

TR-48®/DES-30 HYBRID SIMULATION OF  
SPACE VEHICLE ATTITUDE CONTROL SYSTEM

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### INTRODUCTION

This study describes the simulation of a non-lifting, 2-degrees-of-freedom space vehicle whose attitude is controlled by positioning jets directed by a digital control system. The simulation is performed on the EAI PACE® TR-48 General Purpose Analog Computer used with the EAI DES-30 Digital Expansion System . . . a general-purpose, low cost, digital logic package designed for operation with desk-top analog computers.

The necessary addition of digital functions to the all analog simulation of flight dynamics in this study makes this problem a true hybrid application, and one normally implemented on large scale hybrid systems such as the EAI HYDAC® 2000 HYbrid Digital-Analog Computing System(1).

The DES-30 System, although capable of operating autonomously for use in digital instruction or design, was designed primarily as an expansion to the TR-48 analog computer to provide basic hybrid capabilities to the small computer facility. It is also readily combined with other general-purpose analog or digital computers to provide extended control functions. As such, it makes available to the analog computer in this problem the logic functions needed to implement this essentially hybrid application.

### EQUATIONS

A non-lifting, 2-degrees-of-freedom space vehicle is described approximately by the following equations:

$$(1) \frac{dP}{dt} = \frac{1}{I_x} (I_{xz}PQ + M_x)$$

$$(2) \frac{dQ}{dt} = \frac{1}{I_y} (-I_{xz}P^2 + M_y)$$

$$(3) P = \frac{d\phi}{dt} \quad Q = \frac{d\theta}{dt}$$

where  $\phi$  is roll angle,  $P$  roll rate,  $\theta$  pitch angle,  $Q$  pitch rate,  $I_x$  moment of inertia about the x axis,  $I_y$  moment of inertia about the y axis,  $I_{xz}$  moment of inertia about the xz plane,  $M_x$  moment acting on the x axis,  $M_y$  moment acting on the y axis. The vehicle is operating outside the atmosphere. It uses peroxide jets for attitude control. The jets are controlled by a control system, part of whose operation can be described approximately by the equations:

$$(4) \epsilon_\phi = (\phi_c - \phi) - K_1P$$

$$(5) \epsilon_\theta = (\theta_c - \theta) - K_2Q$$

where  $\epsilon_\phi$  and  $\epsilon_\theta$  are error signals, indicating the discrepancy between the pilot commands  $\phi_c$  and  $\theta_c$  and the actual attitude  $\phi$ ,  $\theta$ . The terms  $-K_1P$  and  $-K_2Q$  are introduced to provide a velocity correction to the error term, to substitute for natural damping which is absent. That is, the error signals are automatically reduced if the vehicle is proceeding towards the desired direction with a high velocity.

These error signals are applied to the jet control portion of the attitude control system. The operation of the jet control can be described approximately by the curve in Figure 1.

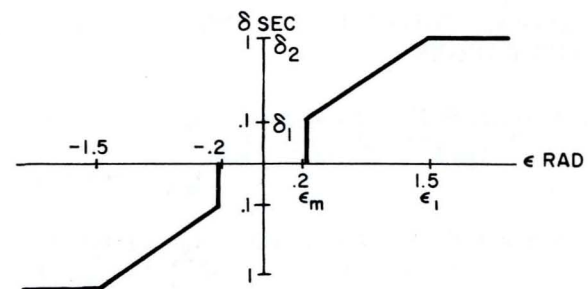


Figure 1: The Operation of the Jet Control System

The jets are operated in on-off fashion, with a fixed amplitude but variable on-off time. The error signals control the ratio of on to off time within a basic cycle of 1 second; that is, the jets are "pulse-width modulated". When the error is below a certain minimum value,  $\epsilon_m$ , the jets are kept off. Between  $\epsilon_m$  and  $\epsilon_p$ , the on time of the jet increases from  $\delta_1$  seconds to  $\delta_2$  seconds, in proportion to the error. If the error exceeds  $\epsilon_1$ , the jets are turned on and left on until the error decreases below  $\epsilon_1$ .

