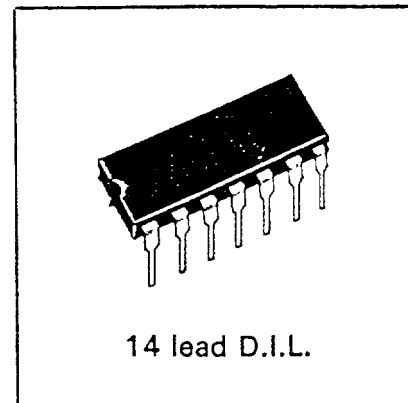# Precision Servo Integrated Circuit

407-574

FEATURES

- Low External Component Count
- Low Quiescent Current (7 mA typical at 4.8V)
- Excellent Voltage and Temperature Stability
- High Output Drive Capability
- Consistent and Repeatable Performance
- Precision Internal Voltage Stabilisation
- Time Shared Error Pulse Expansion
- Balanced Deadband Control
- Schmitt Trigger Input Shaping
- Reversing Relay Output (D.C. Motor Speed Control)

14 lead D.I.L.

DESCRIPTION

The ZN409CE is a precision monolithic integrated circuit designed particularly for pulse-width position servo mechanisms used in all types of control applications. The low number of components required with the ZN409CE, together with its low power consumption, make this integrated circuit ideal for use in model aircraft, boats and cars where space, weight and battery life are at a premium. The amplifier will operate over a wide range of repetition rates and pulse widths and is therefore suitable for the majority of systems. The ZN409CE can also be used in motor speed control circuits.
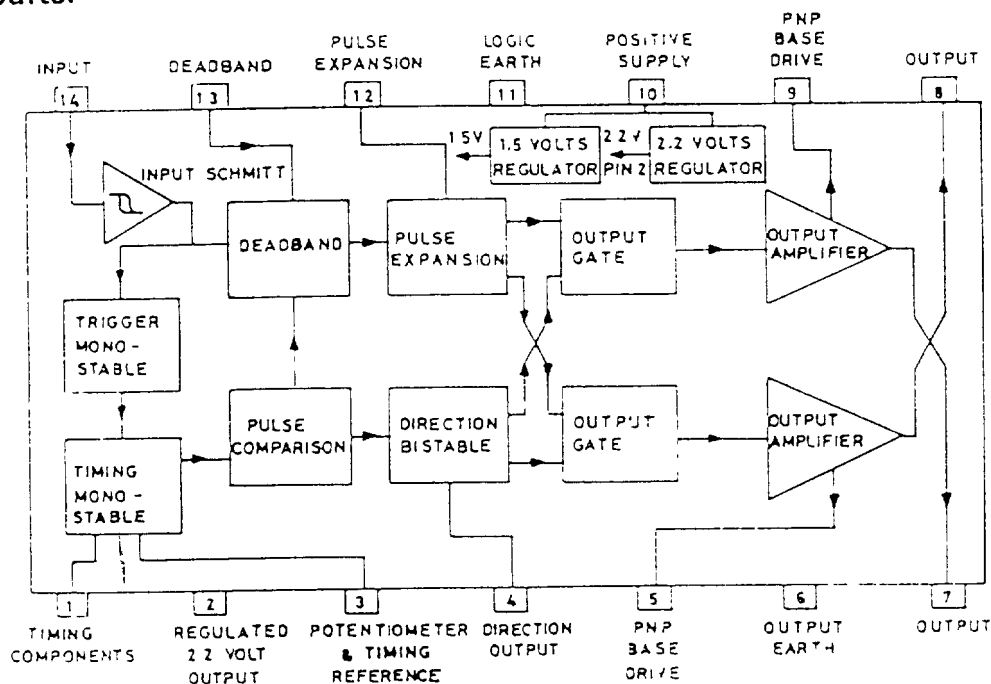
Fig. 1. SYSTEM DIAGRAM

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ZN409CE

ABSOLUTE MAXIMUM RATINGS

Supply Voltage	6.5 Volts
Package Dissipation	300 Milliwatts
Operating Temperature Range	–20°C to +65°C
Storage Temperature Range	–65°C to +150°C

CHARACTERISTICS (V_S = 5V. At 25°C ambient temperature unless otherwise stated).

Parameter	Min.	Typ.	Max.	Unit	Conditions
Input threshold (lower)	1.15	1.25	1.35	V	Pin 14
Input threshold (upper)	1.4	1.5	1.6	V	Pin 14
Ratio upper/lower threshold	1:1	1:2	1:3		–10 to +65°C
Input resistance	20	27	35	kΩ	
Input current	350	500	650	μA	
Regulator voltage	2.1	2.2	2.3	V	–10 to +65°C, 1.3 mA load current
Regulator supply rejection ratio	200	300	—		V_S = 3.5 to 6.5V $$RSRR = \frac{dV_{in}}{dV_{out}}$$
Monostable linearity	—	3.5	4.0	%	±45°, R_p = 1.5 kΩ R_1 = 12 kΩ
Monostable period temperature coefficient	—	+0.01	—	%/°C	Excluding R_T, C_T. R_p = 1.5 kΩ, R_1 = 12 kΩ (potentiometer slider set mid-way)
Output Schmitt deadband	±1	±1.5	±3	μs	C_E = 0.47 μF
Minimum output pulse	2.5	3.5	4.5	ms	C_E = 0.47 μF, R_E = 180 kΩ
Error pulse for full drive	70	100	130	μs	15 ms repetition rate C_E = 0.47 μF, R_E = 180 kΩ
Total deadband	±3.5	±5	±6.5	μs	C_D = 1000 pF
P.N.P. drive	40 35	55 50	70 65	mA mA	T = 25°C T = –10°C
Output saturation voltage	—	300	400	mV	I_L = 400 mA
Direction bistable output	2	2.8	3.6	mA	
Supply voltage range	3.5	5	6.5	V	
Supply current	4.6	6.7	10	mA	Quiescent
Total external current from regulator	1.3	—	—	mA	V_S = 3.5V
Peak voltage $V_{C\ EXT}$ (with respect to 2V regulated voltage)	— —	0.7 0.5	— —	V V	T = 25°C T = –10°C

