Phase compensation design considerations

The new amplifier of the A810 features an advanced phase compensation technique. This article outlines the developments that led to optimum treble record equalization without phase error.

Problem definition

The fundamental purpose of all tape recordings is to store the audio signals in a form that is compatible with other recorders and to ensure that they can be reproduced with high fidelity. However, frequency-response errors occur in the recording as well as the reproduction process. In addition, the peak recording level of a tape depends on the ratio of coating thickness to wave length of the recording frequency. For this reason, tape flux has been defined and standardized in such a way that tape saturation can be prevented.

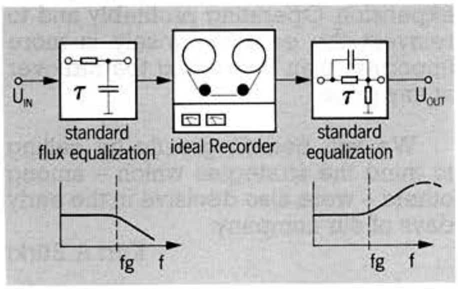

Fig. 1

The simple arrangement illustrated in Fig. 1 ensures that the tape flux remains within the specified standard. It should be noted, however, that current standards refer only to the amplitude response. However, it makes sense to define the phase response as well. In the arrangement illustrated in block diagram 1, both the amplitude response and the phase response are corrected. In our subsequent discussions we simply call this an "ideal recorder".

Recording of the audio signals is disturbed by amplitude errors (treble losses). The most important factors are:
- Coating thickness attenuation
- Self demagnetization
- Attenuation by a recording gap that is not infinitesimally small

These factors produce so-called aperture distortions. A common characteristic is that they do not cause any phase displacement. These treble losses must be compensated in the recording section in order to attain the standard tape flux while simultaneously maintaining the phase response which should also be part of the standard [although it has not (yet) been included]. The following circuit versions illustrate the progress in development that led to the advanced solution.

Implemented circuit versions

1st Version

Recording circuit with record equalization by an RC network.

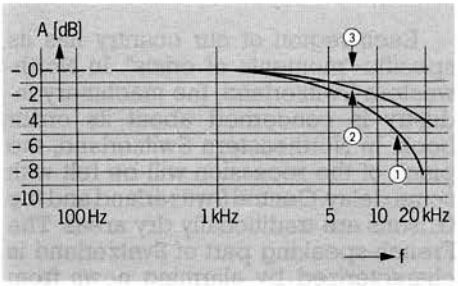

Fig. 2

Curve ① represents the uncorrected frequency response of the "ideal recorder". Frequency response ② results if the norm flux equalization (attenuation), as required to attain the standardized tape flux, is omitted before the signal is processed by the ideal recorder. The remaining boost to obtain a linear frequency response ③ can be accomplished with a simple RC network (Fig. 3).

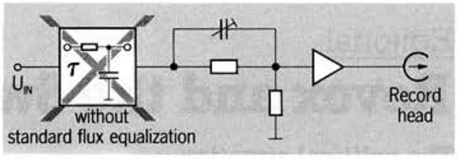

Fig. 3

Advantages:
- Frequency response can be very accurately equalized by any type of network
- Inexpensive

Disadvantages:
- Major errors (required phase response not achieved)
- Adjustment difficult to implement with trimmer potentiometer

2nd Version

Treble boost by adding a differentiated and inverted signal.

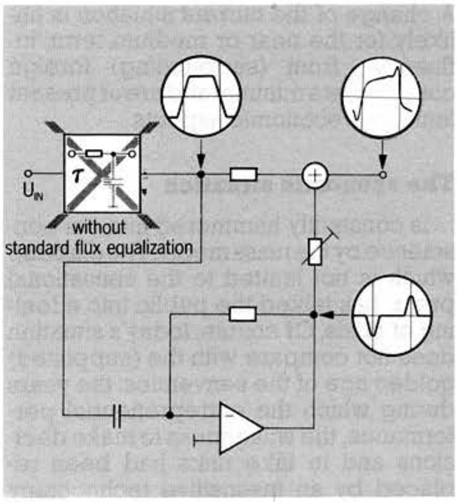

Fig. 4

In this version also, some of the boost is achieved by omitting the standard flux equalization. The additional equalization is better than in version 1 as far as the phase response is concerned.