The error is sampled every 1 second<sup>†</sup>, following which the jets are allowed to correct in accordance with Figure 1; then, the remaining error is sampled again, and so forth.

There are 4 pairs of jets as shown in Figure 2. Jets #1 and 6 are

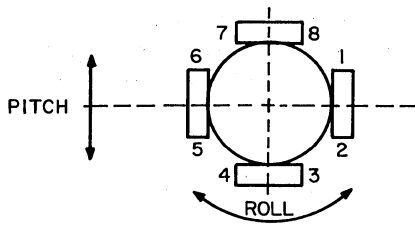


Figure 2: The Attitude Control Jet Pairs

fired to obtain pitching down; 1, 3, 5 and 7 to obtain rolling counterclockwise; etc. While the complete jet selection logic for the 3-degrees-of-freedom case is quite complex, for the purposes of this study it has been reduced to:

To pitch down	fire 1,6 (Pair A)
To pitch up	fire 2,5 (Pair B)
To roll clockwise	fire 3,7 (Pair C)
To roll counterclockwise	fire 4,8 (Pair D)

The vehicle and the control system are to be simulated. The simulation is to run in real time or faster (in fact, as fast as possible).

MAXIMA, CRITICAL QUANTITIES, & PARAMETER RANGES

$$-2 \text{ rad/sec} \leq P \leq 2 \text{ rad/sec} \quad I_x = 2000 \text{ slug-ft}^2$$

$$I_{xz} = 300 \text{ slug-ft}^2$$

$$-2 \text{ rad/sec} \leq Q \leq 2 \text{ rad/sec} \quad I_y = 1800 \text{ slug-ft}^2$$

<sup>†</sup>In the actual system, the error is sampled continuously as long as it is below  $\epsilon_m$ . Many other deviations are included in this study and won't be mentioned, since the principal purpose of the study is tutorial.

$$-2 \text{ rad} \leq \phi \leq 2 \text{ rad}$$

$$-2 \text{ rad} \leq \theta \leq 2 \text{ rad} \quad K_1 = 5.0 \text{ sec}$$

$$K_2 = 2.0 \text{ sec}$$

$$-2 \text{ rad/sec}^2 \leq \dot{P} \leq 2 \text{ rad/sec}^2$$

$$-2 \text{ rad/sec}^2 \leq \dot{Q} \leq 2 \text{ rad/sec}^2 \quad |M_x| = 1000 \text{ ft-lbs}$$

$$|M_y| = 800 \text{ ft-lbs}$$

where  $M_x$   $M_y$  are the moments due to the jet forces ( $F_x = 40 \text{ lbs}$ ,  $F_y = 40 \text{ lbs}$ ) and the effective moment arms ( $l_x = 25 \text{ ft}$ ,  $l_y = 20 \text{ ft}$ ).

METHOD OF SOLUTION

The analog portion is straight forward.

The pulse-width modulation and the jet selection logic are the portions best implemented on the DES-30. The pulse width modulation is generated as in Figure 3.

A saw-tooth voltage of period 1 second is generated. Every time the ramp portion of the saw-tooth wave-shape is started, the absolute value of the error is sampled and held to the end of the basic 1 sec period. This sampled value is compared with the rising ramp. As long as the ramp is below the sampled value of the error, a constant voltage,  $\epsilon^*$ , representing "jet on" is held in the on position; when the ramp exceeds the error, the "jet" is turned off.

The jet selection logic is quite simple and is shown in Figure 4. Signal  $\epsilon^*$ , as discussed above, is ANDed with signals  $\epsilon^+$ ,  $\epsilon^-$  indicating whether the error is in the positive or negative direction; the AND gate signals are then the commands  $C^+$   $C^-$  to the appropriate jet pair. The jets are represented by electronic switches which introduce moments in the form of Figure 3 into equations (1) and (2).

