



TECHNICAL NOTE 143

TIM-DISTORTION IN MONOLITHIC INTEGRATED CIRCUITS: MEASUREMENTS AND SIMULATION

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INTRODUCTION

Linear amplifiers and preamplifiers for audio applications have a well known intrinsic dynamic limitation known as slew-rate (SR) and produce distortion when the output signal slope (SS) tends to equal or exceed this limit.

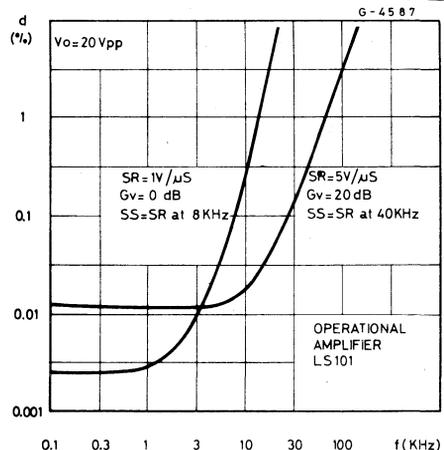
A great deal has been written on this subject over the last few years, but it is only recently that a clear and definitive analysis has been formulated. In a series of papers [2]—Jung, Stephens and Todd—have been able to determine the relevant parameters for the formation of TIM distortion.

It is a widespread belief that the use of large amounts of feedback is the cause of TIM distortion. Only recently has it been concluded that large amounts of feedback do not increase the possibility of TIM if the amplifier has a sufficiently high slew-rate.

In particular, for SS lower than SR an increase in the feedback factor reduces the TIM, while for lower values of SR increasing the feedback increases the TIM, hence the TIM is under control for values

of the ratio $\frac{SS}{SR}$ less than unity (Fig. 1).

Fig. 1 – THD vs Frequency of LS101 for two conditions of Slew-Rate and Gain



The SR of a Hi-Fi audio amplifier is therefore an essential design parameter, whereas the small signal parameters, the feedback factor and the open-loop frequency response are *per se* irrelevant as far as dynamic distortion is concerned.

This TN describes the "IS-TIM" measurement system and the results of experimental and simulation work on the TDA2310 preamplifier and the TDA2040 Hi-Fi power amplifier.

TIM – DISTORTION

Over the last ten years TIM Distortion has attracted considerable interest in audio engineering circles.

Among the many published papers on the subject a number deal with the measurement of TIM.

The best known method consists of feeding sine waves superimposed into square waves into the amplifier under test [9].

The output spectrum is then examined using a spectrum analyser and compared to the input. This suffers from serious disadvantages: the accuracy is limited, the measurement is a rather delicate operation and an expensive spectrum analyser is essential.

Recently, a new approach has been described by S. Takahashi and S. Tanaka [5] [6] which is, in their own words, simple yet precise. This method, which

we will refer to as the "Inverting Sawtooth" method, is also fast, cheap—it requires nothing more sophisticated than an oscilloscope — and sensitive — it can be used down to TIM values as low as 0.002% in high power amplifiers.

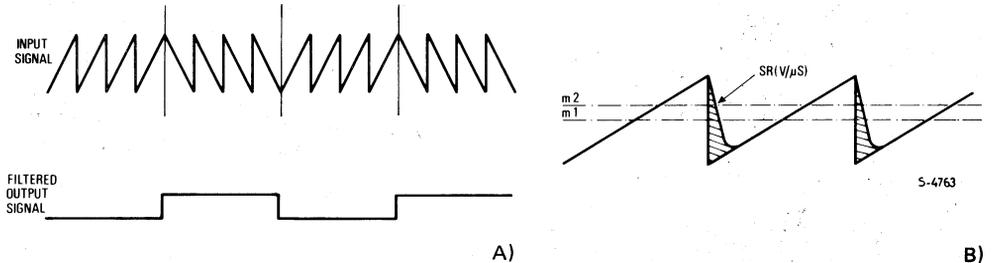
THE INVERTING SAWTOOTH METHOD

The Inverting Sawtooth (IS-TIM) method is based on the response of an amplifier to a sawtooth waveform. The amplifier has no difficulty following the slow ramp but it cannot follow the fast edge. The output will follow the upper line in Fig. 2-B cutting off the shaded area — and thus increasing the mean level. If this output signal is filtered to remove the sawtooth a DC voltage remains which indicates the amount of TIM distortion.

