 By Pierre Touzelet

Setting Feedback On the **Mullard 20**

Demystifying feedback loop gain and compensation networks optimization.

This article shows how you can use network analysis programs to optimize feedback loop gain and associated compensation networks to achieve good damping and stability margins without peaking, when feedback is applied on an amplifier. The amplifier used to illustrate this is the Mullard 20W tube amp[1]. The circuit diagram used to set up the amplifier model is shown in **Fig. 1**.

AMPLIFIER MODEL

The amplifier model has been set up using the ESACAP network analysis program[2]. You can use other network analysis programs, but a copy of the model as developed in ESACAP is available at www.audioXpress.com. The ESACAP model includes the following:

section $$DES—amplifier description

sub-section $FUN: limit (x, min, max);—defines the limit function

sub-section $FUN: pwrs(x,y)—defines the power function

sub-section $CON:—provides input signal parameters, tube parameters, core geometry, OPT magnetic parameters, and topology

sub-section $NET:—describes the complete amplifier network.

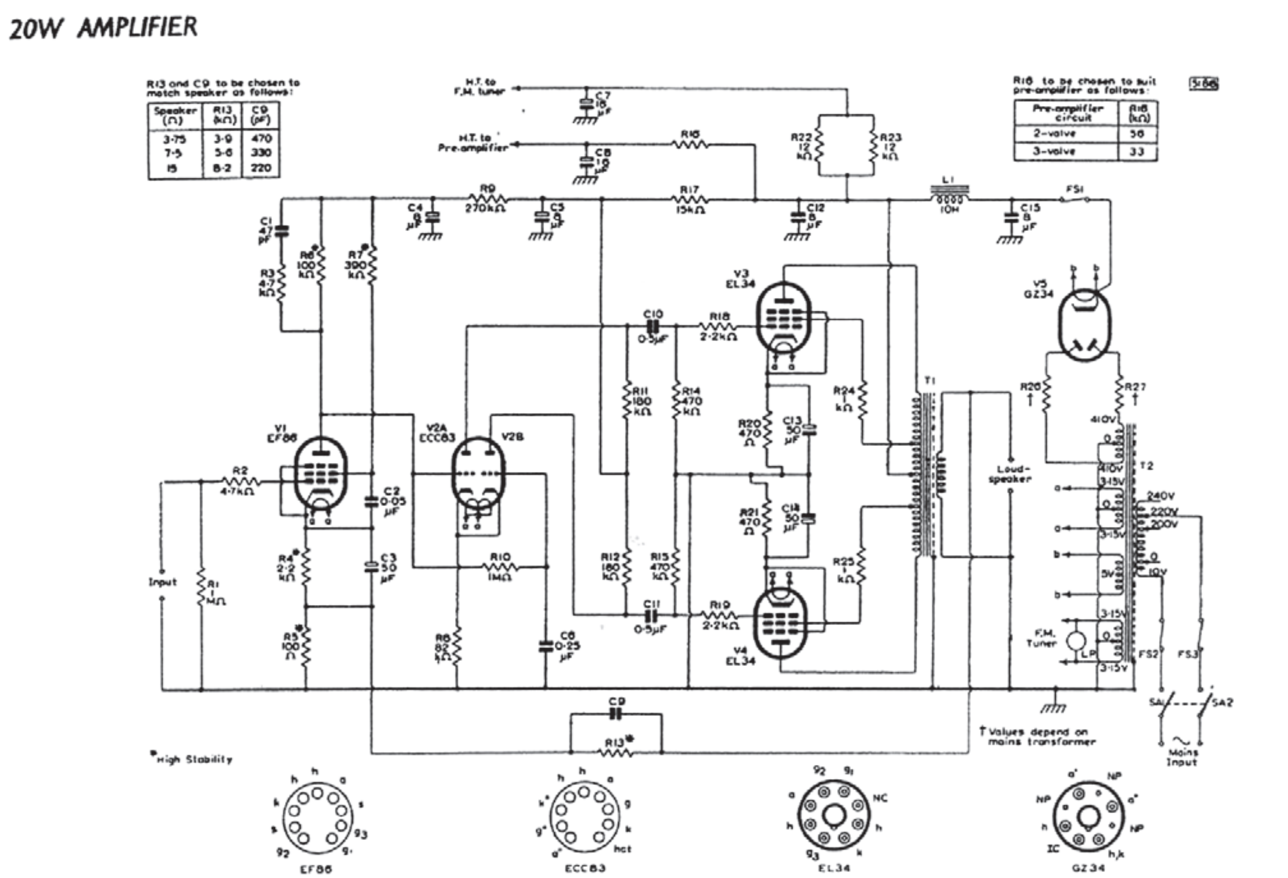

FIGURE 1: Circuit diagram of 20W amplifier.