The sawtooth voltage in Figure 3 can be generated by an EMC integrator.

The deadzone indicated in Figure 1 can be obtained in a number of ways. The method used here is shown in Figure 5. The signal at the output of the OR gate is high whenever  $\epsilon > \epsilon_m$  or whenever  $(\epsilon + \epsilon_m) < 0$ , that is,  $\epsilon < -\epsilon_m$ ; these are the conditions describing the deadzone.

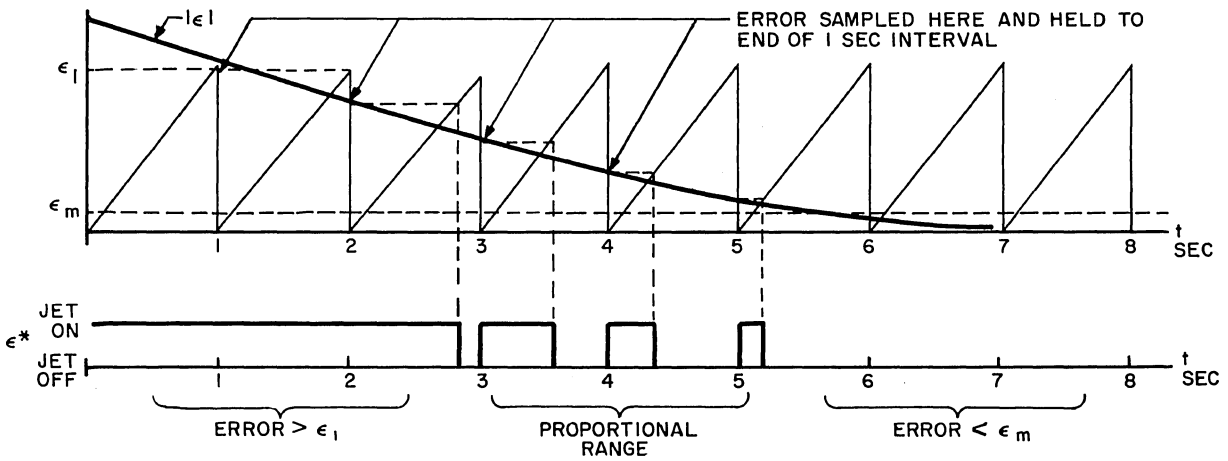


Figure 3: Pulse Width Modulation Scheme

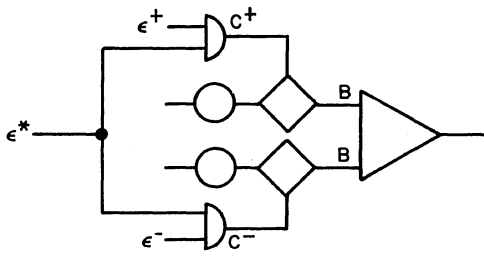


Figure 4: Jet Selection Logic

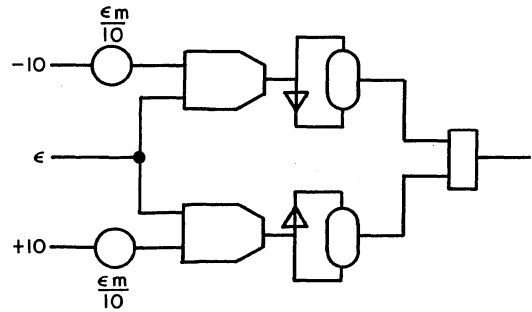


Figure 5: Deadzone Simulation Using Electronic Comparators

SCALING (Normalized Method)

