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STRETCH CIRCUIT MEMO #10

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SUBJECT: Emitter Follower Drivers

SUMMARY: The performance of a driver circuit depends upon its ability to switch a large number of load stages with very little delay. In this report the factors affecting the number of stages that can be driven are discussed and pertinent measurements are indicated. The discussion includes the single and complementary emitter follower drivers.

A transient analysis to determine the cause of the oscillations in the emitter follower is also included. From this analysis and the knowledge of the load impedance on the emitter follower, it is possible to determine whether the problem of oscillations will be serious for any particular applications. Experimental data to varify this analysis is also included.

SINGLE EMITTER FOLLOWER

The emitter follower driver with a typical load stage connected to its output is shown in figure #1. The size of the resistor "R" in the emitter follower depends upon the number of load stages that will be driven. A standard logical block is shown preceeding the driver stage.

NUMBER OF LOAD STAGES -

A power supply voltage of -6 volts has been tentatively established for the "series 7000" transistor circuits. This voltage on the collector, and the maximum power dissipation for the drift transistor, determine the maximum current that can safely flow into the emitter follower. In order to obtain symmetrical rise and fall times, the current source (I) in the emitter must be large which limits the base current permissible from the load stages. These requirements limit the theoretical number of load stages that can be driven to nine stages. The optimum value of "R" for load stages from one to nine are listed in table 1.

As is shown in the following paragraph, six load stages seems to be the maximum that can be driven. Therefore a value of "R" equal to 5.1K ohms would be used in this circuit, since up to four load stages can be driven by a standard logical stage.

EXPERIMENTAL RESULTS -

The circuit shown in figure #1 was set up to observe pertinent waveforms. A resistor was added in series with the line connecting the emitter follower to the load stages in order to damp out the oscillations to a negligible value. Pictures of the delay times observed and output rise and fall times were taken and are shown in pictures #1 through 3. It can be seen from the pictures that the fall time at the output of one of the nine load stages is slow (30 mμsec). This is due to the size of the resistor "R" (6.8k ohms). When this resistor was decreased in value to 5.1k and 6 load stages were driven, the output rise and fall times were both within the required 16 mμsecond limit. From these experimental results, it is concluded that a maximum of six load stages can be driven by the single emitter follower.

It should be pointed out that the delay through the emitter follower driver is very short (approx. 2 mμsec.) The delay measurements shown in picture #2 are taken through two logical stages plus the emitter follower driver.

COMPLEMENTARY EMITTER FOLLOWER

The complementary emitter follower driver is shown in figure 2 with a logical block preceeding it and a typical load stage connected to its output.

NUMBER OF LOAD STAGES -

The complementary emitter follower has an advantage over the single emitter follower in that a current source is not necessary in the emitter load. This means that all of the current through the PNP transistor in the complementary emitter follower can be supplied by the base current flowing back from the load stages. This feature makes it possible for the complementary emitter follower to drive considerably more bases than the single emitter follower without exceeding the power dissipation rating on the transistor. The theoretical maximum number of load stages is 19, which was determined by using MAC circuit design and 5% resistors.

EXPERIMENTAL RESULTS -

The circuit in figure 2 was set up to observe pertinent waveshapes. With 19 stages connected, measurements were made of the delay from input to output, and rise and fall times at the output of one load stage. The effect of the damping resistor (20 Ω) in series with the output of the complementary emitter follower was also observed. These waveforms can be seen in pictures #4 through 6. The circuit was capable of driving the 19 load stages very fast. The transistor power dissipation rating seems to be the main limitation on the number of load stages that can be driven by this driver circuit. If precision resistors were used in the MAC circuit design of the circuits instead of 5% resistors, several more load stages would be permissible on the driver. It is felt that the complementary emitter follower would be able to drive these additional load stages with only a slight decrease in speed.

TRANSIENT ANALYSIS OF EMITTER FOLLOWER

The purpose of this analysis is to determine the cause of the oscillations in the basic emitter follower circuit. When the cause has been determined, methods of eliminating or minimizing the oscillations will be investigated.

EQUIVALENT CIRCUIT -

In the equivalent circuit of the emitter follower (shown in figure 3) it is assumed that a current source is driving it and that the load can be represented by a parallel R-C network. As a simplification, the emitter resistor "re" will be neglected, and therefore C_c and C_1 can be combined into one capacitor "C".

