}{(S-1)}$	SAVE	READ

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1)	READ-IN BOTH SIDES OF CARD				0.
2)	READ IN POLYNOMIAL BY 'fe' (READ)		f	e	
	'm' WILL BE FLASHED FOR EACH a_m,				m
	REQUESTING USER TO KEY-IN a_m DURING	a_m			
	PAUSE, ONCE ENTRY HAS BEEN MADE				
	NEXT 'm' IS FLASHED. STOP DATA				
	ENTRY REQUEST BY 'fd' (SAVE)		f	d	
	– THIS WILL SAVE a_m's IN SECONDARY				
	REG'S IF $n<10$, OTHERWISE IT WILL				
	STORE a_m's ON SCRATCH CARD VIA 'crd'				0.
3)	IF DISCRETE TIME SYSTEM, MAKE				
	$z = (s+1)/(s-1)$ SUBISTUTION BY 'fc'. THIS		f	c	
	WILL GENERATE A NEW POLYNOMIAL IN				
	PLACE OF ORGINAL, REFLECTING SUBISTUTION				0.
4)	IF AXIS SHIFT IS DESIRED, ENTER LOCATION				
	OF NEW ORGIN IN X. EXECUTE	OFFSET	C		
	SHIFT BY 'C' ($s \leftarrow s'+x$). THIS				
	WILL GENERATE A NEW POLYNOMIAL				
	IN PLACE OF ORGINAL, REFLECTING AXIS SHIFT				0.
5)	ROUTH TEST IS EXECUTED BY 'A' (ROUTH TEST)		A		
	PROGRAM PAUSES DURING EXECUTION TO				
	DISPLAY ELEMENTS OF 1st COLUMN				
	IN ROUTH ARRAY. NO. OF SIGN				
	CHANGES INDICATES NO. OF RHP				
	ROOTS. PROGRAM HAULTS, PRINTING #				
	OF RHP ROOTS.				# RHP ROOTS
	NOTE:				
	a) RECURSIVE ALGORITHMS ARE DISTRUCTIVE				
	IN THAT THEY DESTROY THE ORGINAL				
	POLYNOMIAL. FOR ADDITIONAL RUNS,				
	DATA MUST BE RESTORED VIA				
	'D' (RESTORE) IF $n<10$ OTHERWISE		D		
	BY SCRATCH CARD FROM STEP 2.				
	b) POLYNOMIAL MAY BE REVIEWED OR				
	PRINTED FOR RECORDS BY 'E' (WRITE).				
	c) IF AN ERROR IS MADE DURING a_m				
	ENTRY AND DATA IS 'TAKEN', PRESS				
	'B' (ABORT) AND START OVER WITH		B		
	'fe'		f	e	

67 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBL A	31 25 11	
	SCI	32 23	
	DSP 3	23 03	
	Ø	00	
	STO D	33 14	
	*LBL Ø	31 25 00	
	RCL Ø	34 00	
	PAUSE	35 72	
	RCL 1	34 01	
010	X≠Ø?	31 61	
	GTO a	22 31 11	
	CLX	44	
	EEX	43	
	CHS	42	
	5	05	
	0	00	
	STO 1	33 01	
	*LBL a	32 25 11	
	÷	81	
020	STO C	33 13	
	X>Ø?	31 81	
	GTO a	22 31 11	
	RCL D	34 14	
	1	01	
	+	61	
	STO D	33 14	
	*LBL a	32 25 11	
	1	01	
	ST I	35 33	
030	*LBL 1	31 25 01	
	RCL (I)	34 24	
	DSZ	31 33	
	STO (I)	33 24	
	STO (I)	33 24	
	ISZ	31 34	
	ISZ	31 34	ROUTH TEST
	RCL (I)	34 24	
	ISZ	31 34	
	RCL (I)	34 24	
040	RCL C	34 13	
	X	71	
	−	51	
	DSZ	31 33	
	DSZ	31 33	
	STO (I)	33 24	
	ISZ	31 34	
	ISZ	31 34	
	RC I	35 34	
	RCL E	34 15	
050	X>Y?	32 81	
	GTO 1	22 01	
	1	01	
	−	51	
	STO E	33 15	
	RCL (I)	34 24	
	Ø	00	

STEP	KEY ENTRY	KEY CODE	COMMENTS
	STO (I)	33 24	
	DSZ	31 33	
	R↓	35 53	
060	STO (I)	33 24	
	RCL E	34 15	
	X>Ø?	31 81	
	GTO Ø	22 00	
	RCL Ø	34 00	
	PAUSE	35 72	
	RCL D	34 14	
	FIX	31 23	
	DSP Ø	23 00	
	PRINTX	31 84	
070	SPACE	35 84	
	R/S	84	
	GTO B	22 12	
	*LBL C	31 25 13	
	X=Ø?	31 51	
	GTO B	22 12	
	SCI	32 23	
	DSP 4	23 04	
	PRINT X	31 84	
	STO D	33 14	
080	RCL E	34 15	
	STO C	33 13	
	*LBL 2	31 25 02	
	Ø	00	
	ST I	35 33	
	*LBL 3	31 25 03	AXIS SHIFT
	RCL (I)	34 24	
	RCL D	34 14	
	X	71	
	ISZ	31 34	
090	STO+(I)	33 61 24	
	RC I	35 34	
	RCL C	34 13	
	X≠Y?	32 61	
	GTO 3	22 03	
	1	1	
	−	51	
	STO C	33 13	
	X≠Ø?	31 61	
	GTO 2	22 02	
100	GTO B	22 12	
	*LBL c	32 25 13	
	CF 2	35 61 02	
	1	01	
	STO D	33 14	
	*LBL b	32 25 12	
	Ø	00	
	ST I	35 33	
	*LBL 4	31 25 04	
	GSB 5	31 22 05	
110	GSB 6	31 22 06	
	RCL (I)	34 24	
	GSB 6	31 22 06	

REGISTERS

0	1	2	3	4	5	6	7	8	9
a_0	a_1	a_2	a_3	...	...	...	...	...	...

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
a_{10} or a_0	a_{11} or a_1	a_{12} or a_2	a_{13} or a_3	...	....	....	....	....	....