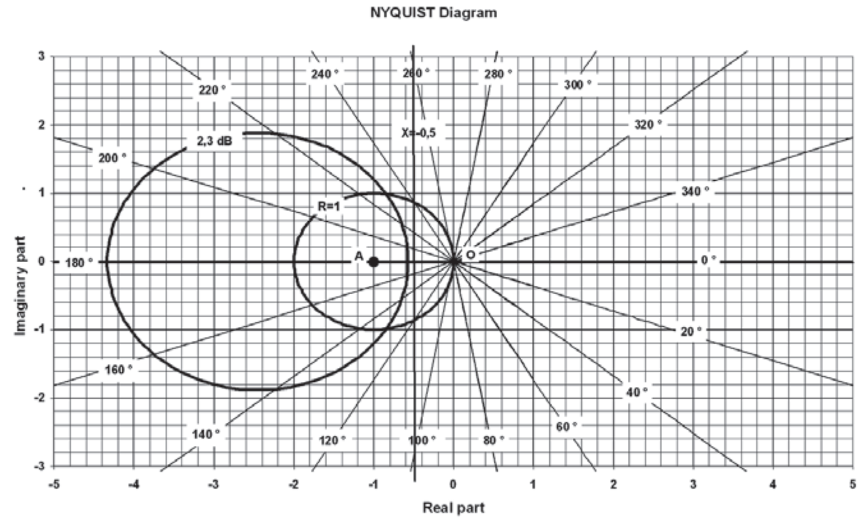

FIGURE 2: Nyquist diagram.

NYQUIST DIAGRAM

The feedback loop transfer function is graphically represented in the Nyquist plane (**Fig. 2**) with the following additions:

The critical point A (-1, 0)

The circle R=1, centered on point A, which defines the area of positive feedback

The circle Q=2.3dB, having limit points A and O, which defines the minimum stability margins

The vertical line x=-0.5, which defines the peaking conditions

FEEDBACK LOOP TRANSFER FUNCTION OPTIMIZATION

To be acceptable, the feedback loop transfer function must be warped in such a way that it stays:

—Outside the circle Q=2.3dB, to achieve good stability and damping

—On the right-hand side of the vertical line x=-0.5, to avoid peaking at both ends of the frequency bandwidth.

These conditions define the strategy for the optimization of the feedback loop transfer function. It is generally achieved using an optimum feedback loop gain and additional compensation networks.

GAIN OPTIMIZATION

The feedback voltage is defined using a voltage divider across the output load R_L (**Fig. 3**). Its transfer function (assuming that $R_t + R_k \gg R_L$) is

where: $H(p) = \dfrac{R_k}{R_t + R_k}$

R_k resistance set to $.1k$ in the Mullard 20W amplifier

R_t resistance to be determined to define the feedback loop gain

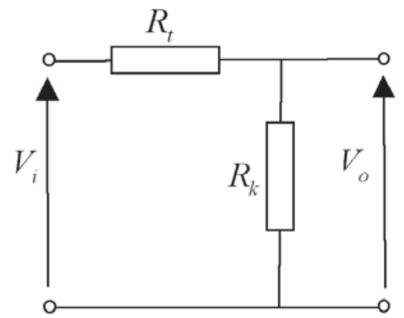

FIGURE 3: Voltage divider.

With the value of R_t set to 9k, the Routh's criterion for the Nyquist diagram of the feedback loop (**Fig. 4**) is not fulfilled. As a result, the amplifier is unstable. However, this choice is maintained because it provides an important feedback loop gain, and I will show that the present amplifier instability can be overcome properly using dedicated compensation networks.