Two node equations can be written from this equivalent circuit:

$$1.\quad I = \frac{V_i}{R} + \frac{V_i - V_o}{r_B}$$

$$2.\quad \frac{\alpha}{1-\alpha}\left(\frac{V_i - V_o}{r_B}\right) = \frac{V_o - V_i}{r_B} + \frac{V_o}{R_L} + C\frac{dV_o}{dt}$$

By substitution and use of Laplace transforms, the following expression must be satisfied to insure that oscillations will not occur.

$$\left[\frac{1}{R'C} + \frac{1}{R_L C} + \omega(1-\alpha)\right]^2 \geq \frac{4\omega}{R_o C}$$

where

$$R' = r_B + R$$

$$\frac{1}{R_o} = \frac{1}{R'} + \frac{1}{R_L}$$

By defining a factor "X" such that $X^2 = \frac{1}{WR_oC}$, the above expression can be reduced to

$$1 - \alpha \geq X(2 - X)$$

A plot of "X" versus "α" shows that the curve is bi-valued. This plot is shown in graph #1.

PROCEDURE FOR DESIGN WITH CURVE -

1. From the transistor data, Ω_B, α, ω, and C_c must be known, although C_c will always be negligible compared to C_L in power driver applications.

2. 2. Calculate "X" from

$$X = \sqrt{\frac{1}{\omega R_o C}} \qquad \text{where} \quad C = C_L + C_c$$

$$\frac{1}{R_o} = \frac{1}{R_L} + \frac{1}{R'}$$

$$R' = \Omega_B + R$$

3. Knowing α, see if the operating point lies in the overdamped region.

CONCLUSIONS -

When the load capacitance is very small, it may be possible to operate in the overdamped region on the upper part of the curve. Increasing the load capacitance would then move the operating point into the oscillatory region. For more heavier capacitive loads, the operating point moves out of the oscillatory region into the lower overdamped region. This agrees with experimental results, as can be seen in picture #7.

Nine transistors were checked for the upper value of load capacitance that would place them in the lower overdamped region of the curve. From their known parameters, "X" was calculated and these experimental values are shown on the theoretical curve plotted in graph #1. These points lie just inside the boundary between the oscillatory and overdamped region. The approximations made in the analysis could account for the slight discrepancies, and also the fact that a linear analysis was applied to a non-linear network. The experimental results also verified that a larger capacitor was necessary to prevent the oscillations for the higher values of "α", as can be seen from graph #1.

Therefore the emitter follower seems to be a good driver for light and heavy loads, but needs some external network for intermediate loads to damp out the oscillations.

For those interested, the complete transient analysis is included in the appendix. This analysis is also reported on in "Handbook of Semiconductor Electronics" in the chapter on switching circuits by J. C. Logue - (pgs. 15-34 to 15-38).