OPERATING AND DESIGN NOTES

1. SERVO APPLICATION

Component Function	Circuit Reference	Value	Comments
Monostable Timing Components	R_T	100 kΩ	Note 1 (e)
	C_T	0.1 μF	
Potentiometer and Timing Reference Components	R_p	1.5 kΩ	Note 1 (e)
		5 kΩ	Note 1 (g)
	R_1	4.7 kΩ	Note 1 (e)
Pulse Expansion	CE	0.47 μF	Note 1 (d)
	RE	180 kΩ	11 Ω Motor
		150 kΩ	8 Ω Motor
Deadband (Note 1 (c))	C_D	1000 pF	11 Ω Motor
		1500 pF	8 Ω Motor
Dynamic Feedback	R_F	330 kΩ	Note 1 (f)
	R_B	330 kΩ	
	R_2	1.2 kΩ	
Input Coupling	C_C	2.2 μF	Note 1 (b)
Motor Decoupling	C_2	0.01 μF	
	C_3	0.01 μF	
R.F. Decoupling	C_1	0.1 μF	Note 1 (h)
Drive Transistors	T1, T2		Note 1 (i)

(a) Introduction

In the standard servo application the displacement of a control stick varies the pulse width of a timing circuit and many such pulses are time division multiplexed and typically modulate a 27 MHz transmitter. A receiver then decodes the transmitted signal and reconstitutes an independent train of pulses for each servo channel. The servo shown in Fig. 2 consists of the ZN409CE integrated circuit, several external components, a power amplifier consisting of two external PNP transistors and two on-chip NPN transistors which form a bridge circuit to drive the d.c. motor. The motor drives a reduction gear box which has a potentiometer attached to the output shaft. This potentiometer in association with R_1 and the timing components C_T and R_T controls the pulse width of the

ZN409CE

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Fig. 2. SERVO SYSTEM USING THE ZN409CE

timing monostable. The input pulse is compared with the monostable pulse in a comparison circuit and one output is used to enable the correct phase of an on-chip power amplifier. The other output from the pulse comparison circuit drives the pulse expansion circuit (C_E, R_E) via the deadband circuit (C_D). Thus any difference between the input and monostable pulses is expanded and used to drive the motor in such a direction as to reduce this difference so that the servo takes up a position which corresponds to the position of the control stick.

(b) Input Circuit

The ZN409CE operates with positive going input pulses which can be coupled either directly or via a capacitor to pin 14. The advantage of a.c. coupling is that should a fault occur in the multiplex decoder which causes the input signal to become a continuous positive level, the servo will remain in its last quiescent position, whereas with direct coupling the servo output arm will rotate continuously. A nominal 27 kΩ resistor is shunted across the input on chip to provide d.c. restoration of the input signal when a.c. coupling is used. The active input circuit is a Schmitt trigger which allows the servo to operate consistently with slow input edges and supplies the fast edge required by the trigger monostable independent of input edge speed.

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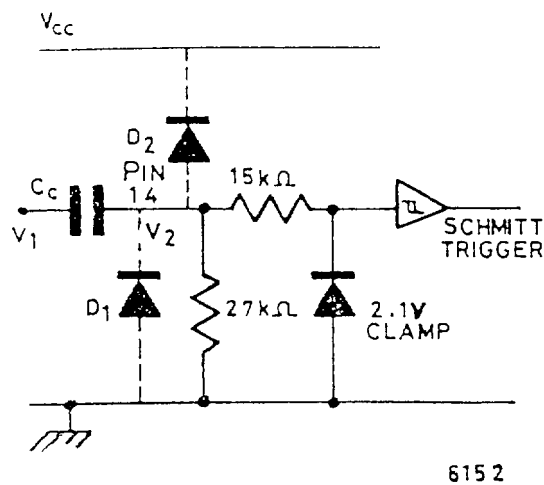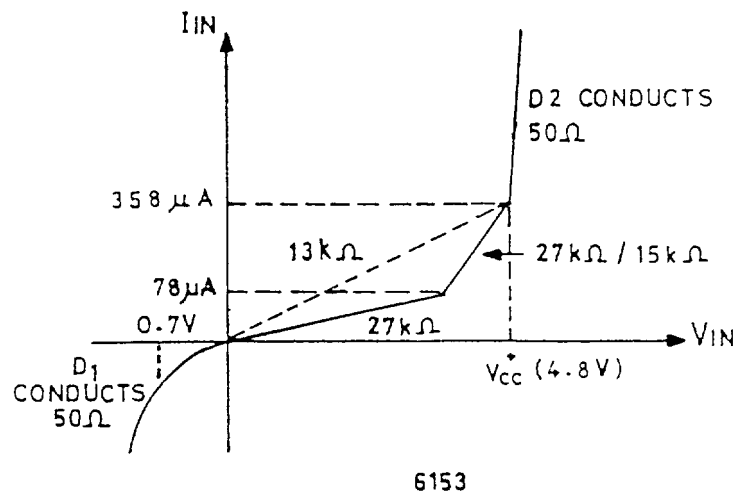
INPUT CIRCUIT

INPUT CHARACTERISTICS

Fig. 3.