DIFFERENTIAL COMPENSATION

The first compensation network is obtained using a bypass capacitor across the resistor R_t of the voltage divider (**Fig. 5**). The transfer function of the compensation network is:

$$H(p) = \frac{R_k}{R_t + R_k}\frac{[1 + R_t C_t p]}{\left[1 + \frac{R_t R_k}{R_t + R_k} C_t p\right]} = \frac{1}{a}\frac{1 + a\tau_d p}{1 + \tau_d p}$$

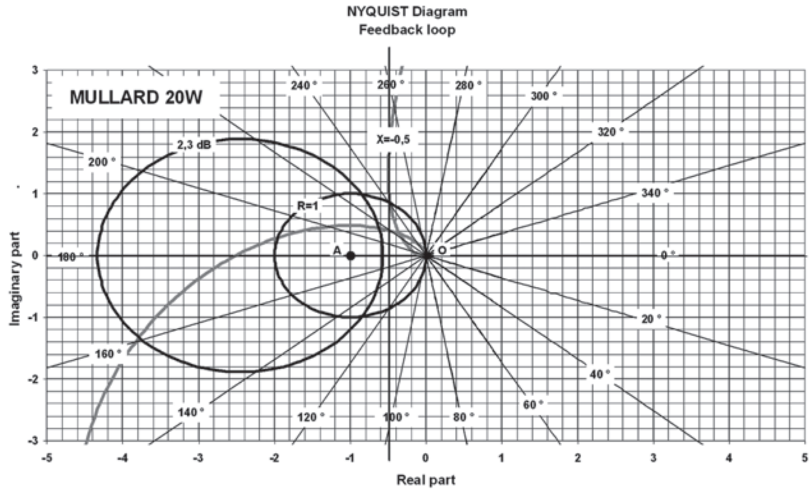

FIGURE 4: Feedback loop Nyquist diagram with a voltage divider.

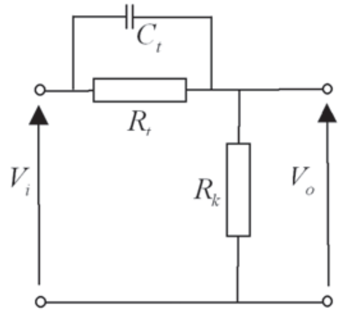

FIGURE 5: Phase lead compensation network.

with:

$$a = 1 + \frac{R_t}{R_k} \text{ and } \tau_d = \frac{R_t R_k}{R_t + R_k} C_t$$

You can recognize[3] the transfer function of a differential or phase lead compensation giving the maximum phase lead

$\varphi_m = Arc\sin\frac{a-1}{a+1}$ for the angular frequency

$\omega_m = \frac{1}{\tau_d \sqrt{a}}$. Applying these results to the Mullard 20W tube amplifier, and using the value defined for R_t in section 5.1, you get

$$a = 91 \qquad \varphi_m = 78\deg$$

C_t must be adjusted to have $\omega_m \approx \omega_r$, where ω_r is the angular frequency resonance of the feedback loop after the phase lead compensation effect. A value of $C_t = 250p$ fulfills this requirement as it is shown on the Nyquist diagram of the compensated feedback loop given in **Fig. 5**.

The main effect of the phase lead

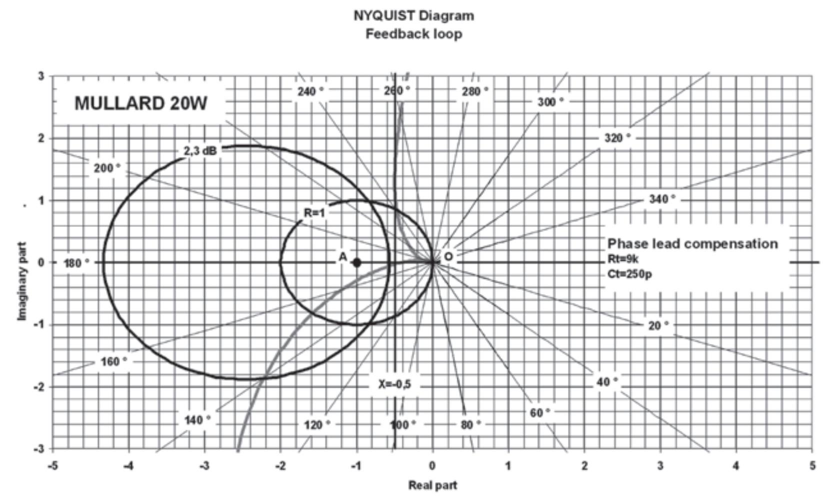

FIGURE 6: Feedback loop Nyquist diagram with a phase lead compensation.