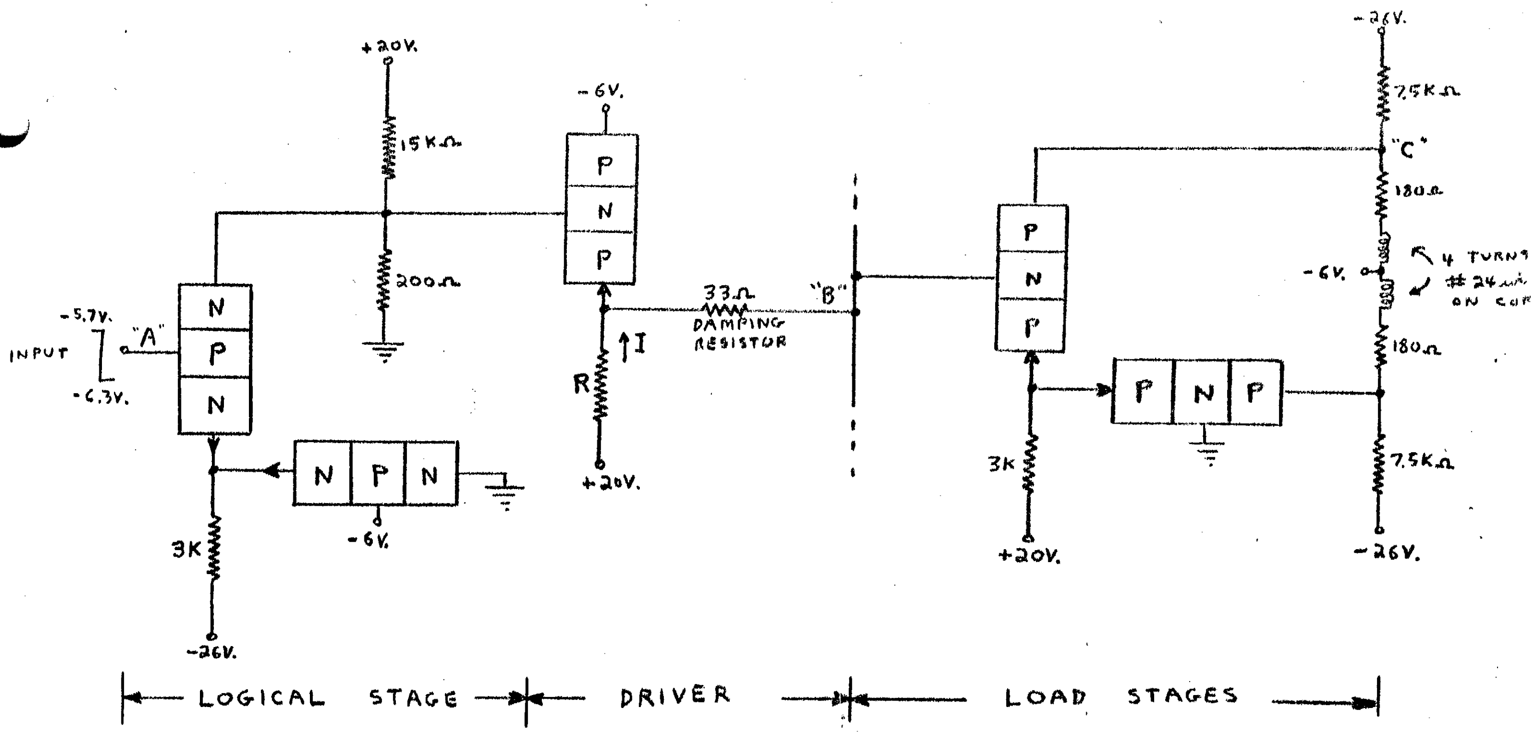


FIGURE 1 : SINGLE EMITTER FOLLOWER DRIVER

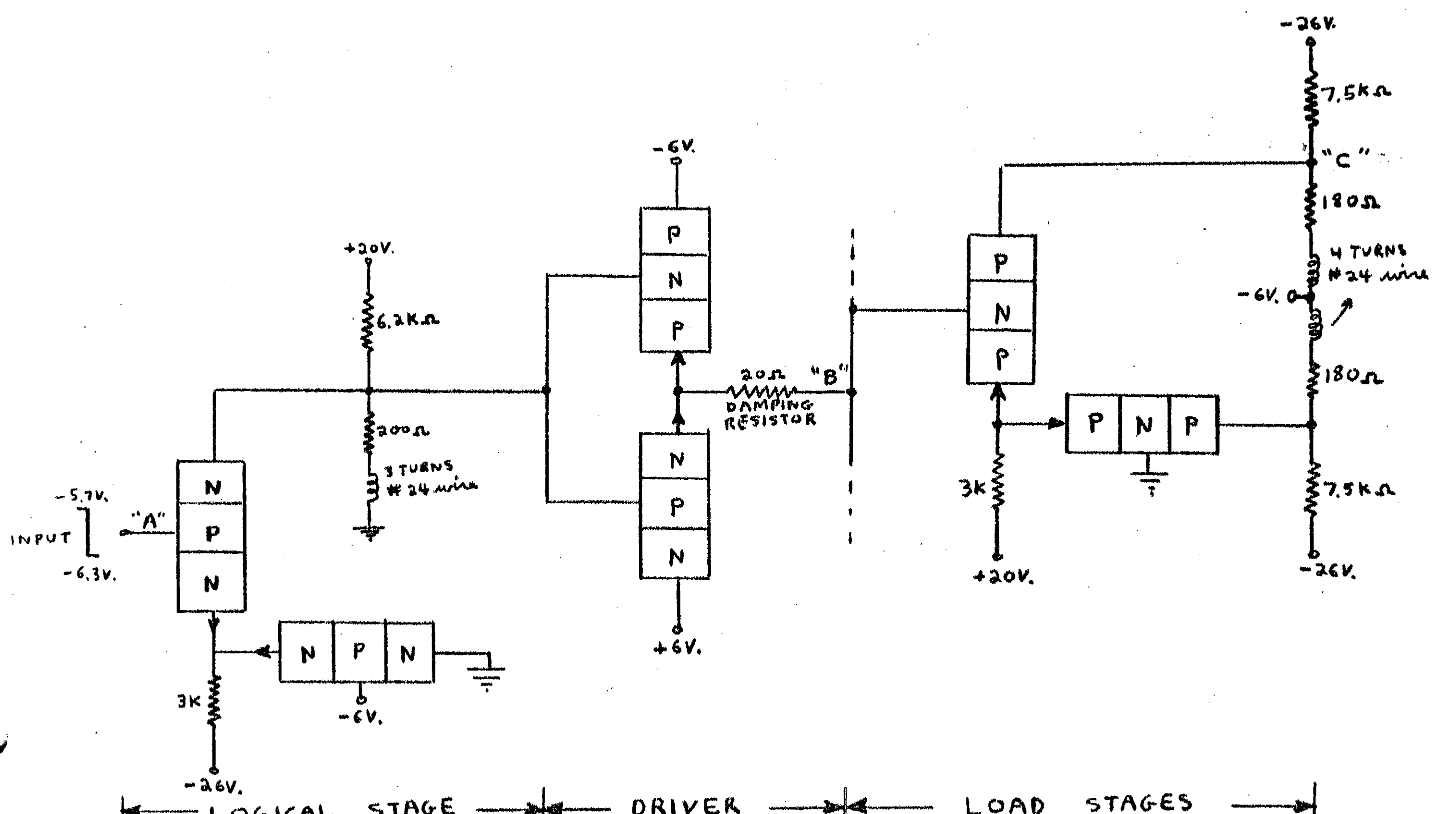


FIGURE 11 : COMPLEMENTARY EMITTER FOLLOWER DRIVER

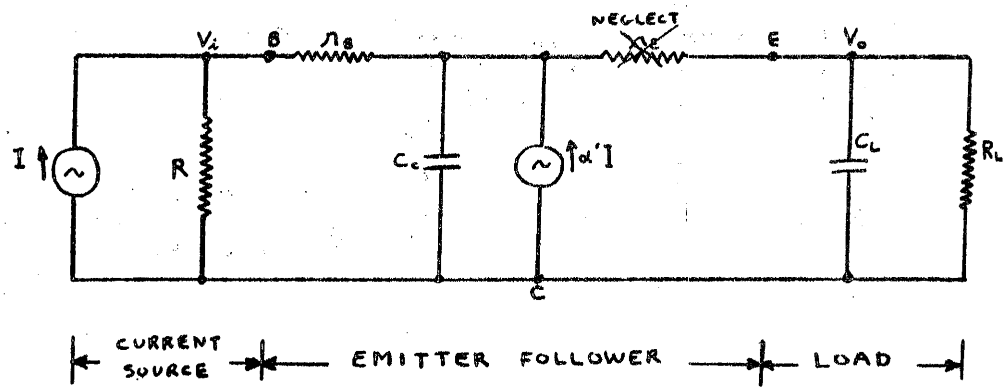


FIGURE 111 : EQUIVALENT CIRCUIT OF BASIC EMITTER FOLLOWER

TABLE 1 : Value of "R" in single emitter follower driver for different number of load stages.

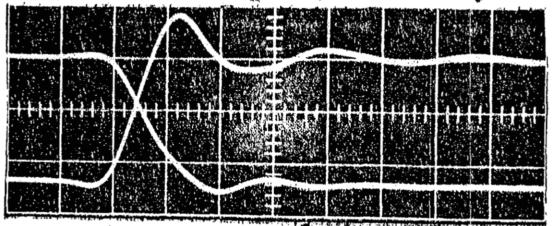
NUMBER OF LOAD STAGES	VALUE OF "R" (OHMS)
3	4.3K
4	4.7K
5	4.7K
6	5.1K
7	5.6K
8	6.2K
9	6.8K

WAVEFORMS FOR SINGLE ENDED EMITTER FOLLOWER DRIVER:

1. Rise and fall time at output of one load stage - (.5 volts/cm)

20 mμsec/cm

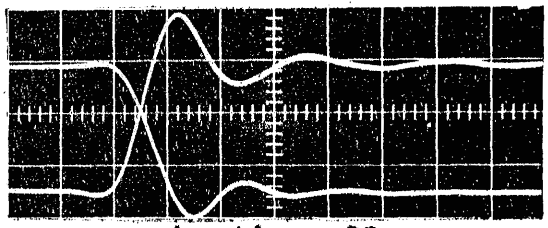
a) with 9 load stages (R = 6.8 K)



rise time = 16 mμsec

fall time = 30 mμsec

b) with 6 load stages (R = 5.1 K)