The input circuit and its V/I characteristic are shown above. D_1 and D_2 are the parasitic substrate and isolation diodes associated with the input resistors. It is advisable that the pulse input amplitude should not fall below 0V nor exceed the supply voltage V_{CC} in order to prevent these diodes from conducting, although a small amount of conduction will not cause the circuit to malfunction. When a.c. coupling is used the value of C_C should be chosen to give a pulse droop not exceeding 0.3 volts

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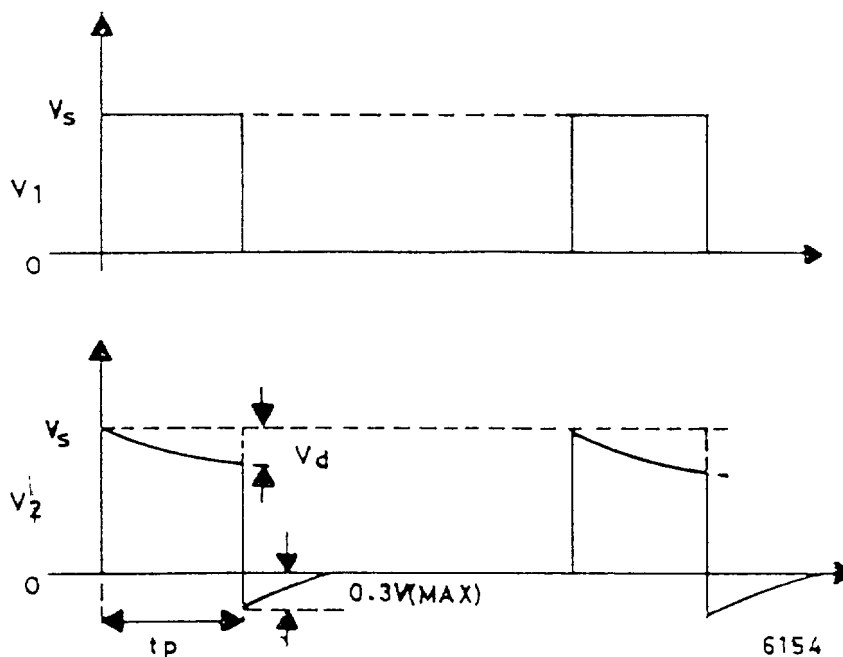
Fig. 4. INPUT WAVEFORMS

ZN409CE

Assuming that the input signal swings between 0V and V_s and taking the input chord resistance R_{in} of 13 kΩ the droop for a pulse of duration t_p msec will be :

$$v_d = \frac{V_s \, t_p}{C_c . R_{in}} \text{ volts} \qquad \begin{array}{l} t_p \text{ (msec)} \\ C_c \text{ (}\mu\text{F)} \\ R_{in} \text{ (k}\Omega\text{)} \end{array}$$

For a nominal pulse width of 1.5 msec and v_d equal to 0.3 volts the required minimum value of C_c can be found as follows :

$$C_c = \frac{4.8 \, . \, 1.5}{0.3 \, . \, 13} = 1.85 \, \mu\text{F}$$

A nominal value of 2.2 μF is chosen (Nearest preferred value).

If it is required to operate the servo with reduced input pulse amplitude the input pulse should exceed the upper Schmitt threshold voltage of 1.5 volts by a reasonable margin and a minimum input pulse amplitude of 2.4 volts is recommended.

(c) Deadband Circuit

The function of the deadband circuit is to provide a small range of output shaft position about the quiescent position where the difference pulse does not drive the motor. This is necessary to eliminate hunting around the quiescent position caused by servo inertia and overshoot. The minimum deadband required is also a function of the pulse expansion characteristics and dynamic feedback component values.
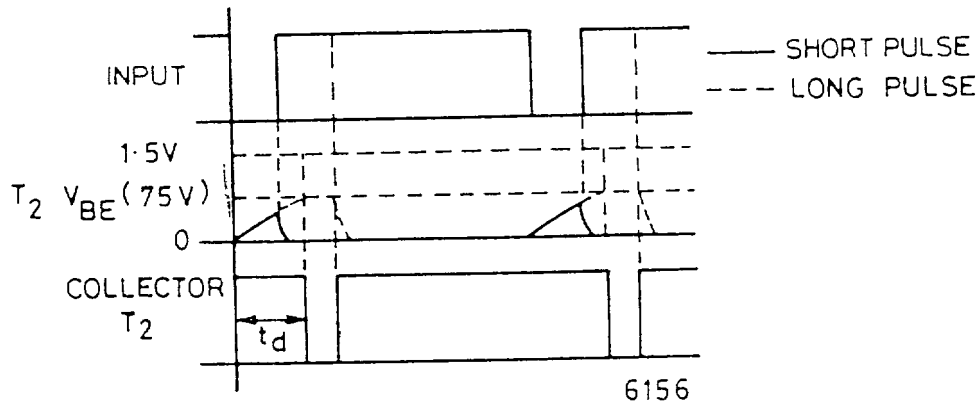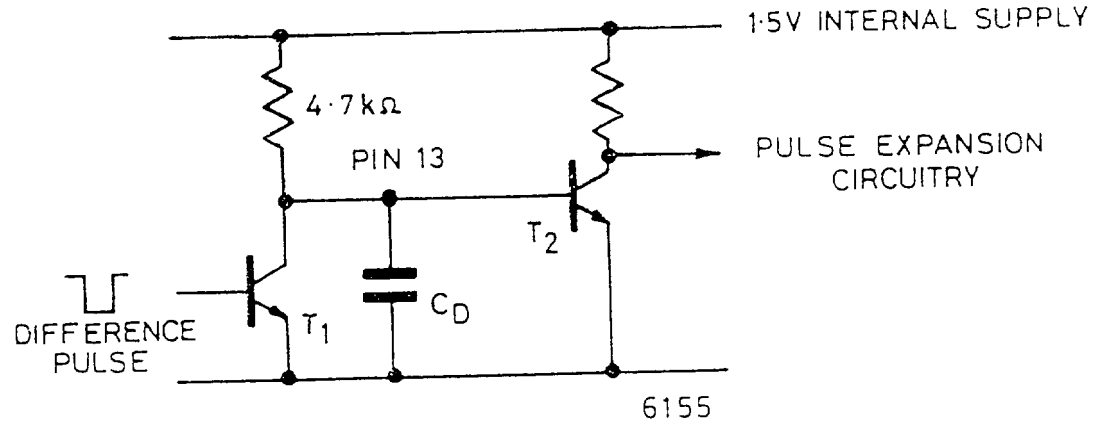

Fig. 5. DEADBAND CIRCUIT AND WAVEFORMS

When the difference pulse is applied T_1 turns off and the base of T_2 rises on an exponential waveform with a time constant of 4.7 kΩ × C_D. If the difference pulse is small the potential reached on the base of T_2 is insufficient to turn T_2 on and no output results.