A	B	C	D	E	I
a_{20}	SCRATCH	SCRATCH	SCRATCH	n	RESERVED

67 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
	X	71	
	+	61	
	RCL (I)	34 24	
	X⇆Y	35 52	
	STO + (I)	33 61 24	
	ISZ	31 34	
	RCL D	34 14	
120	RC I	35 34	
	X≠Y?	32 61	
	SF2	35 51 02	
	R↑	35 54	
	F2?	35 71 02	
	GTO 4	22 04	
	GSB 5	31 22 05	
	RCL (I)	34 24	
	X	71	
	+	61	
130	STO (I)	33 24	
	RCL E	34 15	
	RCL D	34 14	
	X=Y?	32 51	
	GTO B	22 12	
	1	01	
	+	61	
	STO D	33 14	
	GTO b	22 31 12	
	*LBL 5	31 25 05	
140	RC I	35 34	
	X≠0?	31 61	
	GTO 5	22 05	
	1	01	
	STO C	33 13	
	RTN	35 22	Z = (S+1)/(S−1)
	*LBL 5	31 25 05	
	RCL D	34 14	
	−	51	
	1	01	
150	−	51	
	RCL C	34 13	
	X	71	
	STO C	33 13	
	RC I	35 34	
	N!	35 81	
	÷	81	
	RTN	35 22	
	*LBL 6	31 25 06	
	RCL D	34 14	
160	X⇆I	35 24	
	STO D	33 14	
	R↓	35 53	
	RTN	35 22	
	*LBL D	31 25 14	
	RCL B	34 12	
	STO E	33 15	
	P⇆S	31 42	
	*LBL d	32 25 14	

STEP	KEY ENTRY	KEY CODE	COMMENTS
	9	09	
170	RCL E	34 15	
	X≤Y?	32 71	
	GTO d	22 31 14	
	W/DATA	31 41	
	GTO B	22 12	
	*LBL d	32 25 14	
	STO B	33 12	
	ST I	35 33	
	*LBL 9	31 25 09	Restore & Save
	RCL (I)	34 24	
180	P⇆S	31 42	
	STO (I)	33 24	
	P⇆S	31 42	
	DSZ	31 33	
	GTO 9	22 09	
	RCL 0	34 00	
	P⇆S	31 42	
	STO 0	33 00	
	GTO B	22 12	
	*LBL e	32 25 15	
190	CF3	35 61 03	
	0	00	
	ST I	35 33	
	*LBL 7	31 25 07	
	PAUSE	35 72	
	F3?	35 71 03	
	GTO e	22 31 15	
	GTO 7	22 07	Read-in
	*LBL e	32 25 15	
	STO (I)	33 24	
200	RC I	35 34	
	STO E	33 15	
	ISZ	31 34	
	RC I	35 34	
	GTO 7	22 07	
	*LBL E	31 25 15	
	SPACE	35 84	
	SCI	32 23	
	DSP 5	23 05	
	0	00	
210	ST I	35 33	
	*LBL 8	31 25 08	
	RCL (I)	34 24	
	PRINT X	31 84	Printout
	ISZ	31 34	
	RCL E	34 15	
	RC I	35 34	
	X≤Y?	32 71	
	GTO 8	22 08	
	SPACE	35 84	
220	*LBL B	31 25 12	
	CLX	44	
	FIX	31 23	Abort
	DSP 0	23 00	
	R/S	84	

LABELS

A ROUTH	B ABORT	C S←S+X	D RESTORE	E WRITE
a x	b x	c Z = (S+1)/(S−1)	d SAVE	e READ
0 x	1 x	2 x	3 x	4 x
5 x	6 x	7 x	8 x	9 x

FLAGS

0	
1	
2	Z SUB.
3	DATA ENTRY

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	0

Program Description I

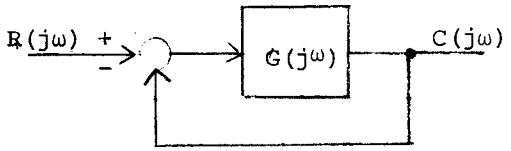
Program Title CONVERT FREQUENCY RESPONSE, OPEN LOOP, CLOSED LOOP

Contributor's Name Hewlett-Packard Company

Address 1000 N.E. Circle Boulevard

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables For a linear, unity feedback control system this program converts open loop frequency response data $\angle G(j\omega)$ (or $\log|G(j\omega)|$ or $20\log|G(j\omega)|$) to closed loop data $\angle\frac{C}{R}(j\omega)$ and $|\frac{C}{R}(j\omega)|$ (or $\log|\frac{C}{R}(j\omega)|$ or or $20\log -(j\omega)|$)



where $$\frac{C}{R}(j\omega) = \frac{G(j\omega)}{1+G(j\omega)}$$

This program also converts from closed loop data

$\angle\frac{C}{R}(j\omega)$ and $|\frac{C}{R}(j\omega)|$

$\angle G(j\omega)$ and $|G(j\omega)|$.

The relationship used is: $$g(j\omega) = \frac{\frac{C}{R}(j\omega)}{1-\frac{C}{R}(j\omega)}$$

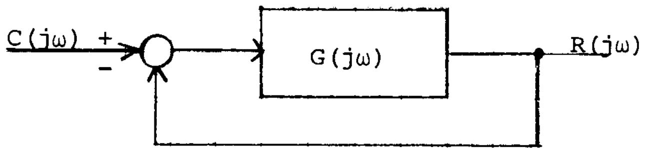
Operating Limits and Warnings

A. When the input phase angle cosine ($\angle\frac{C}{R}(j\omega)$ or $\angle G(j\omega)$) is zero (e.g. $\angle\frac{C}{R}(j\omega) = -90$) the conversion is in inaccurate beyond the 6the decimal place.

B. When input is to be $|G(j\omega)|$ or $|\frac{C}{R}(j\omega)|$ label C is used and $|\frac{C}{R}(j\omega)|$ or $|G(j\omega)|$ is calculated. Similarly when the input is $\log|G(j\omega)|$ or $\log|\frac{C}{R}(j\omega)|$ then $\log|\frac{C}{R}(j\omega)|$ or $\log|G(j\omega)|$. Similarly when input is in decibels the result is decibels.

Program Description II

Sketch(es)



Systems having feedback elements can be converted to an equivalent unity feedback system. See the reference for methods of determining equivalent unity feedback systems.

Sample Problem(s) For the system $G(j\omega) = \frac{4}{j\omega(1 + .25j\omega)(1 + .0625j\omega)}$

For ω=.1, 1 and 10 rad/sec $\angle G(j\omega)$ and $|G(j\omega)|$ are:

ω rad/sec	$\angle G(j\omega)$ degrees	$\lvert G(j\omega)\rvert$
.1	- 91.79	39.99
1	-107.61	3.87
10	-190.20	.13

Determine closed loop frequency response for ω=.1, 1, 10 rad/sec

Solution(s) For each frequency

ω	$\angle \frac{C}{R}(j\omega)$ degrees	$\lvert \frac{C}{R}(j\omega)\rvert$
.1	- 1.43	1.00
1	- 14.96	1.05
10	-191.71	.15

Reference(s) Raven, F.H., Automatic Control Engineering, McGraw-Hill, New York.1968. This program is a translation of the HP-65 Users' Library Program #00892A submitted by Eugene Bahniuk.