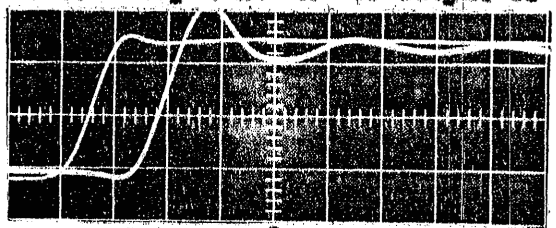


rise time = 12 mμsec

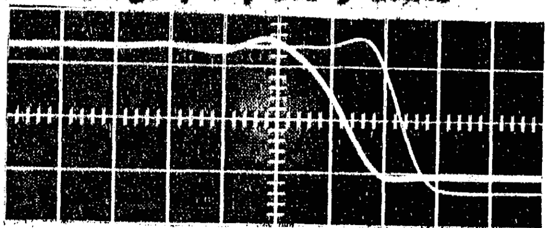
fall time = 16 mμsec

2. Delay time from input at "A" to output of one load stage ("C") for 9 loads -

20 mμsec/cm



delay = 28 mμsec

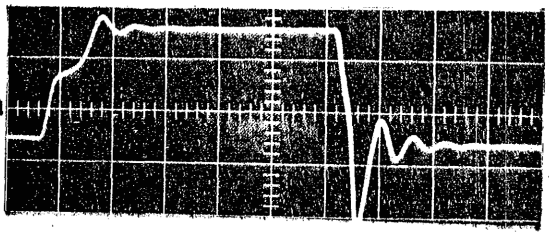


delay = 20 mμsec

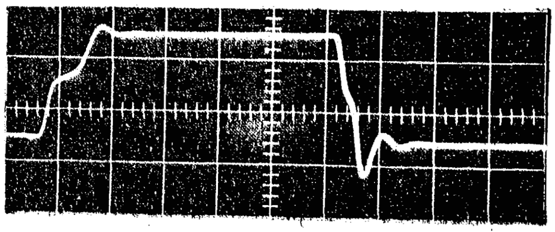
3. Waveform at output of emitter follower ("B") for 9 load stages

100 mμsec/cm

a) without R = 33 Ω

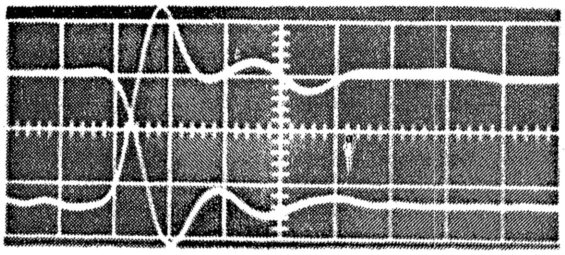


b) with R = 33 Ω



Waveforms for the Complementary Emitter Follower Driver -

4. **Rise and fall time at output of one of nineteen load stages -**

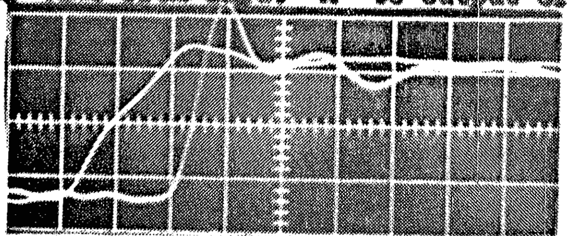


(20 mμsec/cm)