The pulse expansion circuit has a built in deadband of 1.5 μsec with C_E = 0.47 μF and this must be added to the deadband caused by C_D to obtain the total T_d.

$\therefore$
$$T_d = 1.5 + t_d \ \mu sec$$

t_d is found from the exponential equation.

$$V_{be} = V_1 \left[1 - \exp\left(\frac{-t_d}{C_D \ . \ 4.7 \ k\Omega} \right) \right]$$

$\therefore$
$$t_d = C_D. \ 4.7 \ \log_e \left(\frac{V_1}{V_1 - V_{be}} \right)$$

$\therefore$
$$= 3.3 \ C_D \ \mu sec \ (C_D \ in \ nF)$$

(Taking V_1 = 1.5 volts and V_{be} = 0.75 volts)

Thus with C_D equal to 1000 pF (1 nF) t_d = 3.3 μsec and T_d = 4.8 μsec.

The mechanical deadband $\varnothing d$ depends on the chosen sensitivity S_1 of the servo and in the usual radio control application a ±500 μsec input pulse variation causes ±50° rotation, i.e. S_1 = 10 μsec per degree.

Thus $\quad \varnothing d = \dfrac{2.T_d}{S_1}$ degrees $\quad$ (T_d in μsec. S_1 in μsec per degree).

Thus a value for T_d of 5 μsec provides a mechanical deadband $\varnothing d$ of 1°.

And generally:

$$\varnothing d = \frac{2. \ (1.5 + t_d)}{S_1}$$

$$\varnothing d = \frac{3 + 6.6 \ C_D}{S_1} \ degrees \quad \begin{cases} C_D \ in \ nF. \\ S_1 \ in \ \mu sec \ per \ degree. \end{cases}$$

D.C. motors need a certain amount of drive to overcome static friction and the minimum output pulse obtained from this form of pulse expansion characteristic is chosen to ensure that the motor will rotate when driven. A linear initial pulse expansion characteristic would result in the motor remaining stationary and drawing full stall current for small drive periods. If the motor needs 2 msec of drive at a repetition rate of 20 msec to cause rotation, this is equivalent to an average drain of 50 mA for a 0.5A stall current. This is many times more than the quiescent current of the ZN409CE (7 mA) and could considerably reduce flying time for the standard battery operated airborne multichannel radio control system. This effect also causes an annoying buzz from the motor and gearbox. The use of the Schmitt trigger removes these two deficiencies.

The value of t_{min} is determined by the Schmitt trigger hysteresis and the exponential waveform on C_E in the following equation.

$$V_H = (V_{CC} - V_L) \left(1 - \exp \left[\frac{-t_{min}}{C_E R_E} \right] \right)$$

because V_H is small the following linear relationship is sufficiently accurate.

$$V_H = \frac{(V_{CC} - V_L)}{C_E R_E} . t_{min}$$

$$\therefore \quad t_{min} = \frac{V_H}{(V_{CC} - V_L)} . C_E R_E \text{ msec}$$

For nominal operation $V_{CC} = 4.8V$; $V_L = 1.5V$; $V_H = 0.12V$ and:

$$t_{min} \simeq \frac{C_E R_E}{30} \text{ msec} \qquad \begin{cases} C_E \text{ in } \mu F \\ R_E \text{ in } k\Omega \end{cases}$$

and for $C_E = 0.47 \, \mu F$ and $R_E = 180 \, k\Omega$, $t_{min} = 3.5$ msec.

It can be seen from the simple equation that t_{min} is dependent on V_{CC}, and t_{min} will increase with reducing V_{CC}. This variation is put to good use to maintain the initial motor drive, $V_{CC} \times t_{min}$ reasonably constant over the operating voltage range of 3.5 to 6.5 volts.

When the pulse expansion drive is increased above the minimum value the output pulse increases from t_{min} almost linearly until full pulse expansion is reached, i.e. when the output pulse width equals the input pulse repetition rate. The pulse expansion will be almost linear provided that the current source I_E does not saturate, i.e. provided that C_E is not discharged to almost zero volts. Ideally the current source should saturate when full motor drive is obtained but due to component tolerances it is usual to allow some margin to ensure that full motor drive can be obtained. If a margin is allowed, an extended pulse expansion characteristic results (shown dotted in Fig. 6) and if this is excessive it can lead to the servo exhibiting an underdamped characteristic causing jittering or hunting. Thus for full pulse expansion the voltage on C_E should discharge from its quiescent value of 1.5V to 0.75 volts. Thus with $I_E = 3$ mA for the current source:

$$\frac{1.5 - 0.75}{t_e} = \frac{I_E}{C_E}$$

$$\therefore \quad C_E = 4. \, t_e \, \mu F \ (t_e \text{ in msec})$$

For $t_e = 0.1$ msec, a value of 0.47 μF was chosen for C_E.
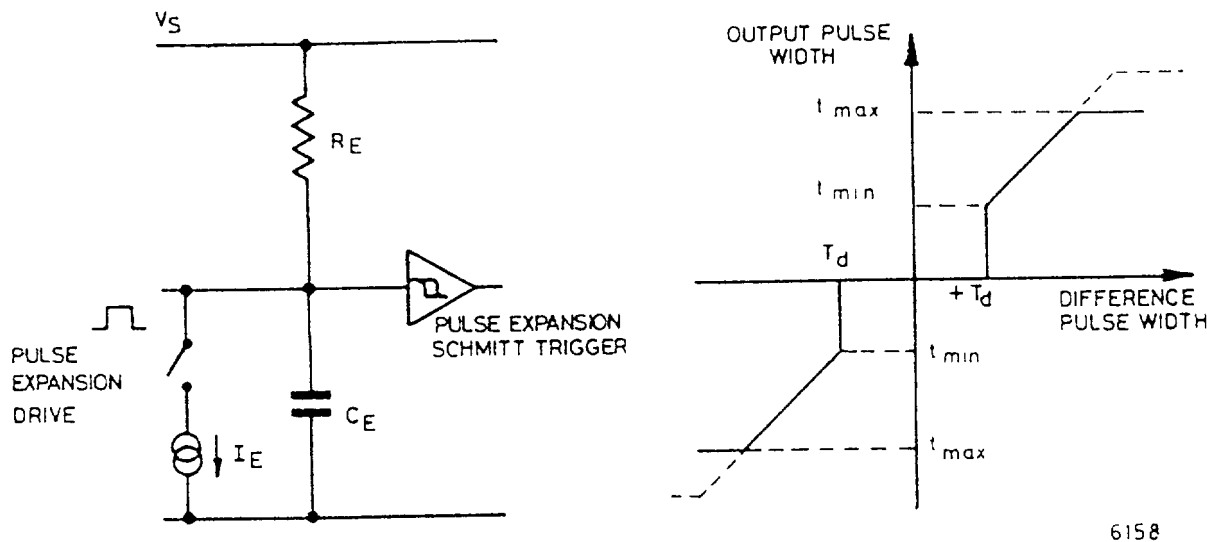
ZN409CE

(d) Pulse Expansion

Fig. 6. PULSE EXPANSION CIRCUIT AND CHARACTERISTIC

A schematic of the pulse expansion circuit is shown in Fig. 6. In the quiescent state with no drive the Schmitt trigger input is biased via R_E and takes up a level just above the lower threshold V_L.

A drive pulse causes a current I_E to be switched on for the duration of the pulse and this discharges C_E linearly with time. Thus, at the end of the pulse the voltage on C_E depends on the duration of the pulse. If the pulse is narrow and just causes the potential on C_E to fall to V_L the Schmitt trigger will switch to the upper threshold V_H and at the end of the drive pulse C_E will start to charge to V_H with a time constant $C_E R_E$. When the potential on C_E reaches V_H the Schmitt will switch to V_L and C_E will discharge to the quiescent level. The output drive is taken from the Schmitt output.
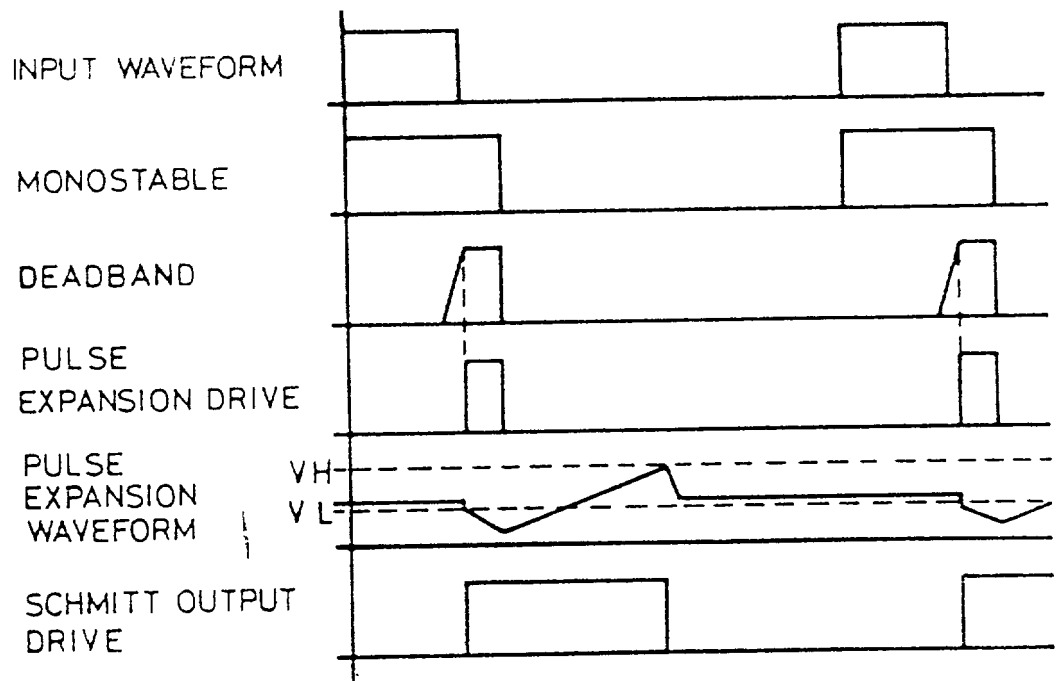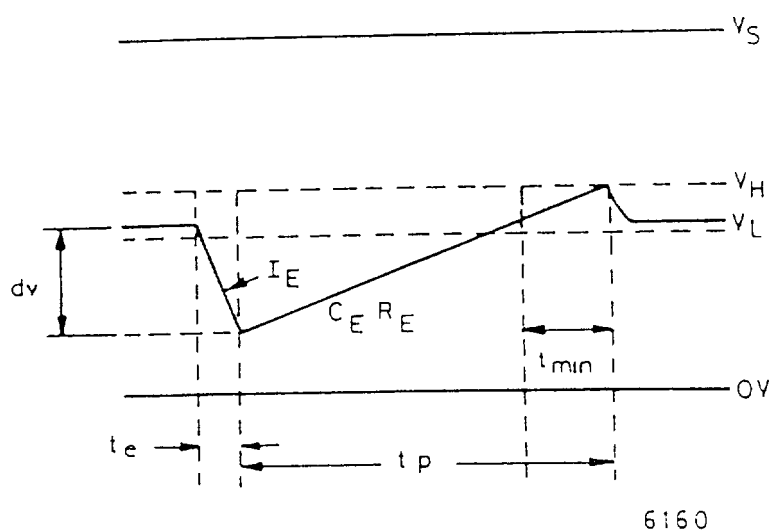