Variable	Approximate Max Value	Scale Factor	Computer Var.
$\dot{P}$	2	.5	$[.5\dot{P}]$
$\dot{Q}$	2	.5	$[.5\dot{Q}]$
P	2	.5	$[.5P]$
Q	2	.5	$[.5Q]$
$P^2$	4	.25	$[.25P^2]$
PQ	4	.25	$[.25PQ]$
$\epsilon_\phi$	2	.5	$[.5\epsilon_\phi]$
$\epsilon_\theta$	2	.5	$[.5\epsilon_\theta]$
$\phi$	2	.5	$[.5\phi]$
$\theta$	2	.5	$[.5\theta]$
$F_i$	40	.02	$[.02F_i]$

The scaled equations are:

$$[.5\dot{P}] = \frac{1}{\left(\frac{I_x}{2000}\right)} \left\{ \left(\frac{I_{xz}}{1000}\right) [.25PQ] + \left(\frac{I_x}{80}\right) [.02F_x] \right\}$$

$$[.5\dot{Q}] = \frac{1}{\left(\frac{I_y}{2000}\right)} \left\{ -\left(\frac{I_{xz}}{1000}\right) [.25P^2] + \left(\frac{I_y}{80}\right) [.02F_y] \right\}$$

$$[.5\epsilon_\phi] = [.5\phi_c] - [.5\phi] - 10 \left(\frac{K_1}{10}\right) [.5P]$$

$$[.5\epsilon_\theta] = [.5\theta_c] - [.5\theta] - 10 \left(\frac{K_2}{10}\right) [.5Q]$$

Figure 6 shows the program.