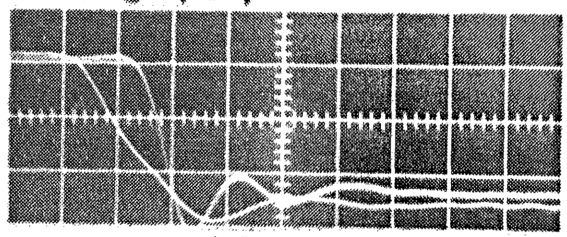
rise time = 12 mμsec

fall time = 14 mμsec

5. **Delay time from input "A" to output of one load stage ("C") -**



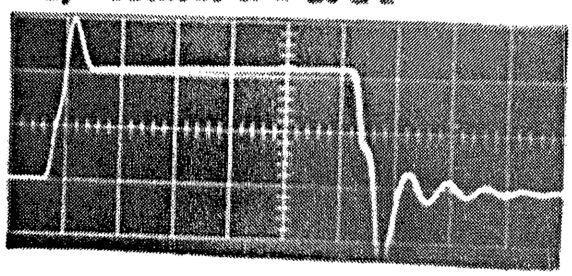
delay = 40 mμsec



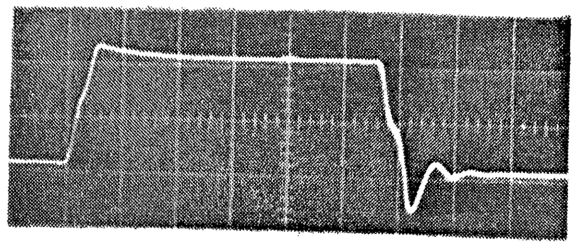
delay = 25 mμsec

6. **Waveform at output of complementary emitter follower ("B")**

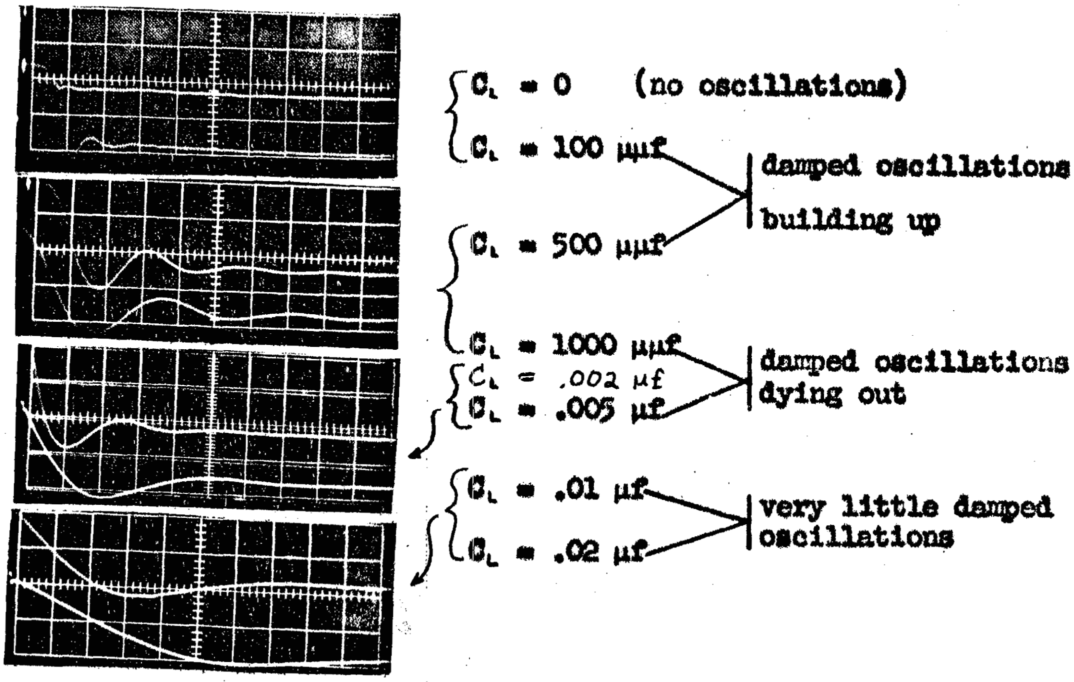
a) without R = 20 Ω



b) with R = 20 Ω



7. **Experimental verification of transient analysis**



APPENDIX

Transient Analysis of Emitter Follower

The equivalent circuit of the basic emitter follower being driven by a current source and having a load that can be represented by a parallel R-C network is shown in figure #3. With "Ω_E" neglected and C_c and C_L combined into one capacitor "C", the following node equations can be written:

$$1. \quad I = \frac{V_i}{R} + \frac{V_i - V_o}{\Omega_B}$$

$$2. \quad \frac{\alpha}{1-\alpha}\left(\frac{V_i - V_o}{\Omega_B}\right) = \frac{V_o - V_i}{\Omega_B} + \frac{V_o}{R_L} + C\frac{dV_o}{dt}$$

By transposing and solving for V_i from equation #1, we obtain

$$V_i\left[\frac{1}{R} + \frac{1}{\Omega_B}\right] = I + \frac{V_o}{\Omega_B}$$

$$\therefore \; V_i = \left(I + \frac{V_o}{\Omega_B}\right)\left(\frac{\Omega_B R}{\Omega_B + R}\right)$$

$$2. \quad \frac{\alpha}{1-\alpha}\left[\frac{\left(I + \frac{V_o}{\Omega_B}\right)\left(\frac{\Omega_B R}{\Omega_B + R}\right) - V_o}{\Omega_B}\right] = \frac{V_o}{\Omega_B} - \frac{\left(I + \frac{V_o}{\Omega_B}\right)\left(\frac{\Omega_B R}{\Omega_B + R}\right)}{\Omega_B} + \frac{V_o}{R_L} + C\frac{dV_o}{dt}$$

By the use of Laplace transforms, this becomes

$$\frac{\alpha\omega}{S + \omega(1-\alpha)}\left[\frac{R}{\Omega_B + R} I(s) + \frac{R}{\Omega_B(R + \Omega_B)} V_o(s) - \frac{V_o(s)}{\Omega_B}\right]$$

$$= \frac{V_o(s)}{\Omega_B} - \frac{R}{\Omega_B + R} I(s) + \frac{R}{\Omega_B(\Omega_B + R)} V_o(s) + \frac{V_o(s)}{R_L} + SCV_o(s)$$

Factoring out I (s) and V_o (s) and combining gives -

$$I(s)\left[\frac{\alpha\omega}{s+\omega(1-\alpha)}\cdot\frac{R}{\Lambda_B+R}+\frac{R}{\Lambda_B+R}\right]=V_o(s)\left[\frac{1}{\Lambda_B}+\frac{R}{\Lambda_B(\Lambda_B+R)}+\frac{1}{R_L}+sC+\frac{\alpha\omega}{s+\omega(1-\alpha)}\cdot\frac{1}{\Lambda_B}-\frac{\alpha\omega}{s+\omega(1-\alpha)}\cdot\frac{R}{\Lambda_B(\Lambda_B+R)}\right]$$