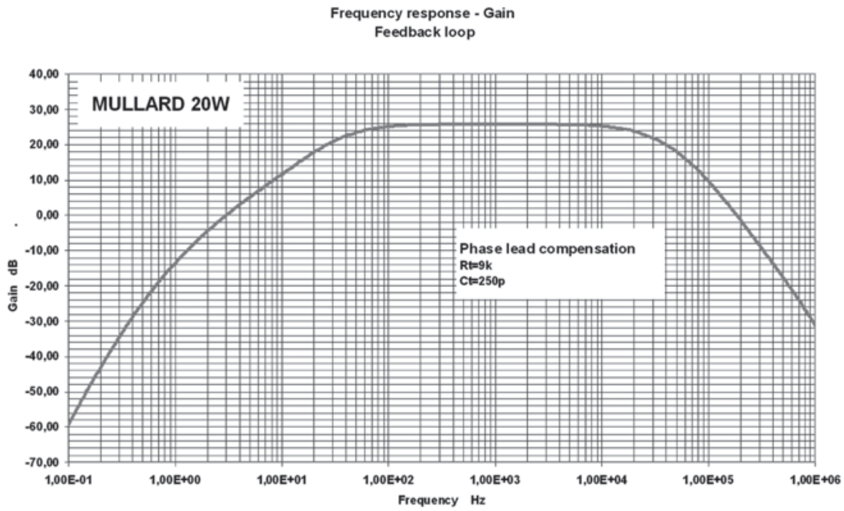

FIGURE 7: Feedback loop gain with a phase lead comparison.

compensation on the feedback loop transfer function is that you achieve stability for the amplifier. However, if the amplifier is now stable, the damping is not sufficient because a part of the feedback loop transfer function is entering into the circle Q=2.3dB. And if no peaking appears at the low end of the frequency bandwidth—because the transfer function stays on the right-hand side of the vertical line x=-0.5—it is unacceptable at the high end of the frequency bandwidth, because a part of the transfer function is on the left-hand side of the vertical line x=-0.5[4,5]. This situation is better shown on the diagrams in **Figs. 7** and **8** giving the feedback loop gain and phase shift versus the frequency and in **Figs. 9** and **10** giving the closed loop gain and phase shift versus the frequency.

As a result, to achieve a better optimization of the feedback loop, it is necessary to improve the present situation by using an additional compensation network.

INTEGRAL COMPENSATION

A second compensation network is obtained using a high-frequency step circuit across the loading plate resistance of the input stage of the amplifier, as shown in **Fig. 11**.

where:

ρ is the internal resistance of the input tube, and

R_p is loading plate resistance

The transfer function of this compensation network is:

$$H(p) = \frac{1 + R_u C_u p}{1 + \left(R_{eq} + R_u\right) C_u p} = \frac{1 + \tau_i p}{1 + b\tau_i p}$$

with:

$$R_{eq} = \frac{\rho R_p}{\rho + R_p} \qquad \tau_i = R_u C_u \qquad b = 1 + \frac{R_{eq}}{R_u}$$

You can recognize[3] the transfer function of a gain reduction or integral compensation. To match this compensation network, it is necessary to have

$$\tau_i \gg \frac{1}{\omega_R}$$

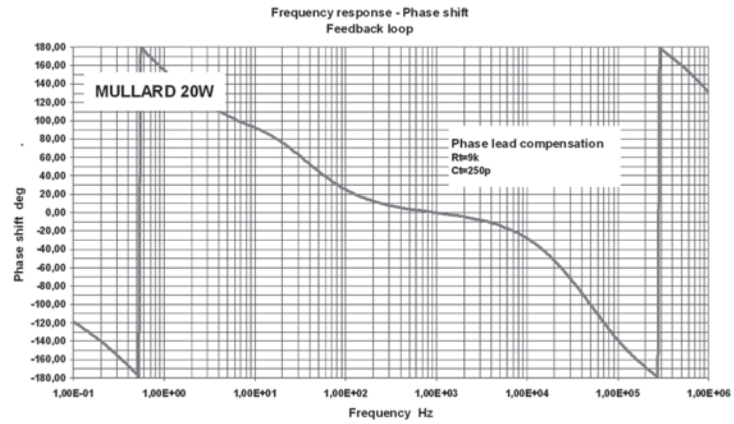

FIGURE 8: Feedback loop phase shift with a phase lead compensation.