User Instructions

FREQUENCY RESPONSE CONVERSION

Open to Close	Closed to Open	Magn.	Log Magn.	DB

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter Program				
2	To convert from open loop response to closed loop response		A		0.00
	or				
	To convert from closed loop response to open loop response		B		0.00
3	Enter open loop phase $\angle G(j\omega)$	$\angle G(j\omega)$ degrees	R/S		1.00
	or				
	Enter closed loop phase $\angle \frac{C}{R}$	$\angle \frac{C}{R}(j\omega)$ degrees	R/S		1.00
4	Enter open loop magnitude	$\lvert G(j\omega)\rvert$	C		$\lvert \frac{C}{R}(j\omega)\rvert$
	or		RCL	2	$\angle \frac{C}{R}(j\omega)$
	Enter open loop log magnitude	$\log\lvert G(j\omega)\rvert$	D		$\log\lvert \frac{C}{R}(j\omega)\rvert$
	or		RCL	2	$\angle \frac{C}{R}(j\omega)$
	Enter open loop decibels	$20\log G(j\omega)$	E		$20\log\lvert \frac{C}{R}(j\omega)\rvert$
	or		RCL	2	$\angle\ (j\omega)$
	Enter closed loop magnitude	$\lvert \frac{C}{R}(j\omega)\rvert$	C		$\lvert G(j\omega)\rvert$
	or		RCL	2	$\angle G(j\omega)$
	Enter closed loop log magnitude	$\log\lvert \frac{C}{R}(j\omega)\rvert$	D		$\log\lvert G(j\omega)\rvert$
	or		RCL	2	$\angle G(j\omega)$
	Enter closed loop decibels	$20\log\lvert \frac{C}{R}(j\omega)\rvert$	E		$20\log\lvert G(j\omega)\rvert$
			RCL	2	$\angle G(j\omega)$
	For a new case go to step 2				

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	Ind. that conv. from open to close loop is to be performed
002	0	00	
003	STO6	35 06	
004	*LBL5	21 05	Enter phase
005	0	00	
006	R/S	51	
007	STO4	35 04	
008	RCL6	36 06	These steps determ. if vector add. or vecotr sub. is performed
009	-	-45	
010	1	01	
011	R/S	51	
012	*LBLB	21 12	For closed to open loop conv. Note: Vector sub. occurs by reversing vector direction then add resultin vector
013	1	01	
014	8	08	
015	0	00	
016	STO6	35 06	
017	GTO5	22 05	
018	*LBLC	21 13	
019	X⇄Y	-41	
020	R↓	-31	
021	STO5	35 05	
022	→R	44	Steps 22 through 34 perform the complex algebra
023	1	01	
024	+	-55	
025	→P	34	
026	RCL5	36 05	
027	X⇄Y	-41	
028	÷	-24	
029	STO1	35 01	
030	X⇄Y	-41	
031	CHS	-22	
032	RCL4	36 04	
033	+	-55	
034	STO2	35 02	
035	X⇄Y	-41	
036	F1?	16 23 01	
037	GTO1	22 01	
038	F0?	16 23 00	
039	GTO2	22 02	
040	R/S	51	
041	*LBLD	21 14	Magnitudes are logarithmic
042	10^x	16 33	
043	SF1	16 21 01	
044	GTOC	22 13	
045	*LBL1	21 01	
046	CF1	16 22 01	
047	LOG	16 32	
048	STO1	35 01	
049	R/S	51	
050	*LBLE	21 15	Indicates magnitudes are decibels
051	2	02	
052	0	00	
053	÷	-24	
054	10^x	16 33	
055	SF0	16 21 00	
056	GTOC	22 13	
057	*LBL2	21 02	
058	CF0	16 22 00	
059	LOG	16 32	
060	2	02	
061	0	00	
062	×	-35	
063	STO1	35 01	
064	R/S	51	
070			
080			
090			
100			
110			

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	2

REGISTERS

0	1	2	3	4	5	6	7	8	9
	computed magnitude	computed phase		entered phase	Ent.magn |G(jω)| or |C/R|	0 180			

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Program Description I

Program Title AID TO ROOT LOCUS PLOTS I - REAL POLES

Contributor's Name Hewlett-Packard Company

Address 1000 N.E. Circle Boulevard

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables Given the forward transfer function of unity gain feedback system

$$KG(s) = \frac{K(s+z_1)(s+z_2)}{s(s+p_1)(s+p_2)(s+p_3)(s+p_4)}$$

where $s = \sigma+i\omega$ is the complex frequency variable and z_1, z_2, p_1, p_2, p_3 and p_4 are real numbers, the program helps in finding the roots of $1 + KG(s) = 0$, which determine the poles of the closed-loop system. It follows that at any point in the s-plane, which is a root of the above equation for some value of K, $G(\sigma+i\omega) = \frac{1}{K} \angle 180°$.

Since the rules for approximate construction of root locus plots are well-known [1,2], this program can be used to obtain the exact location of the roots in certain regions of the s-plane. The user would select a value of σ, say σ_1 and assume a trial value for ω, say ω_1. The program then determines $G^{-1}(\sigma_1+i\omega_1) = Ke^{i\phi}$, and ϕ is displayed. If ϕ is not equal to 180°, a new trial value of $\omega = \omega_2$ is obtained. The process is repeated until ϕ is as closed to 180° as desired. The equation for searching the correct value of ω is

$$\omega_2 = \omega_1\left(4 - \frac{\phi}{60}\right),$$ where ϕ is in degrees.

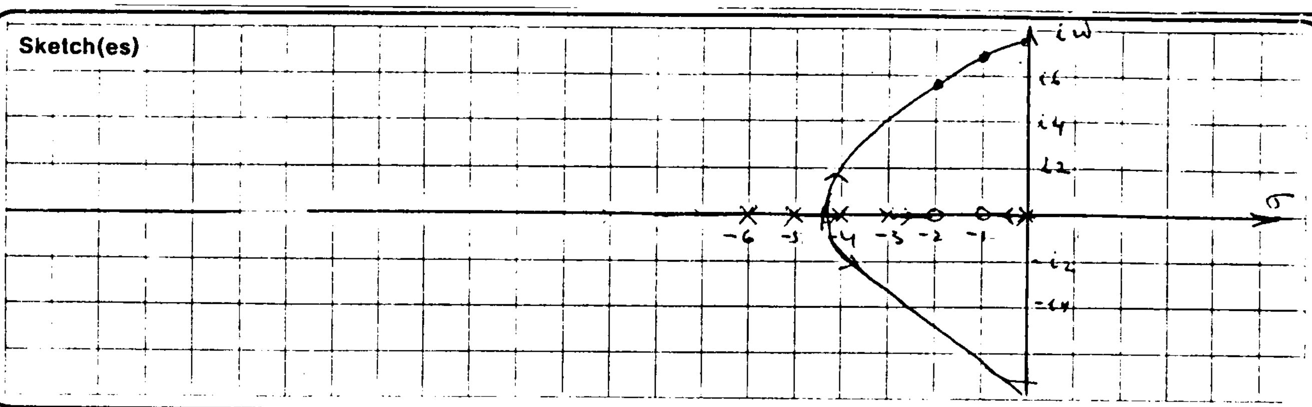
The convergence may be slow when ω approaches zero; in this case the user may often extrapolate mentally to accelerate the convergence. Normally 4 to 8 iterations are sufficient.