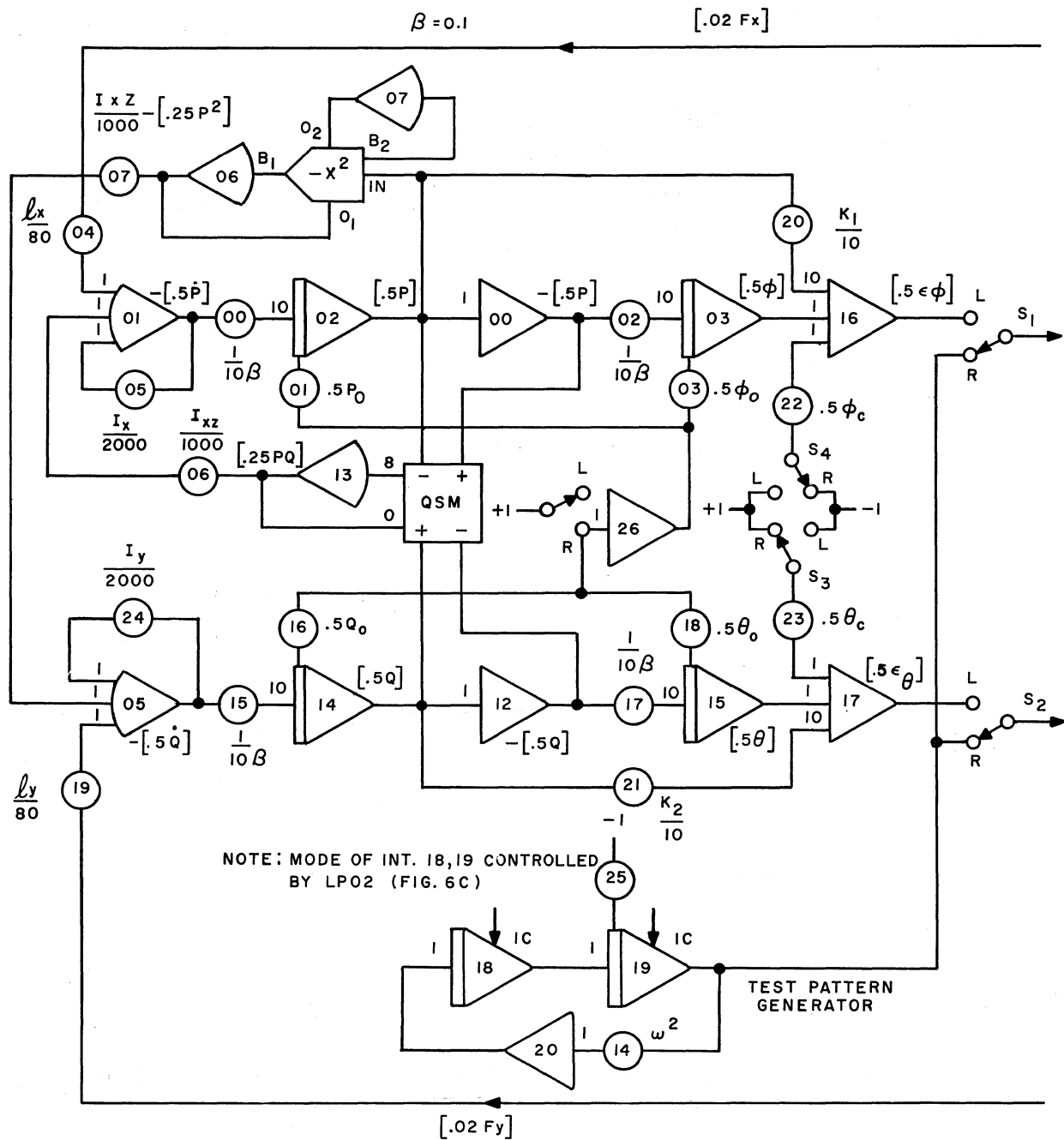


Figure 6a: Vehicle and Control System Dynamics

CHECKOUT (Debugging)

**GENERAL:** The analog static test technique breaks down when logic elements are included. In particular, in situations such as this one where the feedback loop is digital, a straightforward check of the highest derivative is not possible.

Probably the best way to static check a hybrid problem is this. First, as much as possible is checked by straight analog techniques. Checking

the A→D interface is accomplished by setting up some conditions on the analog side and observing the anticipated results on Flip Flop, Counter and GP indicators. Conversely, to check the D→A interface, one sets or resets flip flops manually and observes the results on the analog. The pure logic sections are static tested by holding the analog portion and stepping the digital section clock by clock. For this purpose, a "checkout list" is very useful (see below). This checkout list must be prepared with great care to assure