Advantages:
- Good frequency response achievable
- Control with variable resistor

Disadvantages:
- Residual phase errors
- No limitation of bandwidth

3rd Version

High frequency record equalization by adding a double-differentiated, inverted signal. In this version, the record equalization required for the standard tape flux is not omitted and is left as

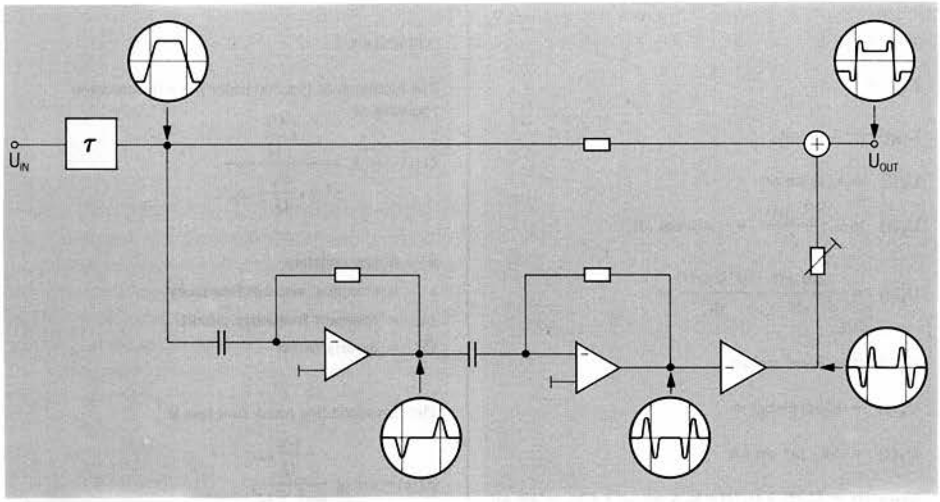

Fig. 5

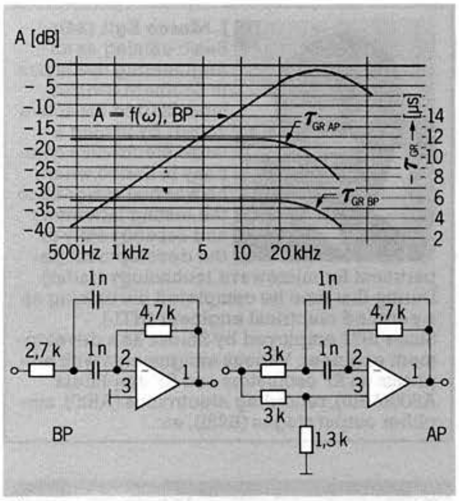

Fig. 8

illustrated in Fig. 1 (Mathematical solution, see Appendix 1).

Advantages:
- Good phase response achievable
- Proper phase relation

Disadvantages:
- No limitation of bandwidth. Whistling noises
- Danger of tape saturation at high frequencies
- High noise levels above 20 kHz alter the bias current

Solution implemented on the STUDER A810

This state-of-the-art solution for optimum phase correction (without the disadvantages of version 3) is based on the following:

① The underlying concept is the same as described for version 3.
② The differentiation stages are replaced by special bandpasses (BP). These feature a frequency-proportional amplitude response in the frequency range of interest.
③ A delay network is inserted into the main branch. Its purpose is to compensate unavoidable bandpass delay.

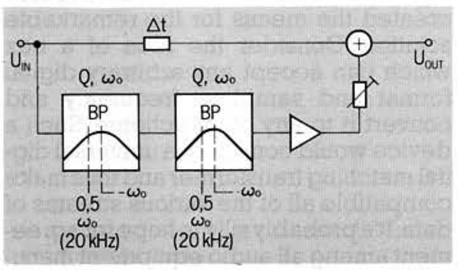

Fig. 6

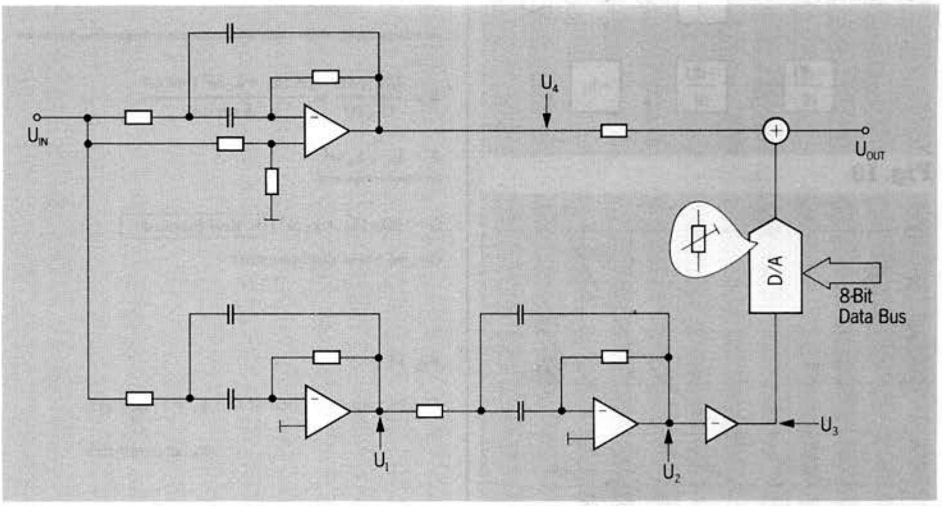

Fig. 7

The operating range is on the lower slope of the bandpasses. For frequencies up to 20 kHz, this slope requires a treble boost with a fixed steepness of 6 dB/octave. Inversion of the frequency response curve limits the bandwidth and unwanted noise above the audio range is consequently eliminated.