The value of the gain constant K required for this location of the root is obtained from y-register.

Operating Limits and Warnings The search equation is based on the assumption that ω_1 is greater than zero. This is no limitation since the root locus is always symmetrical about the real axis of the s-plane.

Program Description II

Sketch(es)



Sample Problem(s) $KG(s) = \frac{K(s+1)(s+2)}{s(s+3)(s+4)(s+5)(s+6)}$

It is desired to obtain the complex roots for σ = 0, σ = -1, and σ = -2.5

Solution(s) i) For σ = 0, starting with ω = 5, after 4 iterations ϕ = 180.01, for ω = 8.545, and K = 999.51

ii) For σ = -1, starting ω=6, after 4 iterations, ϕ = 179.99 for ω = 6.823 and K = 519.61

iii) For σ = -2.5, starting ω = 4, after 5 iterations ϕ = 180.01, for ω = 4.35 and K = 140.52.

Reference(s)

(1) D'Azzo, J.J., Honpis, C.H. "Linear Control System Analysis and Design", McGraw-Hill Book Co. 3rd Edition. 1975. pp.202-242.

(2) Evans, W.R. "Control-System Dynamics", McGraw-Hill Book Co. 1954.

This program is a translation of the HP-65 Users' Library Program #04561A submitted by Naresh K. Sinha.

User Instructions

1 AID TO ROOT LOCUS PLOTS I 2

zeroes and poles | $\sigma_1 \uparrow \omega_1$ | $\rightarrow \omega_2$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter Program				
2		z_1	↑		
3		z_2	A		z_1
4		p_1	↑		
5		p_2	↑		
6		p_3	↑		
7		p_4	R/S		p_1
8		σ_1	↑		
9		ω_1	B		ϕ
10	If $\phi \neq 180°$,		C		ω_2
11	Repeat steps 9 and 10 until $\phi = 180$				$\phi = 180$
12	To obtain K			x⇄y	K
13	To obtain ω at the root		RCL	8	ω_{root}
	For a different value of σ_1, start from step 8.				

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	
002	STO2	35 02	z_2
003	X⇄Y	-41	
004	STO1	35 01	z_1
005	R/S	51	
006	STO6	35 06	p_4
007	R↓	-31	
008	STO5	35 05	p_3
009	R↓	-31	
010	STO4	35 04	p_2
011	R↓	-31	
012	STO3	35 03	p_1
013	RTN	24	
014	*LBLB	21 12	
015	STO8	35 08	ω_1
016	X⇄Y	-41	
017	STO7	35 07	σ_1
018	→P	34	
019	RCL6	36 06	
020	GSBE	23 15	
021	RCL5	36 05	
022	GSBE	23 15	
023	RCL4	36 04	
024	GSBE	23 15	
025	RCL3	36 03	
026	GSBE	23 15	
027	RCL2	36 02	
028	GSBD	23 14	
029	RCL1	36 01	
030	GSBD	23 14	
031	X⇄Y	-41	
032	RTN	24	Display ϕ
033	*LBLC	21 13	
034	6	06	
035	0	00	
036	÷	-24	
037	4	04	
038	-	-45	
039	CHS	-22	
040	RCL8	36 08	
041	×	-35	
042	STO8	35 08	
043	RCL7	36 07	
044	RCL8	36 08	Display ω_2
045	RTN	24	
046	*LBLE	21 15	
047	RCL7	36 07	
048	+	-55	
049	RCL8	36 08	
050	X⇄Y	-41	
051	→P	34	
052	X⇄Y	-41	
053	R↓	-31	
054	×	-35	
055	R↓	-31	
056	+	-55	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	R↑	16-31	
058	RTN	24	
059	*LBLD	21 14	
060	RCL7	36 07	
061	+	-55	
062	RCL8	36 08	
063	X⇄Y	-41	
064	→P	34	
065	X⇄Y	-41	
066	R↓	-31	
067	÷	-24	
068	R↓	-31	
069	-	-45	
070	CHS	-22	
071	R↑	16-31	
072	RTN	24	
073	RCL8	36 08	
074	R/S	51	
080			
090			
100			
110			

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n 2	

REGISTERS

0	1	2	3	4	5	6	7	8	9
	z_1	z_2	p_1	p_2	p_3	p_4	σ_1	ω_1	Used

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Program Description I

Program Title AID TO ROOT LOCUS PLOTS II - COMPLEX POLES

Contributor's Name Hewlett-Packard Company

Address 1000 N.E. Circle Boulevard

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables Given the forward transfer function of a unity feedback system

$$KG(s) = \frac{K(s+z_1)(s+z_2)}{s(s+p_1)(s+p_2)(s+\alpha+i\beta)(s+\alpha-i\beta)}$$

where $s = \sigma + i\omega$ is the complex frequency variable, and z_1, z_2, p_1, p_2, and are real numbers, the program helps in finding the roots of $1 + KG(s) = 0$, which determine the poles of the closed-loop system. It follows that at any point in the s-plane, which is a root of the above equation for some value of K, the argument of G(s) is equal to 180 degrees.

Since the rules for the construction of the approximate root locus plot are well known, this program can be used to obtain the exact location of the roots in critical regions of the s-plane. The user would select a value of σ, say σ_1 and assume a trail value for ω, say ω_1. The program then determines the modules M, and the argument, ϕ of $G^{-1}(s)$ at this point, and the argument ϕ is displayed. If $\phi \neq 180$, a new trial value of = 2 is obtained using the equation

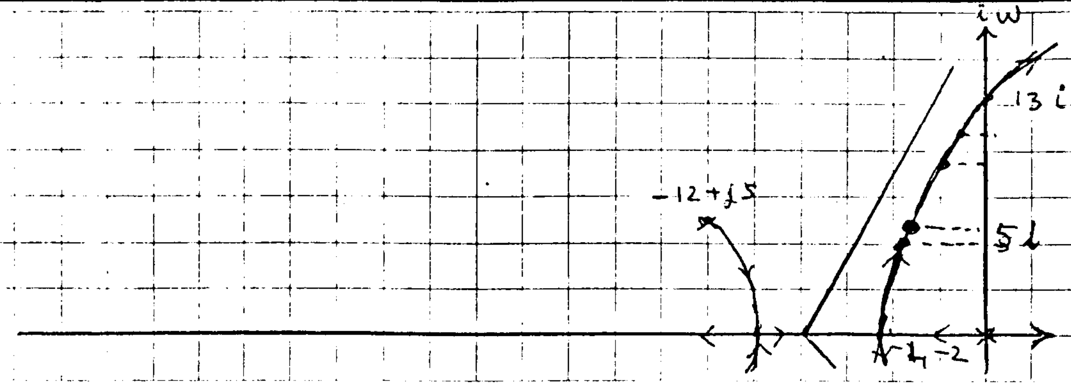
$$\omega_2 = \omega_1(4-\phi/180)$$

The process is repeated until ϕ is as close to 180 as desired. The convergence may be slow when ω approaches zero. In this case, the user may often extrapolate mentally to accelerate convergence. Normally 4 to 8 iterations are sufficient.