This voltage would be difficult to measure because it is indistinguishable from the DC offset of the amplifier. This problem is neatly avoided in the IS-TIM method by periodically phase reversing the sawtooth waveform at a low audio frequency (Fig. 2-A). In the case of the sawtooth in Fig. 2-B the mean level was increased by the TIM distortion; for a sawtooth in the other direction the opposite is true.

This results in an AC signal at the output whose peak-to-peak value is the TIM voltage and can be measured easily with an oscilloscope.

Fig. 2 - Inverting Sawtooth Waveform.



PRACTICAL MEASUREMENTS

The hardware needed to perform IS-TIM measurements is shown in Fig. 3. Some form of signal

generator must be provided to generate the inverting sawtooth waveform. The desired waveform consists of a 20 KHz sawtooth which is phase-inverted every 256 cycles.

Fig. 3 - IS-TIM Distortion Set-up.



The IS generator is followed by a high pass filter which attenuates the 78 Hz switching component of the IS waveform by more than 90 dB. A suitable circuit is shown in fig. 4. This is a straightforward 36 dB/oct. Butterworth filter with a cutoff at ~ 1 KHz.

Before passing the filtered signal to the amplifier under test a simple RC network is used to limit the maximum signal slope to a reasonable value.

The RC network can be switched to supply signals of varying severity to the test amplifier. For most purposes the $f_c = 30$ KHz position can be used. After the amplifier under test the 20 KHz sawtooth must be filtered out so that the TIM induced

voltage can be measured.

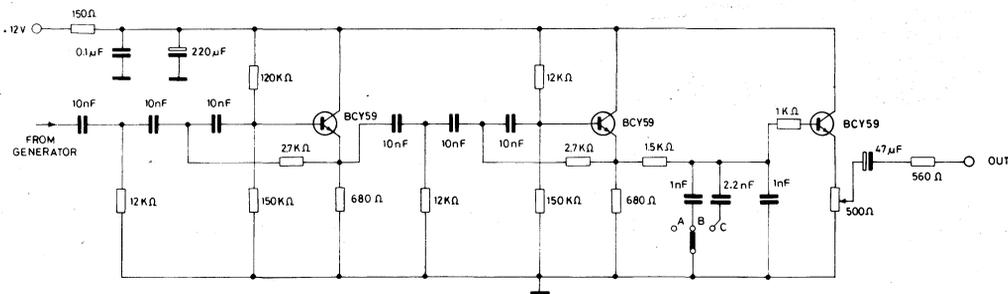
The passive low-pass network in Fig. 5 gives the desired response.

Finally, the filtered output signal is displayed on an ordinary oscilloscope. If the peak-to-peak value of this signal and the peak-to-peak value of the Inverting Sawtooth are measured the TIM can be found very simply from:

$$TIM = \frac{V_{out}}{V_{sawtooth}} \times 100 (\%)$$

where V_{out} and $V_{sawtooth}$ are the peak-to-peak values mentioned above.

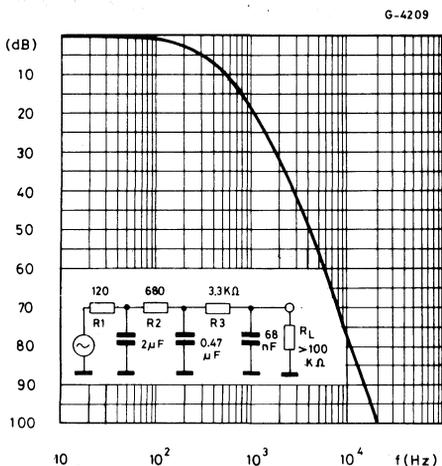
Fig. 4 - Active high-pass Butterworth filter (36 dB/octave)



- A : 100 KHz
- B : 50 KHz
- C : 30 KHz

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Fig. 5 - Simple low-pass filter.



THE INVERTING SAWTOOTH GENERATOR

To generate the special Inverting Sawtooth waveform we designed the simple circuit shown in Fig. 6.