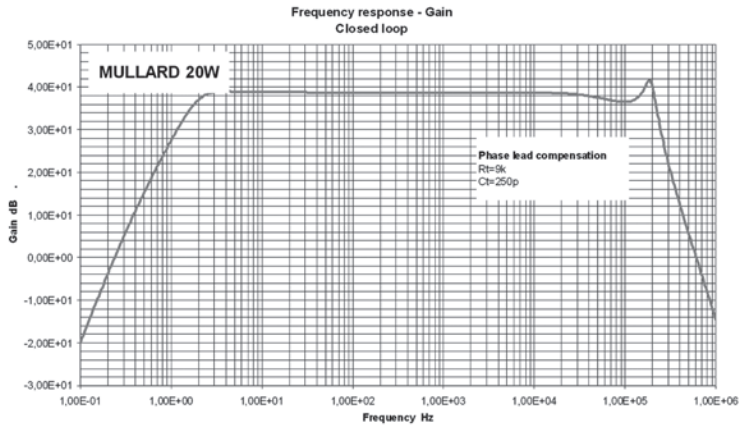

FIGURE 9: Closed loop gain with a phase lead compensation.

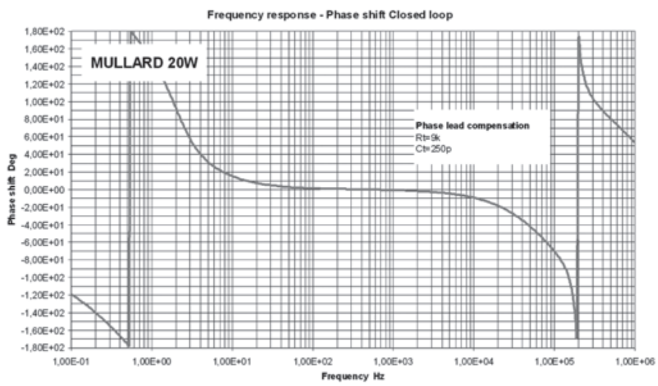

FIGURE 10: Closed loop phase shift with a phase lead compensation.

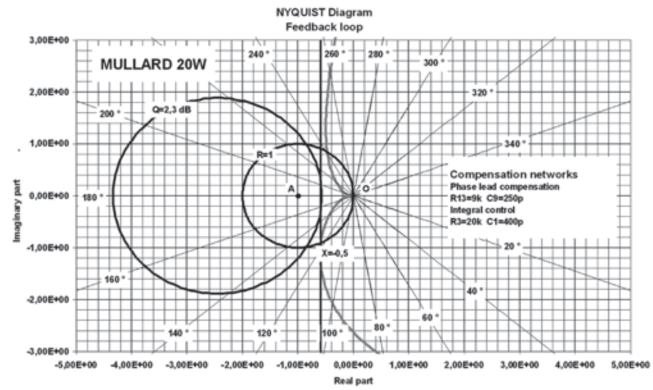

FIGURE 12: Nyquist diagram with a phase lead compensation and an integral control.

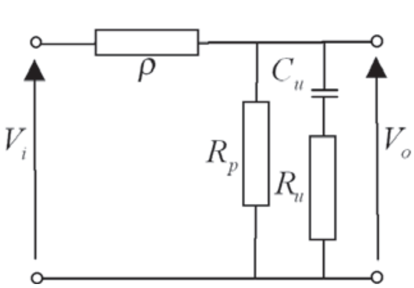

FIGURE 11: Integral compensation network.

For the Mullard 20W tube amplifier, you have:

$$\rho = 2.5M \quad R_p = 0.1k \quad R_{eq} = 96k$$

C_u and R_u must be adjusted so that

$$\tau_i \gg \frac{1}{\omega_r},$$

where ω_r is the angular frequency resonance of the feedback loop after the integral compensation effect. Values of $C_u = 400p$ and $R_u = 20k$ fulfill this requirement, as it is shown on the Nyquist diagram of the compensated feedback loop given in **Fig. 12**.

In conjunction with the differential compensation, the additional effect of the integral compensation on the feedback loop transfer function is that it allows achieving the required damping and stability margins with practically no peaking[4,5]. The transfer function has been warped enough to avoid entering into the circle Q=2.3dB and the left-hand side of the vertical line x=-0.5. This situation is again better shown in **Figs. 13** and **14** giving the feedback loop gain and phase shift versus the frequency and in **Figs. 15** and **16** giving the closed loop gain and phase shift versus the frequency.