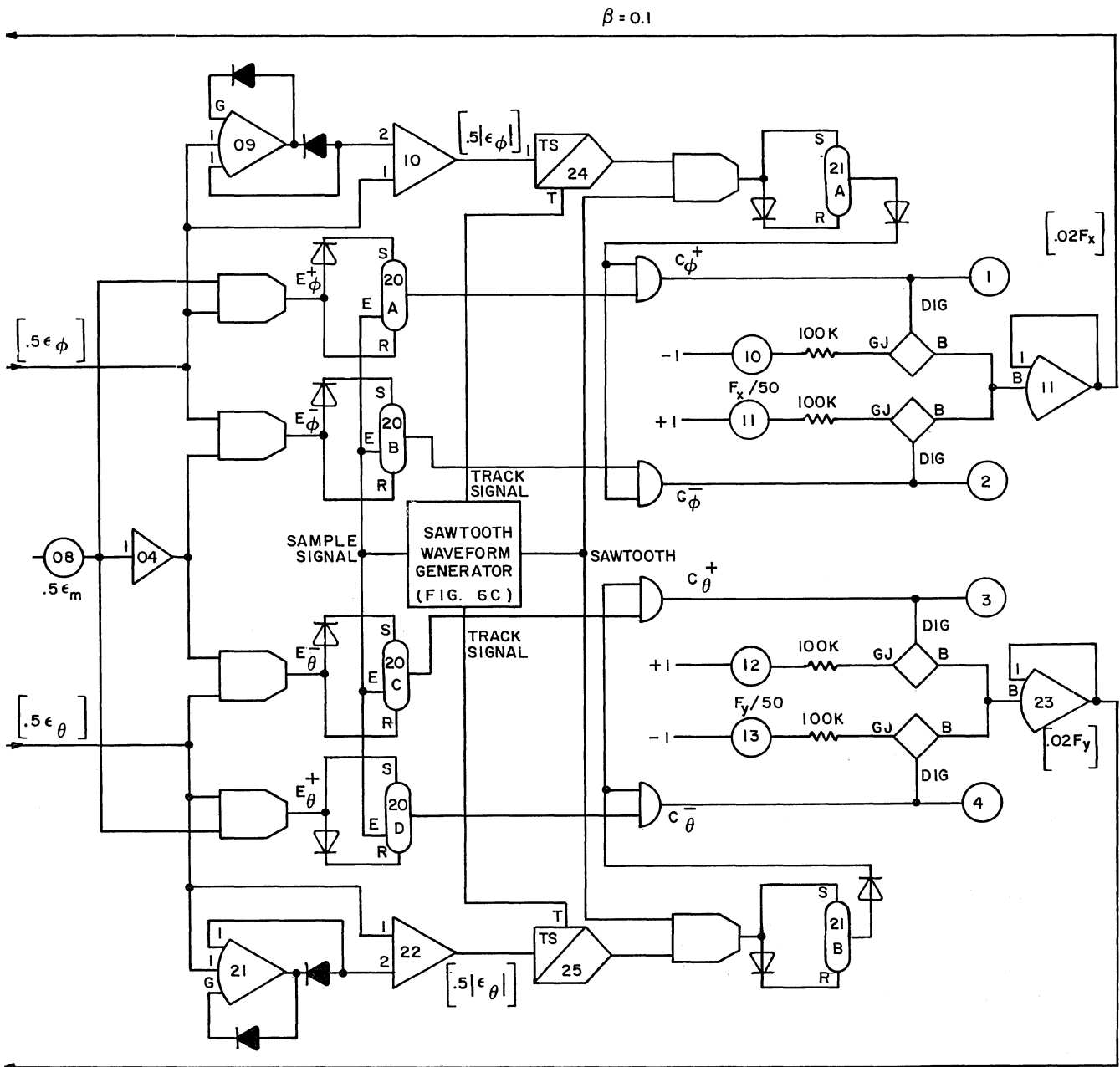


Figure 6b: Digital Controller

the operator that when an expected result does not occur (or an unexpected one shows up), he can immediately assume a patching error or machine malfunction. The preparation of the checkout list also forces the programmer to review his logic program systematically. More often than not, logical errors will be discovered (this is due to empirical rule: “No program is ever right the first time”).

If the logic section passes the clock-by-clock check, a dynamic check is rarely needed. How-

ever, whenever possible, a dynamic check should be performed. For example, the sawtooth generator in this program can be checked dynamically by observing its output on a scope, since it is independent of the rest of the circuit. The jet logic can be checked dynamically by introducing a sinusoidal waveform instead of  $\epsilon_\theta$  and  $\epsilon_\phi$ . Such tests should be considered early enough in the programming so that they may be incorporated in and easily switched into or out of the main program. One must plan for checkout, not leave it to the last minute after the program is already patched.