The operation of this circuit is relatively straightforward.

An ordinary sawtooth signal is generated by a relaxation oscillator consisting of a constant current generator (Q1), a capacitor (C1), inverting triggers (IC1A and IC1B) and an analogue switch (IC2A). C1 is charged by the constant current generator until the voltage across it reaches the upper threshold of the trigger IC1B which is about 6.5V.

This closes the analogue switch and discharges C1. Discharging continues until the voltage across C1 falls to the lower threshold of the trigger, about 3V, when the analogue switch opens and C1 changes again. The frequency at the resulting sawtooth waveform is adjusted to 20 KHz by the trimmer P1.

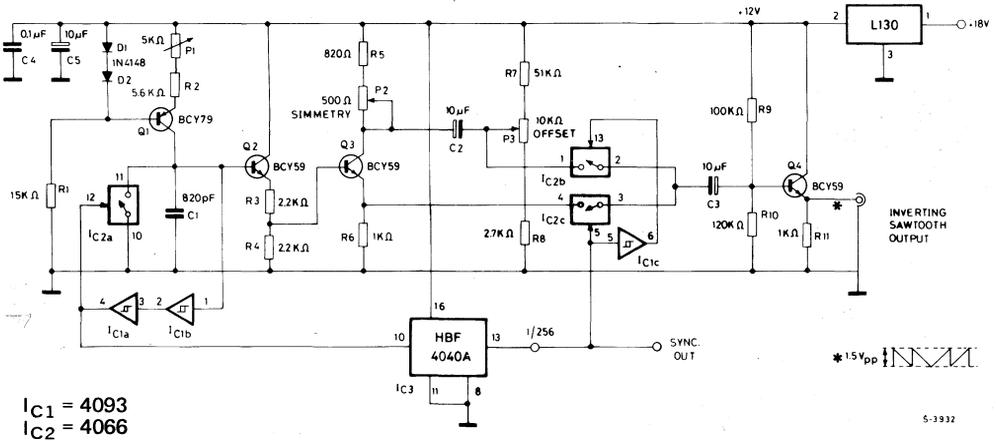
The buffer, (Q2), minimizes the loading on C1 and attenuates the signal to avoid saturating the phase-splitter that follows.

The phase-splitter, (Q3), provides two out of phase sawtooth waveforms: one with an ascending ramp and the other with a descending ramp.

The trimmer P2 adjusts the symmetry of these waveforms. Another trimmer P3, in the inverted signal decoupling network, adjusts the relative offset of the two waveforms. The analogue switches IC2B and IC2C select either the direct or inverted sawtooth under control of the counter. This counter divides the discharge

pulses from the relaxation oscillator by 256 so that the output sawtooth signal changes phase every 256 cycles. The inverting sawtooth is buffered by Q4. The output of the counter also serves to synchronise the oscilloscope used in the measurements. Without this sync. it would be virtually impossible to observe the inverting sawtooth waveform.

Fig. 6 - Inverting - Sawtooth generator



MODELLING AND SIMULATION PROGRAM

In parallel with the experimental activity, using the IS-TIM system described above, a model has been developed for computer simulation.

The computer simulation technique makes it possible to obtain the behaviour of the amplifier under test for practically any condition possible and to verify all the imaginable variants without having to resort to experimental measurements.

The first device tested (the classic and versatile LS148, an op-amp. with external compensation) was simulated by both a physical model representing a complete circuit (Fig. 7) and a macro-model (Fig. 8) designed to respect the dynamic limitations of the amplifier.

The simulations were performed for both of the models using the SPICE IIF program, one of the most widely used in this field thanks to its processing ability (complete DC-AC analysis, Fourier analysis, transients, etc.) and to the accurate transistor models contained in the program.

The results confirm that the models are accurate and reliable.

In the graphs, figs. 10 and 11, and in table I the data for the LS148 is collected.