Operating Limits and Warnings The search equation is based on the assumption that ω is positive. This is no limitation since the root-locus plot is always symmetrical about the real-axis of the s-plane.

Program Description II

Sketch(es)



Sample Problem(s) Consider

$$KG(s) = \frac{K}{s(s+12+5i)(s+12-5i)} = \frac{K(s+1)(s+2)}{s(s+1)(s+2)(s+12+5i)(s+12-5i)}$$

The approximate sketch of the root locus is easily obtained following standard rules (see referencs 1 or 2). It is shown above.

It is desired to obtain the exact locations of the roots for $\sigma = -1$, -2 and -4.

Solution(s) (1) For $\sigma = -1$, starting with $\omega = 12$, after 3 iterations the root is located at $\omega = 11.14$ with $\phi = 180.00$ and $K = 2750$

(2) For $\sigma = -2$, starting with $\omega = 10$, after 3 iterations the root is located at $\omega = 9.22$ with $\phi = 180.01$ and $K = 1780.7$

(3) For $\sigma = -4$, starting with $\omega = 5.5$, after 8 iterations the root is located at $\omega = 5.00$ with $\phi = 180.01$ and $K = 656.3$

Reference(s)
1. Evans, W.R. "Control Systems Dynamics". McGraw-Hill Book Co., 1954.
2. D'Azzo, J.J. and Houpis, C.H., "Linear Control System Analysis and Design". McGraw-Hill Book Co. 3rd Edition. 1975.

This program is a translation of the HP-65 Users' Library Program #04562A submitted by Naresh K. Sinha.

User Instructions

1 AID TO ROOT LOCUS PLOTS II 2

zeroes and poles	$\sigma \uparrow \omega$	$\rightarrow \omega_2$		

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2		z_1	↑		
3		z_2	A		z_1
4		p_1	↑		
5		p_2	↑		
6		α	↑		
7		β	R/S		p_1
8		σ	↑		
9		ω	B		ϕ
10	If $\phi \neq 180$		C		ω_2
11	Repeat steps 9 and 10 until $\phi = 180$				$\phi = 180$
12	To obtain K		g	x⇄y	K
13	To obtain ω at the root		RCL	8	ω_{root}
	For a different value of σ_1, start from step 8				

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	
002	STO2	35 02	z_2
003	X⇄Y	-41	
004	STO1	35 01	z_1
005	R/S	51	
006	STO6	35 06	β
007	R↓	-31	
008	STO5	35 05	α
009	R↓	-31	
010	STO4	35 04	p_2
011	R↓	-31	
012	STO3	35 03	p_1
013	RTN	24	
014	*LBLB	21 12	
015	STO8	35 08	ω_1
016	X⇄Y	-41	
017	STO7	35 07	α_1
018	RCL5	36 05	
019	+	-55	
020	X⇄Y	-41	
021	RCL6	36 06	
022	+	-55	
023	RCL8	36 08	
024	RCL6	36 06	
025	-	-45	
026	R↑	16-31	
027	→P	34	
028	R↓	-31	
029	R↓	-31	
030	GSBE	23 15	
031	RCL4	36 04	
032	RCL7	36 07	
033	+	-55	
034	RCL8	36 08	
035	GSBE	23 15	
036	RCL3	36 03	
037	RCL7	36 07	
038	+	-55	
039	RCL8	36 08	
040	GSBE	23 15	
041	RCL7	36 07	
042	RCL8	36 08	
043	GSBE	23 15	
044	RCL2	36 02	
045	GSBD	23 14	
046	RCL1	36 01	
047	GSBD	23 14	
048	X⇄Y	-41	
049	RTN	24	Display ϕ
050	*LBLC	21 13	
051	6	06	
052	0	00	
053	÷	-24	
054	4	04	
055	-	-45	
056	CHS	-22	
057	RCL8	36 08	
058	×	-35	
059	STO8	35 08	
060	RCL7	36 07	
061	RCL8	36 08	
062	RTN	24	Display ω_2
063	*LBLD	21 14	
064	RCL7	36 07	
065	+	-55	
066	RCL8	36 08	
067	X⇄Y	-41	
068	→P	34	
069	X⇄Y	-41	
070	R↓	-31	
071	÷	-24	
072	R↓	-31	
073	-	-45	
074	CHS	-22	
075	R↑	16-31	
076	RTN	24	
077	*LBLE	21 15	
078	X⇄Y	-41	
079	→P	34	
080	X⇄Y	-41	
081	R↓	-31	
082	×	-35	
083	R↓	-31	
084	+	-55	
085	R↑	16-31	
086	RTN	24	
087	R/S	51	
090			
100			
110			

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	2

REGISTERS

0	1	2	3	4	5	6	7	8	9
	z_1	z_2	p_1	p_2	α	β	σ_1	ω_1	Used
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Program Description I

Program Title Classical Control Gains

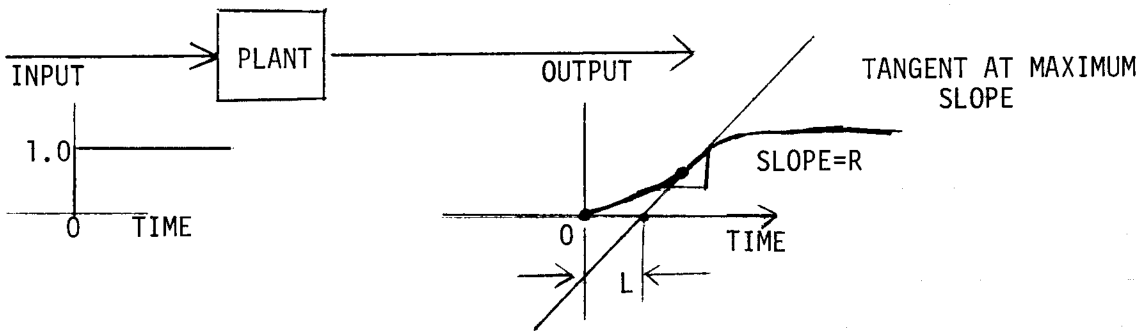
Contributor's Name Hewlett-Packard

Address 1000 N.E. Circle Blvd.