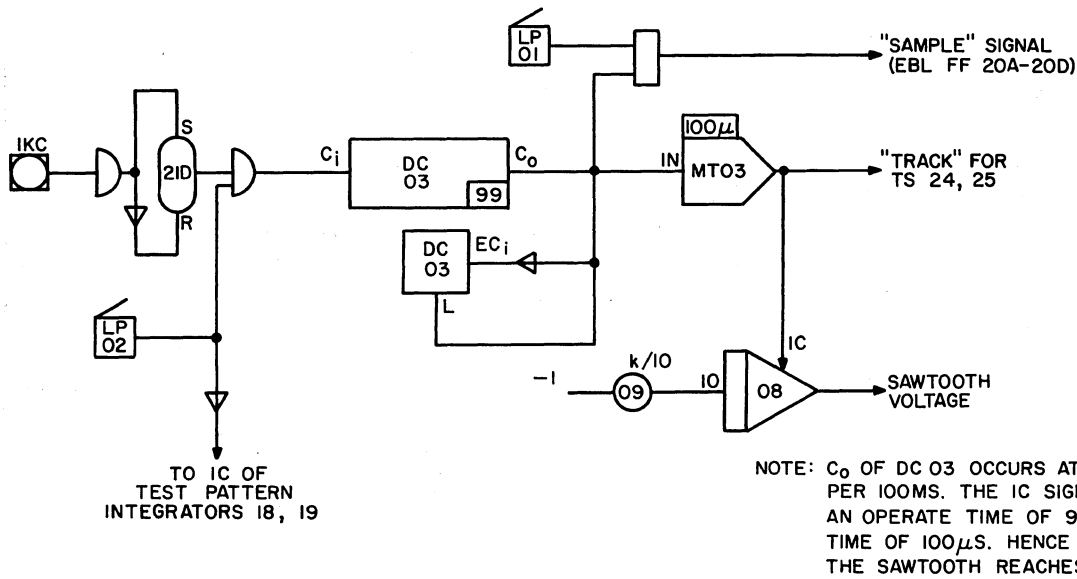


Figure 6c: Sawtooth Wave Form Generator

**TEST PROCEDURE:** The following Test Procedure is used:

1. Clear the DES, place the TR-48 in PS and set the pots. Set FF 20A, 20B, 20C and 20D manually to set pots 10, 11, 12 and 13, respectively. Because of the TR-48 electronic switches, these pots should be set by observing the outputs of A11 and A23 (in RS). FF 21A and 21B should be cleared.

Place the TR-48 on RS and perform the analog static check.  $S_1, S_2$  are left;  $S_3, S_4, S_5$  are right. To read the "second output" of A01 (and A05, also), reset FF 20A and set FF 20B, manually (reset FF 20D and set FF 20C, manually, for A05).

2. Check the A→D interface as follows: with switches  $S_1$  and  $S_2$  in the right position, adjust P25 to obtain +2 volts at the output of integrator 19. Clear the DES. Make sure LP 1 is pressed. Then give 1 manual clock. Check that GPR flip flops 20A, 20B, 20C, and 20D behave according to the table below. Then change P25 so integrator 19 reads 0.5 volts, clear, give a clock, and check the table again. Reverse the reference polarity to P25 and repeat.

Amp 19	FF 20A	20B	20C	20D
+ 2v	1	0	0	1
+ .5v	0	0	0	0
- 2v	0	1	1	0
-.5v	0	0	0	0

3. Check the DA interface by setting and re-setting flip flops 21A, 21B manually and comparing the outputs of amplifiers 01 and 05 against the analog static test list.
4. Check the logic program by performing the operations indicated in the following table:

<u>Set</u>					
FF 20A	20B	20C	20D	21A	21B
1	1			0	
1	1			1	
0	1			0	
1	0			0	
		1	1		0
		1	1		1
		0	1		0
		1	0		0

<u>Read</u>			
IND1	IND2	IND3	IND4
1	1		
0	0		
0	1		
1	0		
		1	1
		0	0
		0	1
		1	0

5. Dynamically check the ramp generator and the jet control logic by switching  $S_1, S_2$  to the right, pressing LP2, and observing the output