Tab I - IS-TIM simulation for LS148 with $f_{RC} = 30 \text{ kHz}$ (input filter)

| Slew-Rate (V/ μ s) | Output Voltage (V _{pp}) | Mean Value (mV) | | Mean Value (mV) | TIM (%) |
|------------------------|-----------------------------------|-----------------|--------|-----------------|---------|
| | | | | | |
| 0,5 | 1.25 | 3.33 | -0.33 | 3.66 | 0.3 |
| | 2.5 | 19.7 | -15.1 | 34.8 | 1.4 |
| | 5.0 | 193.8 | -178.3 | 372.1 | 7.44 |
| 1,5 | 1.25 | 1.36 | 1.43 | 0.07 | 0.006 |
| | 2.5 | 2.24 | -0.78 | 3.02 | 0.12 |
| | 5.0 | 10.9 | -6.3 | 17.2 | 0.34 |
| | 10.0 | 153.3 | -127.0 | 280.3 | 2.80 |
| 5 | 20.0 | 46.0 | -28.5 | 74.5 | 0.37 |

From the experimental results it can be seen that the TIM/peak output voltage slope is different for low slew-rate and for higher slew-rates.

Other devices chosen for measurements and simulation were the Hi-Fi audio devices:

- TDA2310 Very low distortion high dynamic range RIAA/TAPE preamplifier;
- TDA2040 Hi-Fi power amplifier (min. 20W-0,5% THD).

The application circuits for these devices are shown in Figs. 9 and 12. The results of the measurements compared with the simulation results are shown in Fig. 13 (TDA2310) and Fig. 14 (TDA2040).

The simulation work was undertaken using both the physical model and the macromodel. As can be seen, the results indicate the reliability and accuracy of the models.

Fig. 7 - Operational amplifier Physical Model.

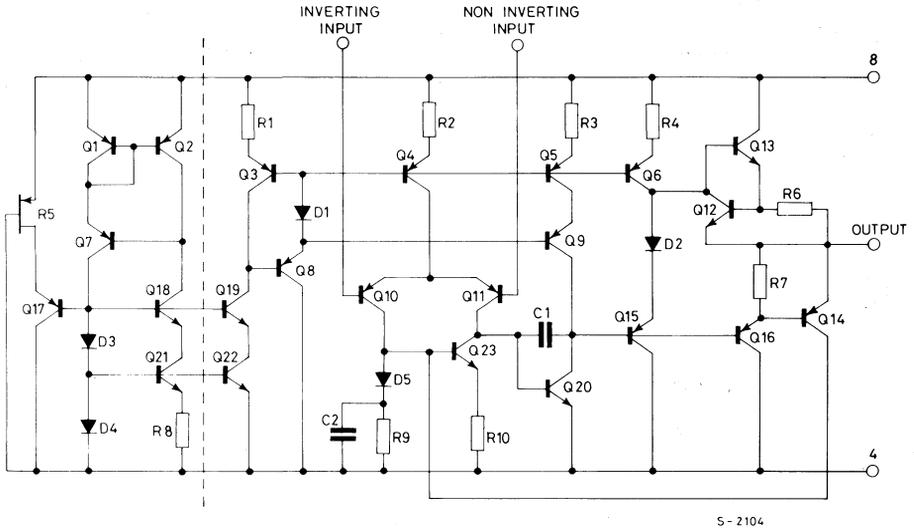


Fig. 8 - Macromodel of Operational Amplifier.