COMMENTS

With the defined feedback loop gain and associated compensation networks, the objective was to warp the feedback loop transfer function so that it stays outside the circle Q=2.3dB and on the right-hand side of the vertical line x=-0.5. This has been achieved. As a result, a feedback loop gain of at least 20dB from 30Hz to 6kHz and 15dB from 15Hz to 15kHz is available. These results are interesting if you consider that the amplifier shows no peaking at both ends of the frequency bandwidth, with excellent damping and stability margins.

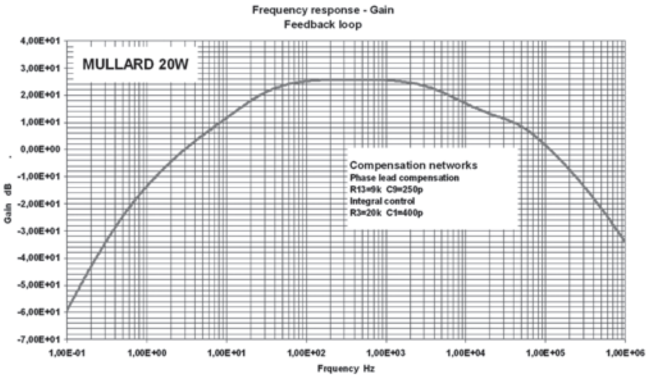

FIGURE 13: Feedback loop gain with a phase lead compensation and an integral control.

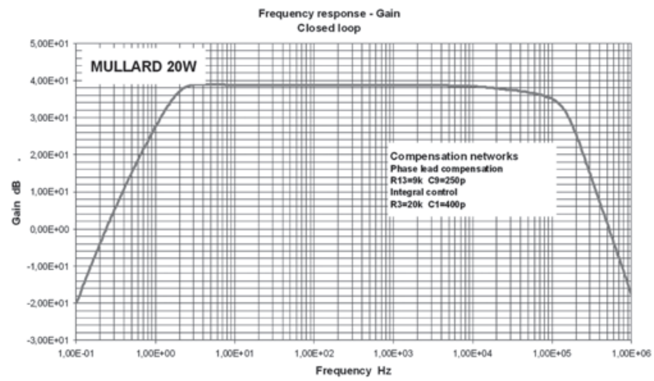

FIGURE 15: Closed loop gain with a phase lead compensation and an integral control.

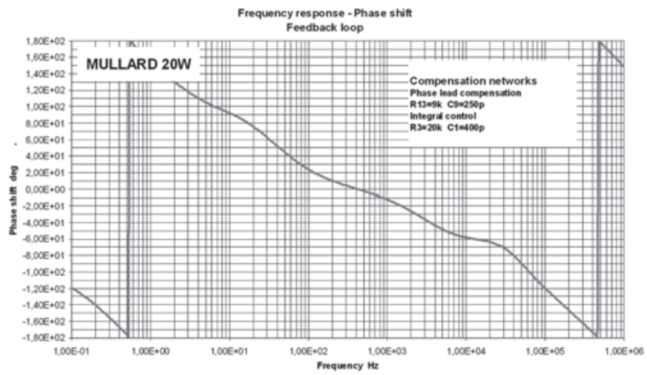

FIGURE 14: Feedback loop phase shift with a phase lead compensation and an integral control.

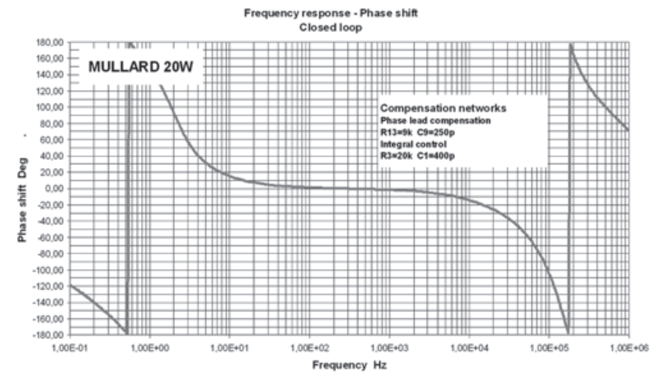

FIGURE 16: Closed loop phase shift with a phase lead compensation and an integral control.

CONCLUSION

Applying a certain amount of feedback on an amplifier is a difficult exercise according to the predefined optimization requirements. From that point of view, it is clear that using a network analysis program is helpful, as I have shown, because it allows you to define simply and surely feedback loop gain and associated compensation networks. *aX*

REFERENCES

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