Fig. 7. PULSE EXPANSION TIMING DIAGRAM

Fig. 8. PULSE EXPANSION WAVEFORM

If t_p is the maximum motor drive pulse length required, i.e. equal to the input pulse repetition period for full pulse expansion, and the mean value of the potential on C_E is taken as 1.2 volts, then :

$$dv = \frac{(t_p - t_{min})}{C_E R_E}. \ (V_{CC} - 1.2)$$

And for the discharge period t_e :

$$dv = \frac{I_E \cdot t_e}{C_E}$$

$$\therefore \qquad R_E = \frac{(t_p - t_{min})}{I_E t_e}. \ (V_{CC} - 1.2)$$

For nominal values of $V_{CC} = 4.8V$ and $I_E = 3$ mA

$$R_E = 1.2 \frac{(t_p - t_{min})}{t_e} \ k\Omega$$

and for $t_p = 20$ msec, $t_{min} = 3.5$ msec, $t_e = 0.1$ msec, $R_E = 180$ kΩ (Nearest preferred value).
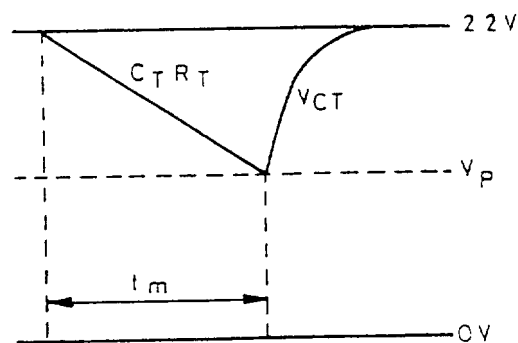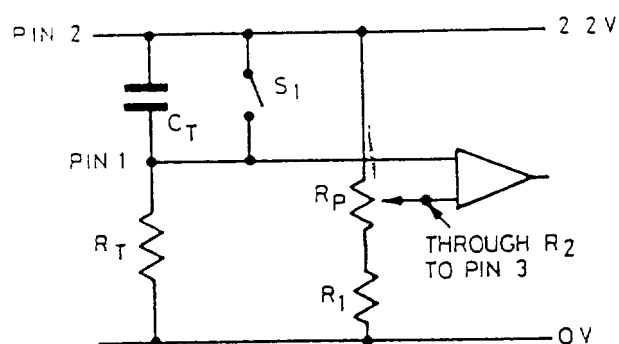
(e) Monostable Timing

Fig. 9. MONOSTABLE TIMING CIRCUIT AND WAVEFORM

The leading edge of the input waveform triggers the timing monostable by opening switch S_1. C_T then charges until the differential amplifier detects that the timing waveform potential has fallen to V_p, the potential on the potentiometer wiper and switch S_1 is closed to terminate the timing pulse. Thus the monostable period is determined by the setting of the potentiometer wiper. In the standard application the servo centre position pulse width is 1.5 msec with a range of $\pm 50°$ rotation at 10 μsec per degree. Thus the 2.0 msec maximum monostable period $t_{mono(max)}$ corresponds to a potentiometer setting of 200° (for a linear relationship) and since the potentiometer has a total rotation of approximately 270° and the maximum allowable swing on pin 3 is specified as 0.5 volt, the value of $C_T R_T$ can be calculated as follows:

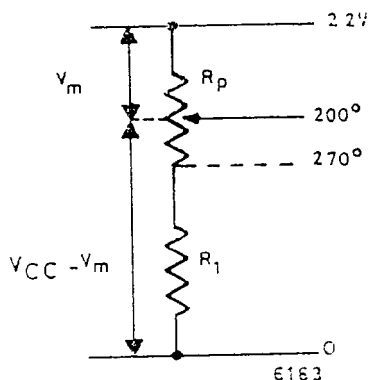$$\frac{0.5}{t_{mono(max)}} \simeq \frac{2}{C_T R_T}$$

$$\therefore \quad C_T R_T = 4 . \; t_{mono(max)}$$

Thus if $t_{mono(max)} = 2$ msec, $C_T R_T = 8$ msec.
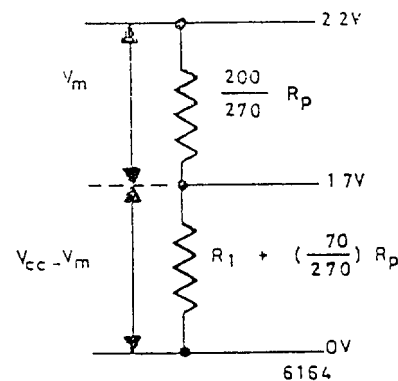
The optimum value of R_T is 100 kΩ due to the design of the on-chip monostable circuit, giving $C_T = 0.1$ μF (nearest preferred value).

$$R_T = 100 \, k\Omega \qquad C_T = 0.1 \, \mu F$$

The value of R_1 can now be calculated from the actual voltage swing with a potentiometer setting of $\emptyset p = 200°$ and $\emptyset max = 270°$.