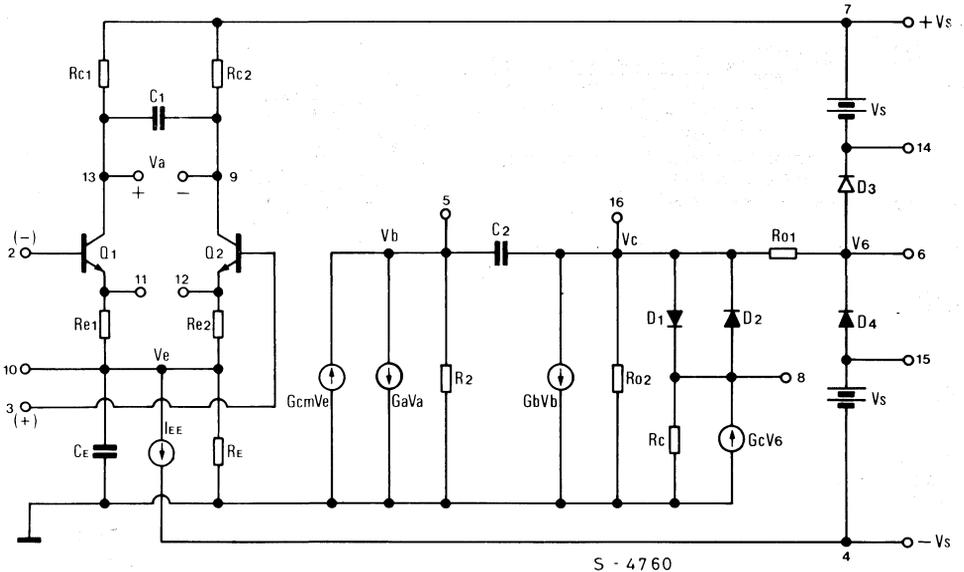


Fig. 9 - RIAA Preamplifier for Hi-Fi using TDA2310.

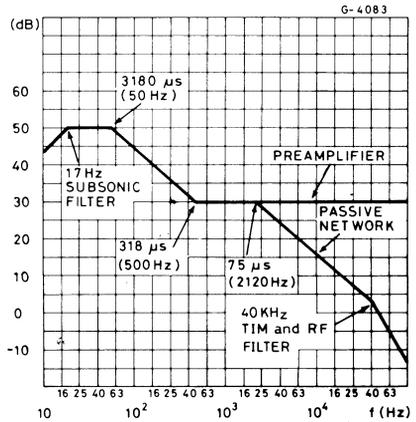
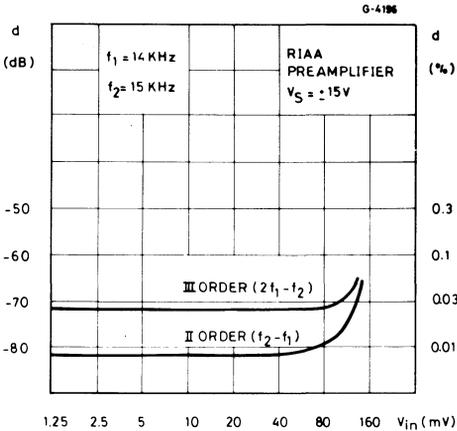
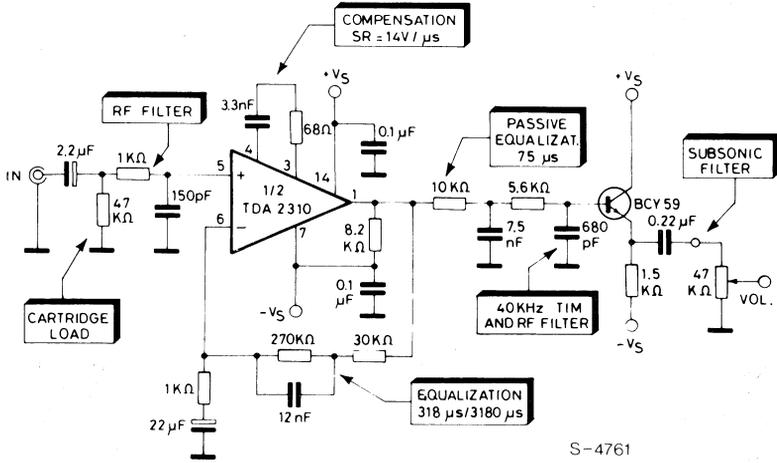


Fig. 10 - IS-TIM Distortion of Op-Amp. LS148 (f_{RC} = 30 KHz) Fig. 12 - Application circuit of TDA2040, mono-
 lithic power amplifier.

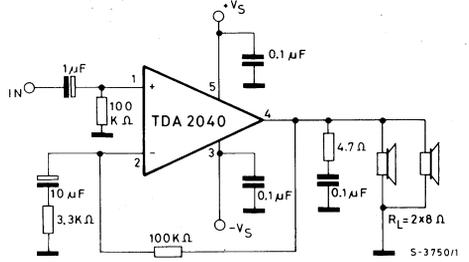
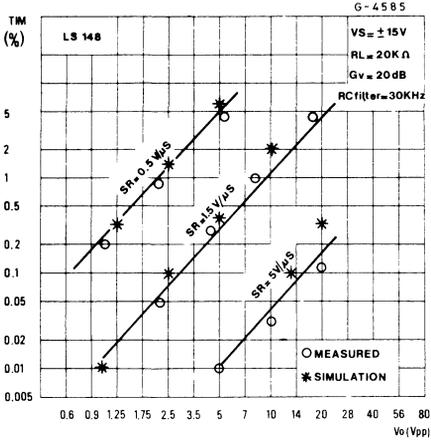