TR-48 POTENTIOMETER ASSIGNMENT SHEET

P00-P29

DATE _____		PROBLEM _____				
POT NO	PARAMETER DESCRIPTION	SETTING STATIC CHECK	STATIC CHECK OUTPUT VOLTAGE	SETTING RUN NUMBER I	NOTES	POT NO
00	$1/10\beta$	1.000	→			00
01	$.5P_0$	.500	→		TEST ONLY	01
02	$1/10\beta$	1.000	→			02
03	$.5\phi_0$	.600	→		TEST ONLY	03
04	$I_x/80$	.312	→			04
05	$I_x/2000$	1.000	→			05
06	$I_{x2}/1000$	.300	→			06
07	$I_{x2}/1000$	.300	→			07
08	$.5E_m$	.100	→			08
09	$k/10$	.750	→			09
10	$F_x/50$	.800	→		NOMINAL*	10
11	$F_x/50$	.800	→		"	11
12	$F_y/50$	.800	→		"	12
13	$F_y/50$	.800	→		"	13
14	$\omega^2$	1.000	→		TEST ONLY*	14
15	$1/10\beta$	1.000	→			15
16	$.5\phi_0$	.750	→		TEST ONLY	16
17	$1/10\beta$	1.000	→			17
18	$.5\theta_0$	.150	→		TEST ONLY	18
19	$k/80$	.250	→			19
20	$k/10$	.100	→	.500	CONTROL PARAMETER	20
21	$k/10$	.200	→		" "	21
22	$.5\phi_c$	.500	→	.500	"PILOT COMMAND" $.5 \rightarrow .1$	22
23	$.5\theta_c$	.750	→	.500	" " $.5 \rightarrow .1$	23
24	$I_x/2000$	.900	→			24
25	TEST IC	1.000	→		TEST ONLY*	25
26						26
27						27
28						28
29						29

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Figure 7: TR-48 Potentiometer Assignment Sheet

of integrator 19 and amplifiers 11 and 23 on a scope or a strip chart recorder. Set P14 to a desired frequency (not shorter than 1 sec or .1 sec in real time or for B = .1 respectively). Run the DES with the 1 MC clock.

- Return  $S_1$   $S_2$  to the left; release LP1,  $S_5$  to left, clear the DES, adjust pots to their run values, etc., before going to run by pressing SLAVE on the TR-48 and LP2 on the DES-30 (1 MC clock).

DATE _____		PROBLEM _____					
AMP NO	FB	OUTPUT VARIABLE	STATIC CHECK				NOTES
			CALCULATED		MEASURED		
			CHECK PT.	OUTPUT	CHECK PT.	OUTPUT	
00	I	$-.5P$		-500			
01	HG	$-.5\dot{P}$		-352			see test description
				+147			
02	I	$.5P$		+500			
03	I	$.5\phi$		+600			
04	I	$.5E_m$		+100			
05	HG	$-.5\dot{Q}$		-306			see test description
				+139			
06	HG	$-.25P^2$		-250			
07	HG	SQUARER					
08	I	$V_R$		0			SAWTOOTH SIGNAL GENERATOR
09	HG	ABS. VAL.					
10	$\Sigma$	$.5 E_\phi $		+600			S1 LEFT
11	SP	$.02F_x$		$\pm 800$			FF 20A & 20B
12	I	$-.5Q$		+750			
13	HG	$.25PQ$		-375			
14	I	$.5Q$		-750			
15	I	$.5\theta$		-150			
16	$\Sigma$	$.5E_\phi$		-600			
17	$\Sigma$	$.5E_\theta$		+900			
18	I	$w \sin wt$		0			see test description
19	I	$\cos wt$		+1000			" " "
20	I	$-w^2 \cos wt$		-1000			" " "
21	HG	ABS. VAL.					
22	$\Sigma$	$.5 E_\theta $		+900			S2 LEFT
23	SP	$.02F_y$		$\pm 800$			FF 20D & 20C
24	HG	$- E_\phi $ STORED					T/S
25	HG	$- E_\theta $ STORED					T/S
26	I	-REFERENCE		-1000			

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Figure 8: TR-48 Amplifier Assignment Sheet

REFERENCE

- Simulation of a Space Vehicle with Reaction Jet Control System, EAI Applications Reference Library, Application Study: 3.4.1h, Bulletin No. ALHC 6251-1ab

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