Multiply through by S + ω ($1-\alpha$) -

$$I(s)\left[\frac{\alpha\omega R}{\Lambda_B+R}+\frac{R}{\Lambda_B+R}\{s+\omega(1-\alpha)\}\right]=V_o(s)\left[\frac{s+\omega(1-\alpha)}{\Lambda_B}+\frac{R\{s+\omega(1-\alpha)\}}{\Lambda_B(\Lambda_B+R)}+\frac{s+\omega(1-\alpha)}{R_L}+sC\{s+\omega(1-\alpha)\}+\frac{\alpha\omega}{\Lambda_B}-\frac{\alpha\omega R}{\Lambda_B(\Lambda_B+R)}\right]$$

THIS BECOMES -

$$I(s)\left[\frac{R}{R+\Lambda_B}(s+\omega)\right]=V_o(s)\left[s^2C+s\left\{\frac{1}{\Lambda_B}-\frac{R}{\Lambda_B(\Lambda_B+R)}+\frac{1}{R_L}+C\omega(1-\alpha)\right\}+\frac{\omega(1-\alpha)}{\Lambda_B}-\frac{R\omega(1-\alpha)}{\Lambda_B(\Lambda_B+R)}+\frac{\omega(1-\alpha)}{R_L}+\frac{\alpha\omega}{\Lambda_B}-\frac{\alpha\omega R}{\Lambda_B(\Lambda_B+R)}\right]$$

Dividing through by C and solving for V_o (s) gives

$$V_o(s)=\frac{\frac{R}{C(\Lambda_B+R)}(s+\omega)\,I(s)}{s^2+s\left[\frac{1}{\Lambda_BC}\left(1-\frac{R}{\Lambda_B+R}\right)+\frac{1}{R_LC}+\omega(1-\alpha)\right]+\frac{\omega(1-\alpha)}{\Lambda_BC}\left(1-\frac{R}{\Lambda_B+R}\right)+\frac{\omega(1-\alpha)}{R_LC}+\frac{\alpha\omega}{\Lambda_BC}\left(1-\frac{R}{\Lambda_B+R}\right)}$$

Since $1-\frac{R}{\Lambda_B+R}=\frac{\Lambda_B}{\Lambda_B+R}$, the denominator becomes

$$s^2+s\left[\frac{1}{(\Lambda_B+R)C}+\frac{1}{R_LC}+\omega(1-\alpha)\right]+\frac{\omega(1-\alpha)}{(\Lambda_B+R)C}+\frac{\omega(1-\alpha)}{R_LC}+\frac{\alpha\omega}{(\Lambda_B+R)C}$$

OR -

$$s^2+s\left[\frac{1}{(\Lambda_B+R)C}+\frac{1}{R_LC}+\omega(1-\alpha)\right]+\frac{\omega}{(\Lambda_B+R)C}+\frac{\omega(1-\alpha)}{R_LC}$$

Working on the denominator only, the roots are

$$s_1,s_2=\frac{-\left[\frac{1}{(\Lambda_B+R)C}+\frac{1}{R_LC}+\omega(1-\alpha)\right]\pm\sqrt{\left[\frac{1}{(\Lambda_B+R)C}+\frac{1}{R_LC}+\omega(1-\alpha)\right]^2-4\left[\frac{\omega}{(\Lambda_B+R)C}+\frac{\omega(1-\alpha)}{R_LC}\right]}}{2}$$

Three conditions are possible. If the radical is negative, an oscillatory condition will exist. If the square root is zero, the circuit will be critically damped, and if it is positive, the circuit will be overdamped. Therefore, to insure that oscillations will not occur, the following equation must be satisfied:

$$\left[\frac{1}{(r_B+R)C} + \frac{1}{R_L C} + \omega(1-\alpha)\right]^2 \geqq 4\left[\frac{\omega}{(r_B+R)C} + \frac{\omega(1-\alpha)}{R_L C}\right]$$

By letting $R' = r_B + R$ and $\frac{1}{R_o} = \frac{1}{R'} + \frac{1}{R_L}$, this becomes

$$\left[\frac{1}{R_o C} + \omega(1-\alpha)\right]^2 \geqq \frac{4\omega}{C}\left[\frac{1}{R_o} - \frac{\alpha}{R_L}\right]$$

If the load is such that $\frac{1}{R'} + \frac{1}{R_L} >> \frac{\alpha}{R_L}$, then

$$\left[\frac{1}{R_o C} + \omega(1-\alpha)\right]^2 \geqq \frac{4\omega}{R_o C}$$

By letting $X^2\omega = \frac{1}{R_o C}$:

$$\left[\frac{1}{R_o C} + \frac{1-\alpha}{X^2 R_o C}\right]^2 \geqq \frac{4}{X^2 (R_o C)^2}$$

Taking the square root of both sides gives -

$$\frac{1}{R_o C} + \frac{1-\alpha}{X^2 R_o C} \geqq \frac{2}{X R_o C}$$

Cancelling the R_oC terms -

$$1 - \alpha \geqq X(2 - X)$$

where $X = \frac{1}{\sqrt{\omega R_o C}}$

$\frac{1}{R_o} = \frac{1}{R_L} + \frac{1}{R'}$

$R' = r_B + R$

This equation was plotted up on graph #1.