Fig. 11 - IS-TIM Distortion of Op-Amp. LS148 (f_{RC} = 100 KHz)

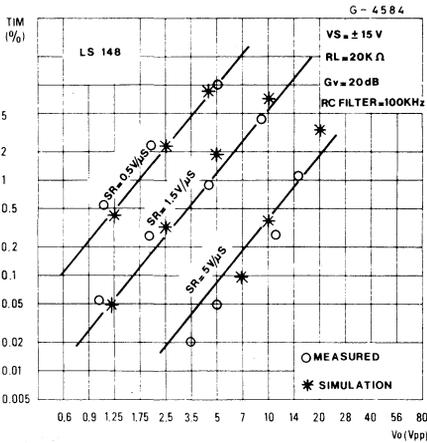


Fig. 13 - TIM distortion of the TDA2310.

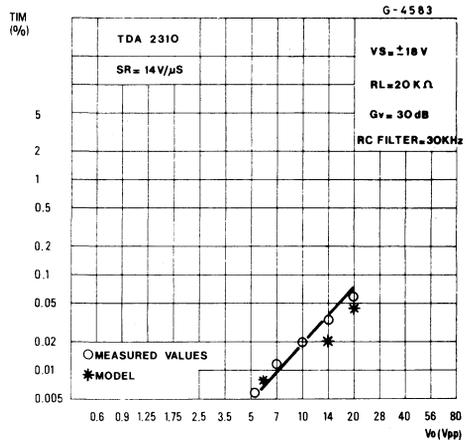


Fig. 14 - TIM distortion of the TDA2040.

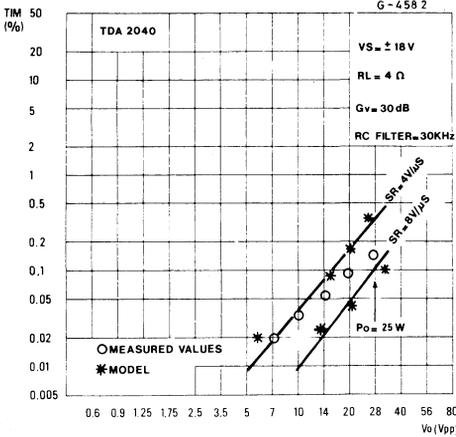
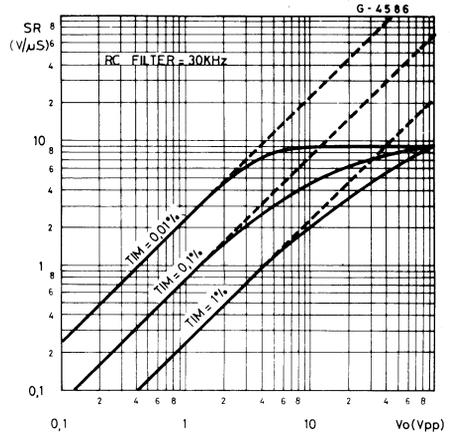


Fig. 15 - TIM design diagram ($f_{RC} = 30 \text{ KHz}$).



DESIGNING FOR LOW TIM

A simple RC filter on the input of the amplifier to limit the maximum signal slope (SS) is an effective way to reduce TIM.

Figs. 15 and 16 can be used to find the Slew-Rate (SR) required for a given output power or voltage and a TIM design target. For example, if an anti-TIM filter with a cutoff at 30 KHz is used and the max peak-to-peak output voltage is 20V then referring to Fig. 15, a Slew-rate of 6V/μs would be necessary for 0,1% TIM. Fig. 17 converts output power to output voltage for use in the other charts. One interesting point to note in Fig. 15 and Fig. 16 is that slew-rates above 15V/μs do not contribute to a further reduction in TIM.