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables This program computes the Ziegler-Nichols recommended settings for P, PI, and PID control. Data is required from one of two tests: the general control form is $G_c = k_c[1 + \frac{1}{T_i s} + T_D s]$

A] OPEN LOOP TEST - input step function, measure response, draw tangent at point of maximum response slope, scale L & R.



R= maximum slope

L= time intercept of maximum slopeline

Then for P control, $k_c = 1/RL$; PI control, $k_c = .9/RL$, $T_i = 3.3L$;

for PID control, $k_c = 1.2/RL$, $T_i = 2L$, $T_0 = L/2$

Operating Limits and Warnings

Note that plant must be greater than first order for open loop test

(s is Laplace operator)

Program Description I

Program Title Classical Control Gains

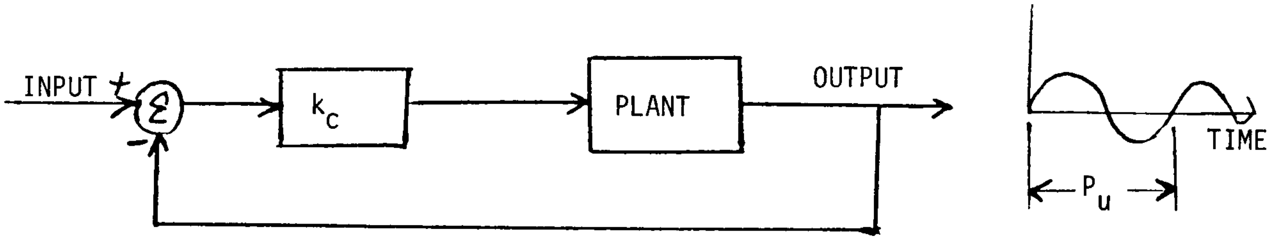
Contributor's Name Hewlett-Packard

Address 1000 N.E. Circle Blvd.

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables

B CLOSED LOOP TEST - Increase k_c until plant is near instability (oscillating output). Let the magnitude of k_c at that point be called k_u, and the period of oscillation be called P_u.



Then for P control, let $k_c = .5k_u$

PI control, let $k_c = .45k_u$, $T_i = 0.83P_u$

PID control, let $k_c = 0.6k_u$, $T_i = .5P_u$, $T_0 = P_u/8$

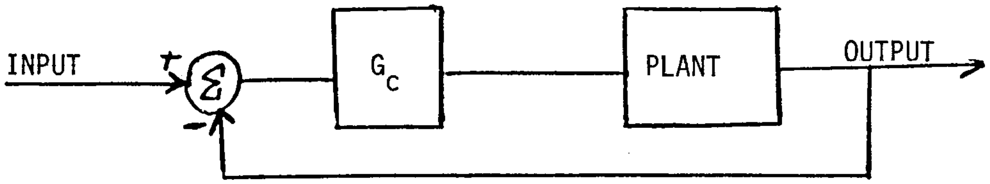
General control form is = $G_c = k_c[1 + \frac{1}{T_i s} + T_0 s]$

Operating Limits and Warnings

Plant must be greater than second order for closed loop test.

Program Description II

Sketch(es)



Final form of controlled plant

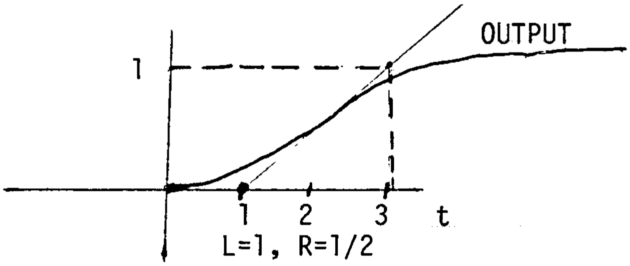
P control→$G_c = k_c$; PI control→$G_c = kc[1 + \frac{1}{T_i s}]$

PID control→$G_c = k_c[1 + 1/T_i s + T_0 s]$

Sample Problem(s)

1. For the following open loop test data, compute the control coefficients for:
   a.) P control
   b.) PI control
   c.) PID control

   (unit step input)



2. During a closed loop P control test, the plant output became oscillatory with $k_c = k_u = 10$, the period of oscillations was 50 sec. Compute coefficients for:
   a.) p control
   b.) PI control
   c.) PID control

Solution(s)

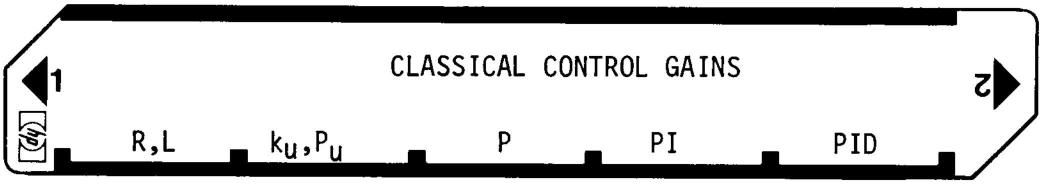
1. L=1, R=1/2
   a.) $k_c = 2$
   b.) $k_c = 1.8$, $T_i = 3.3$
   c.) $k_c = 2.4$, $T_i = 2.0$, $T_0 = 0.5$
2. $k_u = 10$, $P_u = 50$
   a.) $k_c = 5$
   b.) $k_c = 4.5$, $T_i = 41.5$
   c.) $k_c = 6$, $T_i = 25$, $T_0 = 6.25$

Reference(s)

OGATA; Modern Control Engineering, Prentice-Hall.

This program is a translation of the HP-65 Users' Library program #04463A submitted by Randy A. Coverstone.

User Instructions



STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1.	Enter program			
2.	For 0pen Loop Test Data:			
	INPUT R	R	↑	R
	THEN L	L	A	0.00
2.	For Closed Loop Test Data:			
	INPUT k_u	k_u	↑	k_u
	THEN P_u	P_u	B	0.00
3.	For P Control, calculate k_c		C	k_c
3.	For PI Control, calculate k_c		D	k_c
	THEN T_i		R/S	T_i
3.	For PID Control, calculate k_c		E	k_c
	THEN T_i		R/S	T_i
	THEN T_0		R/S	T_0
4.	For new case go to step 2			