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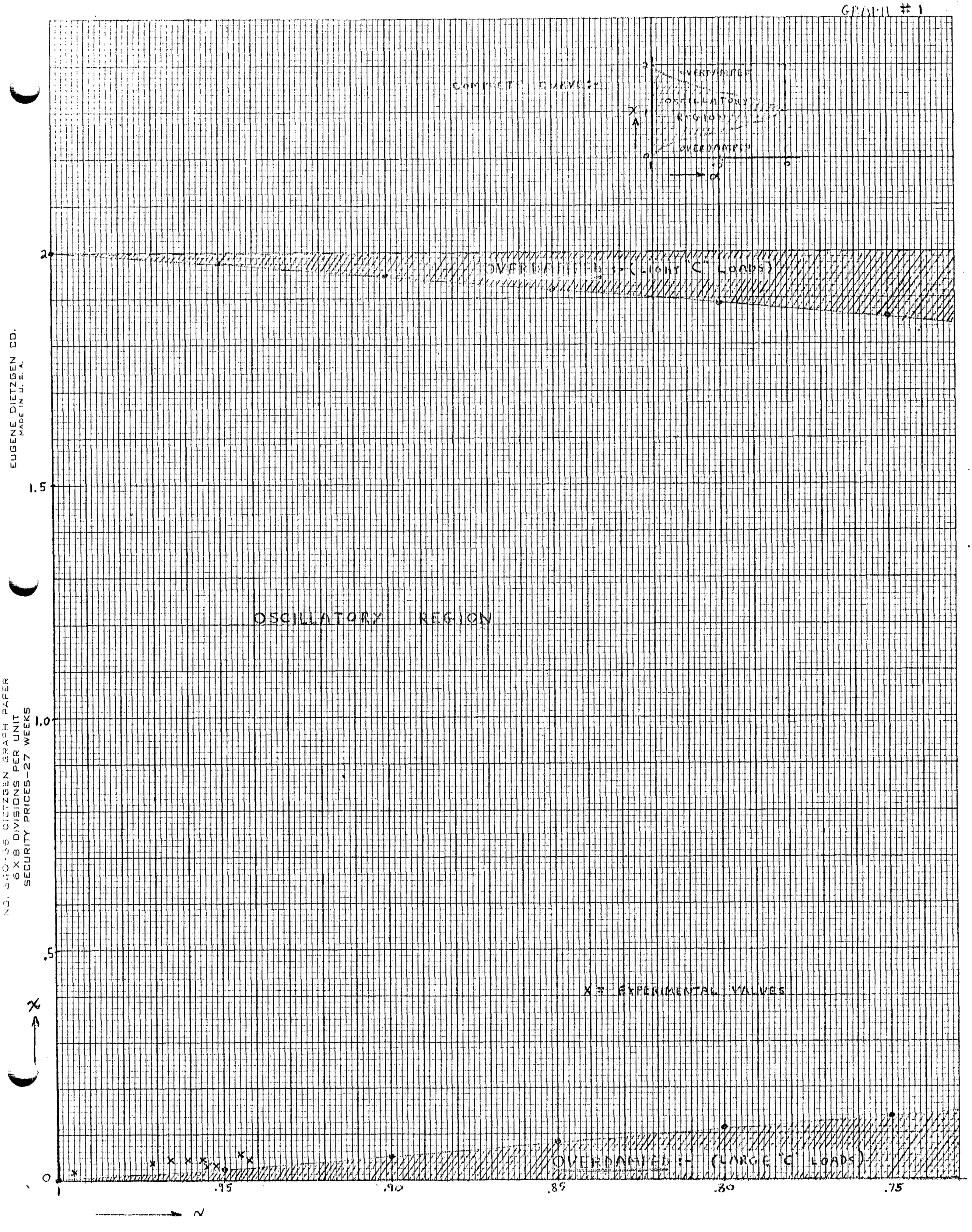
GRAPH #1



COMPLETE CURVE:-
OVERDAMPED
OSCILLATORY REGION
OVERDAMPED
OVERDAMPED :- (LIGHT 'C' LOADS)
OSCILLATORY REGION
X = EXPERIMENTAL VALVES
OVERDAMPED :- (LARGE 'C' LOADS)
2
1.5
1.0
.5
0
1
.95
.90
.85
.80
.75