Slew-rates of 100V/μs are not only useless but also a disadvantage in Hi-Fi audio amplifiers because they tend to turn the amplifier into a radio receiver. For high quality amplifiers the designers should aim to operate in the optimal design area as shown in Figs. 17, 19 and 20.

The use of a simple RC input filter is highly recommended.

Fig. 16 -- TIM design diagram ($f_{RC} = 100 \text{ KHz}$)

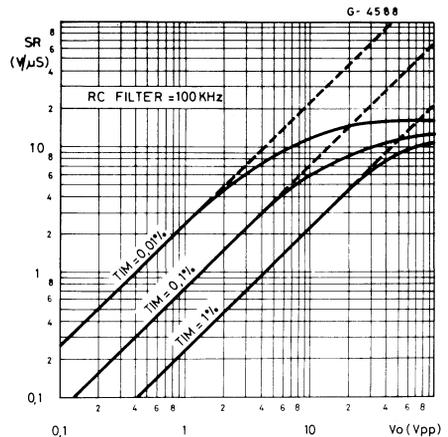


Fig. 17 - Conversion chart (V_{pp}/P_o).

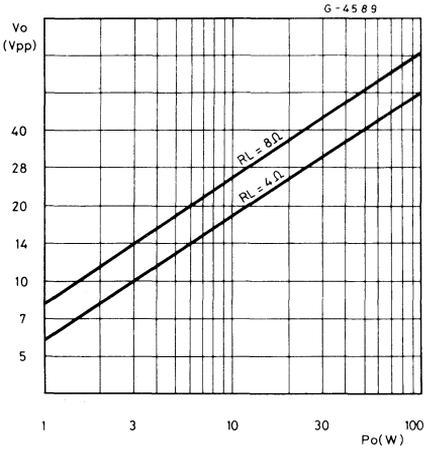


Fig. 19 - Optimum Slew-Rate and Power Bandwidth for Hi-Fi amplifiers Vs. Output Power ($R_L = 8\Omega$).

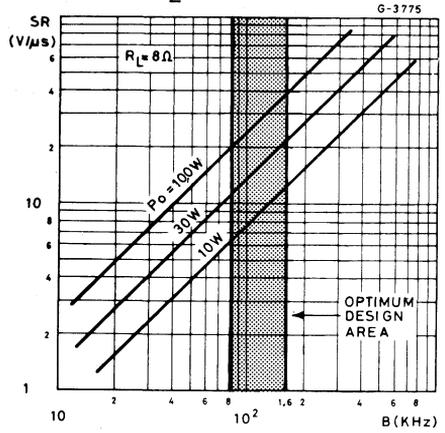


Fig. 18 - Optimum Slew-Rate and Power Bandwidth for Hi-Fi amplifiers Vs. peak to peak Output Voltage.

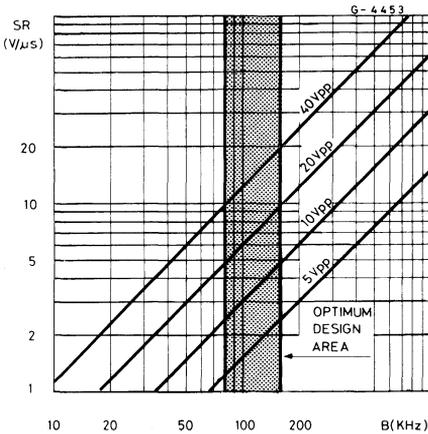
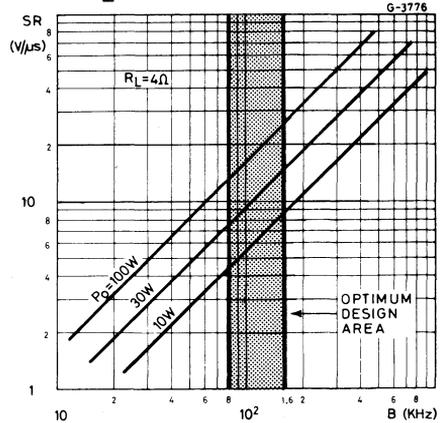


Fig. 20 - Optimum Slew-rate and Power Bandwidth for Hi-Fi amplifiers Vs. Output Power ($R_L = 4\Omega$).



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