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	Open loop test data
002	STO2	35 02	
003	×	-35	
004	1/X	52	
005	STO1	35 01	
006	STO3	35 03	
007	.	-62	
008	9	09	
009	×	-35	
010	STO4	35 04	
011	RCL1	36 01	
012	1	01	
013	.	-62	
014	2	02	
015	×	-35	
016	STO5	35 05	
017	RCL2	36 02	
018	2	02	
019	×	-35	
020	STO7	35 07	
021	1	01	
022	.	-62	
023	6	06	
024	5	05	
025	×	-35	
026	STO6	35 06	
027	RCL2	36 02	
028	2	02	
029	÷	-24	
030	STO8	35 08	
031	CLX	-51	
032	RTN	24	
033	*LBLB	21 12	Closed loop test data
034	STO2	35 02	
035	R↓	-31	
036	STO1	35 01	
037	2	02	
038	÷	-24	
039	STO3	35 03	
040	.	-62	
041	9	09	
042	×	-35	
043	STO4	35 04	
044	RCL1	36 01	
045	.	-62	
046	6	06	
047	×	-35	
048	STO5	35 05	
049	RCL2	36 02	
050	2	02	
051	÷	-24	
052	STO7	35 07	
053	4	04	
054	÷	-24	
055	STO8	35 08	
056	RCL2	36 02	
057	.	-62	
058	8	08	
059	3	03	
060	×	-35	
061	STO6	35 06	
062	CLX	-51	
063	RTN	24	
064	*LBLC	21 13	P control
065	RCL3	36 03	
066	RTN	24	
067	*LBLD	21 14	PI control
068	RCL4	36 04	
069	R/S	51	
070	RCL6	36 06	
071	RTN	24	
072	*LBLE	21 15	PID control
073	RCL5	36 05	
074	R/S	51	
075	RCL7	36 07	
076	R/S	51	
077	RCL8	36 08	
078	RTN	24	
079	R/S	51	
090			
100			
110			

SET STATUS

FLAGS	ON	OFF
0	☐	☒
1	☐	☒
2	☐	☒
3	☐	☒

TRIG	
DEG	☒
GRAD	☐
RAD	☐

DISP	
FIX	☒
SCI	☐
ENG	☐
n	2

REGISTERS

0	1	2	3	4	5	6	7	8	9
	A-T/RL B-k_c	A-L B-P_u	P-k_c	PI-k_c	PID-k_c	PI-T_i	PID-T_i	PID-T_0	
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Program Description I

Program Title FIRST ORDER REGULATOR

Contributor's Name Hewlett-Packard Company

Address 1000 N.E. Circle Boulevard

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables Given a system;

$$\dot{x} = \frac{dx}{dt} = ax + bu$$

where x = system state

u = system control

a,b constant.

This program solves the regulator problem i.e. determines the optimal feedback gain to minimize the following performance index:

$$\text{performance index} = J = 1/2 \int_0^\infty (qx^2+ru^2)dt$$

the solution is:

$u = -cx$, where $c = \frac{b}{r} S$ and S is the positive solution to the Riccati equation:

$$0 = -2as + \frac{s^2b^2}{r} - q$$

Then:

$$\dot{x} = \bar{a}x \quad \text{where } \bar{a} = a-bc$$

$$\text{and } x = x_0 e^{-\frac{t}{\tau}} \text{ where } \tau = -\frac{1}{\bar{a}}$$

Operating Limits and Warnings

$q \geqslant 0$

$r > 0$

$b \neq 0$

Program Description II

Sketch(es)

Sample Problem(s) $\dot{x} = ax + bu$, $J = 1/2 \int_0^\infty [(\frac{x}{x_{max}})^2 + (\frac{u}{u_{max}})^2]\,dt$

1. $a = -1$, $b = 1$, $q = (\frac{1}{x_{max}})^2 = 0$, $r = (\frac{1}{u_{max}})^2 = 1$
2. $a = 1$, $b = 1$, $q = 0$, $r = 1$
3. $a = 1$, $b = 1$, $q = 1$, $r = 1$
4. $a = 1$, $b = 2$, $q = 3$, $r = 4$

Solution(s)

1. $c = 0$, $s = 0$, $\bar{a} = -1$, $\tau = 1$
2. $c = 2$, $s = 2$, $\bar{a} = -1$, $\tau = 1$
3. $c = 2.41$, $s = 2.41$, $\bar{a} = -1.41$, $\tau = 0.707$
4. $c = 1.5$, $s = 3.0$, $\bar{a} = -2$, $\tau = 1/2$

Reference(s)

Shultz and Melsa, State Functions and Linear Control Systems, McGraw-Hill, 1967.

This program is a translation of the HP-65 Users' Library Program #04464A submitted by Randy A. Coverstone.

User Instructions

FIRST ORDER REGULATOR

a,b	q,r	c,s	a	τ

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input a	a	↑		a
	then b	b	A		0.00
3	Input q	q	↑		q
	then r	r	B		0.00
4	Calculate c		C		C
	(optional) then s		R/S		S
5	(Optional) Calculate $\bar{a}$		D		$\bar{a}$
6	(Optional) Calculate $\tau = -1/\bar{a}$		E		τ
7	To change q and r go to step 3				
8	For new case go to step 2				

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	
002	STO2	35 02	b →R2
003	R↓	-31	
004	STO1	35 01	q→ R1
005	CLX	-51	
006	RTN	24	
007	*LBLB	21 12	
008	STO4	35 04	r→ R4
009	R↓	-31	
010	STO3	35 03	q→ R3
011	CLX	-51	
012	RTN	24	
013	*LBLC	21 13	
014	RCL1	36 01	
015	RCL2	36 02	
016	÷	-24	
017	X²	53	
018	RCL3	36 03	
019	RCL4	36 04	
020	÷	-24	
021	+	-55	
022	√X	54	
023	RCL1	36 01	
024	RCL2	36 02	
025	÷	-24	
026	+	-55	Calculate C
027	R/S	51	
028	RCL4	36 04	
029	X	-35	
030	RCL2	36 02	
031	÷	-24	
032	RTN	24	C
033	*LBLD	21 14	
034	RCL1	36 01	
035	X²	53	
036	RCL2	36 02	
037	X²	53	
038	RCL3	36 03	
039	X	-35	
040	RCL4	36 04	
041	÷	-24	
042	+	-55	
043	√X	54	
044	CHS	-22	
045	RTN	24	S
046	*LBLE	21 15	
047	GSBD	23 14	
048	1/X	52	
049	CHS	-22	
050	RTN	24	$\bar{a}$
051	R/S	51	

STEP	KEY ENTRY	KEY CODE	COMMENTS
060			
070			
080			
090			
100			
110			

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n 2	

REGISTERS

0	1	2	3	4	5	6	7	8	9
	a	b	q	r					

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Program Description I

Program Title SECOND ORDER REGULATOR

Contributor's Name Hewlett-Packard Company

Address 1000 N.E. Circle Boulevard

City Corvallis **State** Oregon **Zip Code** 97330

Program Description, Equations, Variables Given a system and a quadratic performance index as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} u$$

$$J = 1/2 \int_0^\infty \left\{ [x_1 \quad x_2] \begin{bmatrix} q_{11} & q_{12} \\ q_{12} & q_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + u^2 r \right\} dt$$

where: x_1, x_2 are the system states
u is the control
J is the performance index to be minimized.