With respect to the bandpass filters, the previously mentioned group delay problem must be solved. In the operating range, this delay should be independent of the frequency. This requirement has been satisfied by the accurate definition of the filter Q's (0.57 to 0.6) (mathematical derivation, see Appendix 2). It is thus possible to compensate the group delay of the bandpasses by a delay network in the direct path. The delay correction network is implemented by an allpass of the 2nd order. Mathematically accurate correction of the delay occurs when the Q factors and ω_0 of the allpass correspond to those of the bandpasses.

Fig. 8 illustrates the characteristics and the component values of the equalizer section.

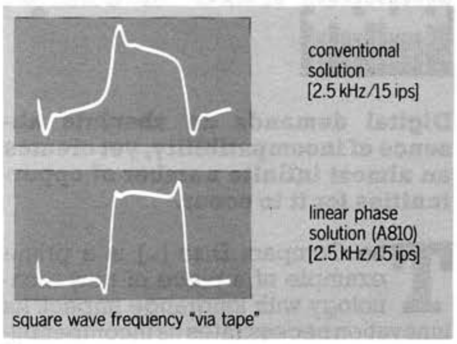

Fig. 9

Fig. 9 gives a comparison of squarewave frequencies via tape (2.5 kHz at 15 ips) obtained with phase compensation (A810) and without (conventional record amplifier).

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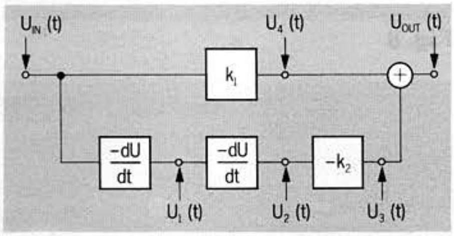

Fig. 10

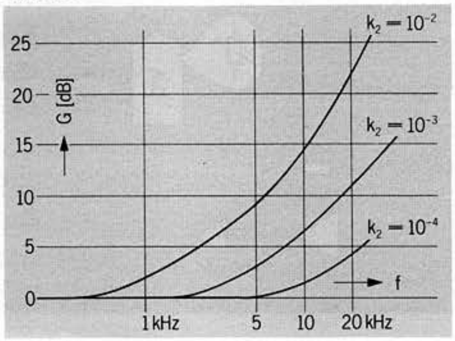

Fig. 11

APPENDIX 1

Fig. 10

$U_{IN}(t) = A \sin \omega t$

$U_4(t) = k_1 A \sin \omega t$

$U_1(t) = -\frac{d\,U_{IN}(t)}{dt} = -A\omega \cos \omega t$

$U_2(t) = -\frac{dU_1(t)}{dt} = \frac{d^2 U_{IN}(t)}{dt^2} \Rightarrow$

$U_2(t) = -A\,\omega^2 \sin \omega t$

$U_3(t) = U_2(t)(-k_2) \Rightarrow$

$U_3(t) = Ak_2\,\omega^2 \sin \omega t$

$U_{OUT}(t) = U_4(t) + U_3(t) = k_1 A \sin \omega t + Ak_2\,\omega^2 \sin \omega t$

$U_{OUT}(t) = A(k_1 + k_2\,\omega^2) \sin \omega t$

===

$\vartheta = \frac{U_{OUT}(t)}{U_{IN}(t)} = \frac{A(k_1 + k_2\omega^2) \sin \omega t}{A \sin \omega t}$

$\vartheta = k_1 + k_2\omega^2$

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$G = 20 \lg (k_1 + k_2\omega^2)$ ≙ Real function!

(i.e. no phase displacement)

Fig. 11

Graphic representation of G; $k_1 = 1$; $\omega = 2\pi f$;

k_2 as parameter

APPENDIX 2

The bandpass of the 2nd order has a transmission response of:

$$G(s) = k \frac{s\frac{\omega_o}{Q}}{s^2 + s\frac{\omega_o}{Q} + \omega_o^2}$$

k = any constant

s = complex, variable frequency

ω_o = resonant frequency circuit

Q = quality factor

The corresponding phase function is:

$$\varphi(\omega) = \text{arc tg} \frac{-\frac{\omega_o}{Q}\omega}{\omega_o^2 - \omega^2}$$

It can be represented as a series:

$$\varphi(\omega) = -\left[\omega \frac{1}{Q\omega_o} + \omega^3 \frac{1}{\omega_o^3}\left(\frac{1}{Q} - \frac{1}{3Q^3}\right) + \ldots\right]$$

By differentiating the phase after ω we obtain the group delay

$$\tau_{GR} = -\left[\frac{1}{Q\omega_o} + 3\omega^2 \frac{1}{\omega_o^3}\left(\frac{1}{Q} - \frac{1}{3Q^3}\right) + \ldots\right]$$

If τ_{GR} at $\omega = 0$ must be retained for as long as possible, the dominating interference term of the 2nd order must disappear. This leads to the condition:

$Q = \sqrt{\frac{1}{3}} \approx 0{,}577.$

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