POTENTIOMETER SET AT 200°   EQUIVALENT CIRCUIT

Fig. 10

Thus from the equivalent circuit

$$\frac{V_m}{\frac{200}{270} . \, R_p} = \frac{(V_{CC} - V_m)}{R_1 + \frac{70}{270} R_p}$$

where V_m is calculated from the actual values of C_T and R_T chosen using the relationship

$$V_m = \frac{2.0 . \; t_{mono(max)}}{C_T R_T}$$

since $C_T = 0.1$ μF (nearest preferred value) was chosen with $R_T = 100$ kΩ, $V_m = 0.4$ V and hence

$$R_1 = 3.1 \, R_p$$

If $R_p = 1.5$ kΩ then $R_1 = 4.7$ kΩ.

ZN409CE

(f) Dynamic Feedback

Without dynamic feedback in the standard application the inertia of the motor and gearbox causes the servo output shaft to overshoot the set position which results in the servo 'hunting'. If the deadband was widened to stop this effect an unacceptably large deadband would result and the servo would still be underdamped. The dynamic feedback circuit utilises the motor back emf (which is proportional to motor speed) and feeds back a proportion of this signal to the wiper of the potentiometer. The phase of the feedback signal is chosen to modify the potential on the wiper so that the monostable period is dynamically varied to reduce the motor drive as the servo output shaft approaches the set position and the values of the feedback resistors are chosen to achieve optimum settling characteristics.

The value for R_F and R_B of 330 kΩ will suit the normal type of servo mechanism, however if the servo is fairly fast this can be decreased to 300 kΩ to minimise any tendency to overshoot. Where the servo is slow R_F and R_B can be increased to 360 kΩ or 390 kΩ.

(g) Alternative Value of R_p

Although a 1.5 kΩ feedback potentiometer is the most common value of R_p, 5 kΩ potentiometers are used in some servo mechanisms. In order to use this value with the ZN409CE a 2.2 kΩ resistor is usually connected across the potentiometer to maintain the values of R_F and R_B at 330 kΩ and R_1 at 4.7 kΩ. R_2 is omitted. i.e. the wiper of the potentiometer is connected directly to Pin 3 of the ZN409CE.

(h) R.F. Decoupling

C_1 (typical value 0.1 μF) is only necessary where strong R.F. fields may affect the operation of the circuit.

(i) Transistors T1 and T2

The external PNP transistors are usually selected for a low $V_{CE(sat)}$ to obtain maximum output drive and the recommended types are the ZTX550 or ZTX750.

2. MOTOR SPEED CONTROL

(a) Introduction

In the motor speed control application the ZN409CE is used as a linear pulse width amplifier. The d.c. motor is driven via a power amplifier with a train of pulses whose mark/space ratio can vary between zero and one to control the motor speed from zero to maximum. The ZN409CE operates
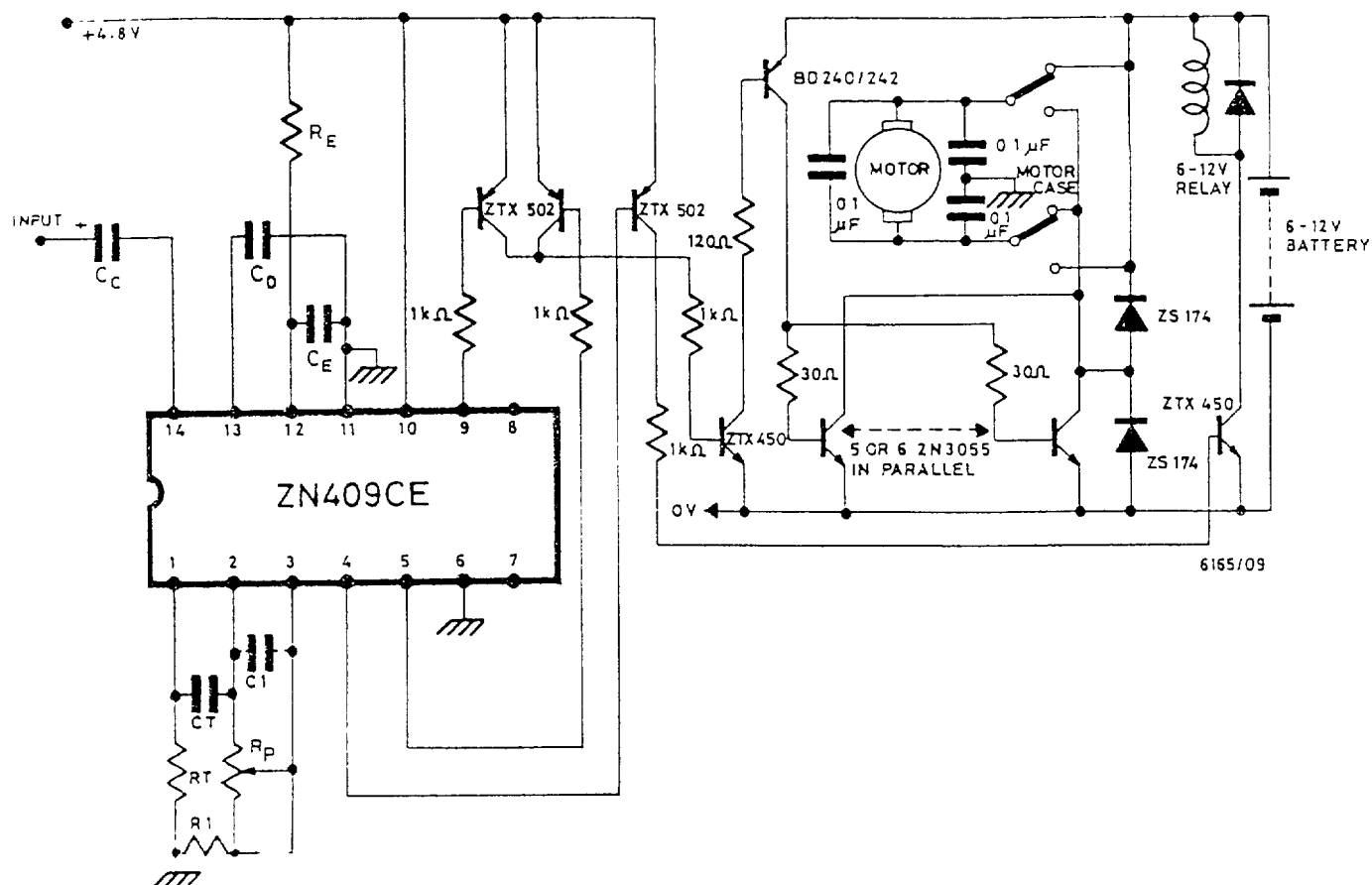
Component Function	Circuit Reference	Value
Monostable timing components	R_T	100 kΩ
	C_T	0.1 μF
Potentiometer and timing reference components	R_p	1 kΩ
	R_1	4.7 kΩ
Pulse expansion	R_E	82 kΩ
	C_E	1 μF
Deadband	C_D	0.022 μF
Input coupling	C_C	2.2 μF
Motor decoupling. See note 1(h)	C_1	0.01 μF