The optimal control is given by:

$$u = -c_1, x_1 - c_2 x_2 \qquad \text{and } [\mathring{x}] = [\bar{A}][x] \qquad [A] = [A] - [\mathring{b}][c_1 - c_2]$$

where: $c_1 = \frac{1}{b}(c_1^* + a_{11} c_2^*) \qquad c_2 = \frac{1}{b}(a_{12} c_2^*)$

$$c_1^* = a_1 + \sqrt{a_1^2 + q_1 \frac{b^2}{r}} \qquad c_2^* = a_2 + \sqrt{a_2^2 + 2c_1^* + q_3 \frac{b^2}{r}}$$

$$a_1 = a_{12} a_{21} - a_{11} a_{22} \qquad q_1 = q_{11} - 2 \frac{q_{12} a_{11}}{a_{12}} + \frac{q_{22} a_{11}^2}{a_{12}^2}$$

$$a_2 = a_{11} + a_{22} \qquad q_3 = q_{22}$$

Operating Limits and Warnings

$$q_{11}, q_{12}, q_{13} \geq 0 \quad ; \quad q_{11} + q_{12} + q_{13} \neq 0$$

$$r > 0$$

Program Description II

Sketch(es)

Sample Problem(s) $\ddot{y} + \theta\dot{y} + \phi = u$ · second order system

let $x_1 = y$

$x_2 = \dot{y}$

so $\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\ -\phi & -\theta\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}0\\ 1\end{bmatrix} u$ suppose $\phi = 2$, $\theta = 3$

Find the optimal control that minimizes:

1. $J = 1/2 \int_0^\infty (x_1^2+x_2^2+u^2)dt$, i.e. $q_{11} = 1$, $q_{12} = 0$, $q_{22} = 1$, $r = 1$

2. $J = 1/2 \int_0^\infty (4x_1^2+u^2)dt$, i.e. $q_{11} = 4$, $q_{12} = 0$, $q_{22} = 0$, $r = 1$

3. $J = 1/2 \int_0^\infty u^2dt$ - note that this case violates $q_1+q_2+q_3 \neq 0$

Solution(s) $A = \begin{bmatrix}0 & 1\\ -2 & -3\end{bmatrix}$ $b = 1$ $u = -c_1x_1 - c_2x_2$

1. $Q = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$, $r = 1$ $\rightarrow u = -.236x_1 - .236x_2$

2. $Q = \begin{bmatrix}4 & 0\\ 0 & 0\end{bmatrix}$, $r = 1$ $\rightarrow u = -.828x_1 - .264x_2$

3. $Q = \begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix}$, $r = 1$ $\rightarrow u = 0$

Reference(s) Shultz and Melsa, State Functions and Linear Control Systems, McGraw-Hill, 1967.

This program is a translation of the HP-65 Users' Library Program #04465A submitted by Randy A. Coverstone.

User Instructions

SECOND ORDER REGULATOR

[A] | b | [Q], r | c_1, c_2

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program				
2	Input A matrix: input a_{11}	a_{11}	↑		a_{11}
	then a_{12}	a_{12}	↑		a_{12}
	then a_{21}	a_{21}	↑		a_{21}
	then a_{22}	a_{22}	A		a_{11}
3	Input b	b	B		b
4	Input Q and r: input q_{11}	q_{11}	↑		q_{11}
	then q_{12}	q_{12}	↑		q_{12}
	then q_{22}	q_{22}	↑		q_{22}
	then r	r	C		q_1/r
5	Calculate feedback coefficients		D		c_1
			R/S		c_2
	(Optional)* Calculate [Ā] (closed loop				
	dynamics matrix)		R/S		
	Recall [Ā]		RCL	1	a_{11}
			RCL	2	a_{12}
			RCL	3	a_{21}
			RCL	4	a_{22}
6	To change Q and r go to step 4				
7	For new case go to step 2				
**	DO NOT CALCULATE [Ā] IF STEP #6 IS TO BE EXECUTED, AS [A] REPLACES THE ORIGINAL [A] MATRIX AND STEP 5 MUST OPERATE ON [A], NOT [A]				

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} u$$

$$J = 1/2 \int_0^\infty (q_{11}x_1^2 + 2q_{12}x_1x_2 + q_{22}x_2^2 + ru^2)\,dt$$

$$\text{minimize } J \rightarrow u = -c_1x_1 - c_2x_2$$

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	Store [A]
002	STO4	35 04	
003	R↓	-31	
004	STO3	35 03	
005	R↓	-31	
006	STO2	35 02	
007	R↓	-31	
008	STO1	35 01	
009	R/S	51	
010	*LBLB	21 12	Store b
011	STO5	35 05	
012	RTN	24	
013	*LBLC	21 13	
014	STO7	35 07	
015	÷	-24	
016	STO8	35 08	
017	LSTX	16-63	
018	×	-35	
019	RCL1	36 01	
020	×	-35	
021	RCL2	36 02	
022	÷	-24	
023	X⇄Y	-41	
024	2	02	
025	×	-35	
026	-	-45	
027	RCL1	36 01	
028	×	-35	
029	RCL2	36 02	
030	÷	-24	
031	+	-55	
032	RCL7	36 07	
033	÷	-24	
034	STO7	35 07	
035	RTN	24	
036	*LBLD	21 14	
037	RCL2	36 02	
038	RCL3	36 03	
039	×	-35	
040	RCL1	36 01	
041	RCL4	36 04	
042	×	-35	
043	-	-45	
044	STO6	35 06	
045	RCL7	36 07	
046	√X	54	
047	RCL5	36 05	
048	×	-35	
049	RCL6	36 06	c_1*
050	→P	34	
051	RCL6	36 06	
052	+	-55	
053	STO6	35 06	
054	2	02	
055	×	-35	
056	RCL5	36 05	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	X²	53	c2*
058	RCL8	36 08	
059	×	-35	
060	+	-55	
061	√X	54	
062	RCL1	36 01	
063	RCL4	36 04	
064	+	-55	
065	STO7	35 07	
066	→P	34	
067	RCL7	36 07	
068	+	-55	
069	STO7	35 07	
070	RCL1	36 01	
071	×	-35	
072	RCL6	36 06	
073	+	-55	
074	STO6	35 06	
075	RCL5	36 05	
076	÷	-24	
077	R/S	51	Display c_1
078	RCL7	36 07	
079	RCL2	36 02	
080	×	-35	
081	STO7	35 07	
082	RCL5	36 05	
083	÷	-24	
084	R/S	51	Display c_2
085	RCL2	36 02	
086	RCL3	36 03	
087	RCL6	36 06	
088	-	-45	
089	RCL4	36 04	Compute [A]
090	RCL7	36 07	
091	-	-45	
092	RCL1	36 01	
093	R↓	-31	
094	GTOA	22 11	
095	R/S	51	
100			
110			

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	2

REGISTERS

0	1	2	3	4	5	6	7	8	9
	a_{11}	a_{12}	a_{21}	a_{22}	b	temp	temp	temp	R→P

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

NOTES

NOTES

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