Fig. 11. HIGH PERFORMANCE PROPORTIONAL MOTOR SPEED CONTROL CIRCUIT AND RECOMMENDED COMPONENT VALUES

ZN409CE

with fixed timing components and a fixed resistor replaces the position feedback potentiometer. The nominal monostable period represents zero motor speed and input pulses less than or greater than nominal drive the motor in the forward and reverse direction respectively. The motor direction is usually controlled by a relay operated from pin 4, the direction output. Pulse expansion components C_E and R_E are chosen to obtain the required relation between control stick deplacement and motor speed and it is usual to operate with a much larger deadband than that used in the servo application.

Because high current motors are used to drive the wheels or propellors of model cars or boats a separate supply of 6 to 12 volts is used, and to provide reasonable running time between recharging the battery, a capacity of 1.2 Amp. hr. is usual.

$1/_{12}$ scale cars with reasonable performance can be powered by a 5 amp stall current motor such as the 'Marx Monoperm' (6 – 12 volts) driven from a single 2N3055 power transistor. However, if very high performance is required then five or six 2N3055 power transistors are used in parallel as shown in Fig. 11 to drive a 25 amp stall current motor. The 'Mabuchi RS54' operates from 6 to 8 volts and will provide a top speed of about 25 mph in a $1/_8$ scale car. Acceleration is superb and the car wheels can be spun easily even on the best surfaces although the 1.2 amp hr. battery will need a full recharge after some ten minutes of racing. The motor and 2N3055 transistors dissipate a great deal of power especially at low speed and almost full stall current drive so the power transistors need to be mounted on a good heat sink such as the aluminium chassis of the car and a motor with crimped commutator connections rather than soldered connections is necessary since soldered connections have been seen to melt under stall conditions.

The outputs from pins 9 and 5 of the ZN409CE integrated circuit are combined using two ZTX502 PNP transistors to provide a pulsed output whose mark/space ratio varies from 0 to 1 depending on the deflection of the control stick.

This signal is then used to drive the motor via the power amplifier.

The ZN409CE has additional circuitry which performs the motor reversing function by taking the output from the direction bistable and provides either zero current or approximately 3 mA sink current at pin 4, depending on the state of the direction bistable. This current is amplified and used to drive the relay coil (100 mA) via the ZTX450 transistor thus controlling the motor direction via the relay changeover contacts.

It is usual to have a relatively wide deadband and $C_D = 0.022$ μF provides a deadband of about 14% (± 7 degrees).

The pulse expansion components C_E and R_E are chosen to give full motor drive at about 90% full stick displacement and using the formulae derived earlier yields values of $C_E = 1$ μF, $R_E = 82$ $k\Omega$. The monostable timing component values remain unchanged at $C_T = 0.1$ μF, $R_T = 100$ $k\Omega$. A 1 $k\Omega$ potentiometer (R_p) can be used to set up the zero output condition with the control stick in its central position.

PACKAGE OUTLINE
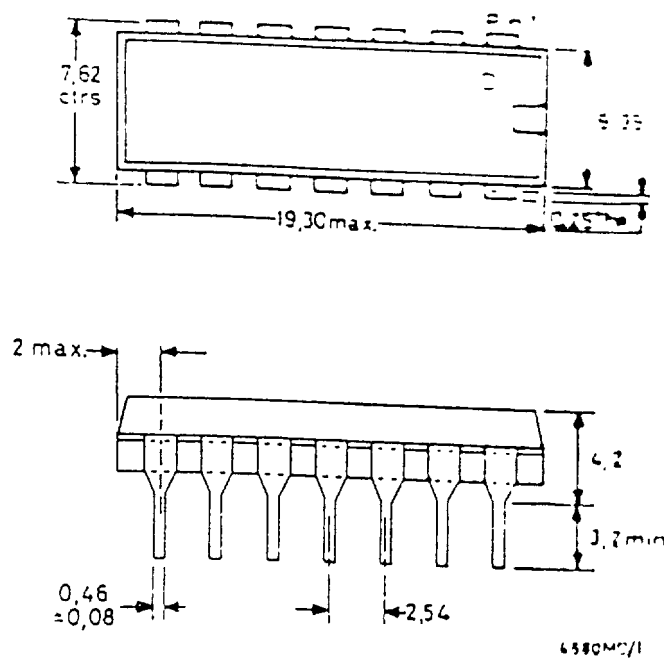
14 Lead Moulded D.I.L.

Dimensions in millimetres