The Interaction Concept in Feedback Design

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A new attack, followed by mathematical proof, on the problems of visualizing the behaviour of feedback amplifiers, enables these circuits to be better understood and more easily predicted.

In Two Parts—Part I

IN THE DESIGN of a complete amplifier there are so many variables to consider, some of which may be somewhat difficult to determine, that it is often difficult to know where to begin. The available design data usually predicts only the performance of the amplifier as a complete loop. In consequence, the effect of any circuit change has to be determined by calculating out the complete loop performance again. The process of approaching a design optimum can become extremely protracted,

In the old-fashioned amplifier without feedback, it was a relatively simple matter to localize the various components contributing to the over-all performance. The frequency and phase response were merely a summation of the responses of the individual stages and the over-all distortion was a combination of the distortion of the individual stages. But, as soon as feedback is applied, this is no longer true. For this reason some amplifier designers have sought a method of approach to negative feedback design that will separate the effect of closing the feedback loop in a manner similar to the way the performance of individual stages can be isolated.

The difficulty in this can be seen from the simple case when the feedback path consists of only resistors. Closing the loop can introduce considerable additional frequency discrimination not present in the absence of feedback. In theory a network consisting of resistors only cannot introduce frequency discrimination, so it is difficult to see how the closing of the loop can be visualized as contributing some erratic frequency discrimination to the over-all performance.

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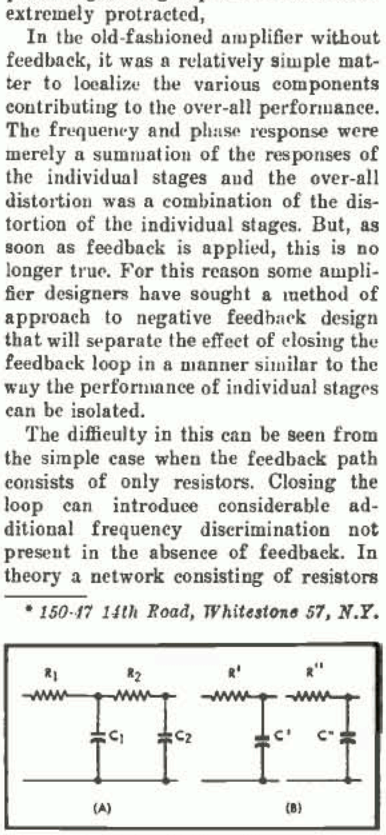

Fig. 1. Equivalent interacting and non-interacting networks producing a high-frequency rolloff. Equivalence is discussed in the text, and the mathematical treatment given in the appendix.

It is further evident that, although the resistors in the feedback path may have the same value, the result of closing the loop will not necessarily be consistent for this particular combination of resistors: it is further dependent upon the amplification and response characteristic of the forward part of the amplifier.

This, of course, is further complicated when the feedback path does contain frequency discriminating elements. Then the closing of the feedback loop produces a difference in response dependent upon (a) the nature of the performance with the loop open, (b) the over-all gain and response around the loop to be closed and (c) the response of the feedback path only.

Basic Elements

How then can we regard the closing of the feedback loop as contributing something to the performance of the amplifier that can be isolated and considered as a separate entity? It is at this point that the interaction concept proves a useful tool. To apply this concept, the over-all performance is considered as being built up from a number of two element networks, consisting of resistance and a single reactance. Each of these, according to its configuration, will contribute to either a low- or high-frequency rolloff:

A resistance in series with a capacitance in shunt produces a high-frequency rolloff.

A capacitor in series with a resistance in shunt produces a low-frequency rolloff.

With combinations of inductance and resistance the order is reversed. Most modern amplifiers avoid the use of inductances as far as possible, the only inductances normally encountered being associated with the output transformer.

In resistance/capacitance coupled stages the resistances are those of the actual circuit, plus the plate resistances of the tubes, while the capacitances are (1) the coupling capacitors effecting low-frequency rolloff, and (2) stray circuit capacitance effecting high-frequency rolloff.

The same theory can be applied to the computation of either low- or high-frequency performance. For this reason in this article we shall not go into both in detail but the high-frequency performance will be considered and the low-frequency response can always be interpreted from this, merely by reversing the position of the various elements.

Interacting Pairs

Consider the two pairs of resistances and capacitors shown in *Fig.* 1. At (A) the four elements are connected together in tandem. At (B) they are considered as separate two element networks. These two networks may be separated in fact by a stage of amplifiers to prevent interaction between their respective components.

In either case the over-all response of the combined networks will take the general form shown in *Fig.* 2. Each pair

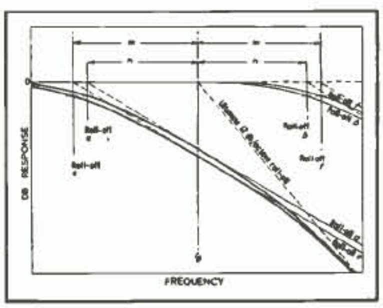

Fig. 2. Illustrating the way interaction modifies response in the circuit of (A) in Fig. 1. The ultimate 12 db/octave rolloff is the same whether interaction occurs or not, but interaction increases attenuation in the vicinity of the frequency f_0, where phase shift is 90 deg. and rolloff sides 6 db/octave.

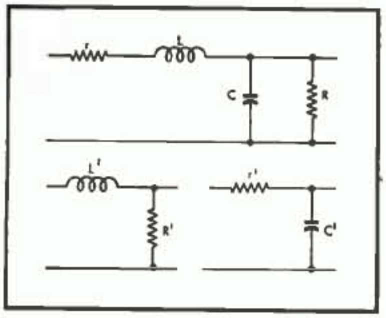

Fig. 3. Interaction also occurs when opposite kinds of reactance are combined in a circuit, as at (A). Sometimes this can be resolved into non-interacting equivalents, as at (B), but quite frequently the interaction goes into a region that cannot be represented by real values in this form.

of elements will contribute to a composite rolloff—each two-element network will produce its own rolloff dependent upon the time constant of the resistance/capacitance combination. We will consider, for convenience, that one combination produces a rolloff at a frequency n^2 times the other combination. This means that one rolloff will be n times a mean frequency while the other will be the same frequency divided by n.

We can assume that the connected arrangement of (A) in *Fig.* 1 can be represented by separate elements as at (B). In this case we can represent the one in terms of the other using real values throughout. If the two networks were not connected together in (A) C_1 would act with R_1 and C_2 would act with R_2. But because of the interconnection C_1 acts with R_1 and also partially with R_2 which means that C_1 will not be shunting such a high value of resistance as R_1 by itself. At the other end C_2 is not feeding out of the simple resistor R_2 as a source but has an additional component of resistance source due to the presence of R_1.

If R_2 is very large compared to R_1 the constant k, used in the formula given in the appendix, will be very small, signifying that there is little interaction between the rolloff effects of R_1 and C_1 and R_2 and C_2. As shown in *Fig.* 2 the effect of interconnection is to spread the equivalent non-interacting components to frequencies further apart, to the ratio represented by m in the formula in the appendix and also in the figure.

The mean frequency remains unchanged in this case so, as shown in *Fig.* 2, the combined response of the over-all arrangement reaches the same ultimate rolloff whether an interconnection is made between R_1 and C_1 with R_2 and C_2 or not. The effect of the interconnection changes the response to a maximum degree at the mid-frequncy, which is a mean between the rolloffs of the individual two-element networks and in this example always deteriorates or increases the attenuation of the response in this range.

As has been shown in previous articles, the attenuation at this mean frequency has a slope of 6 db per octave while the transfer phase shift is 90 deg. In this case interaction does not alter the phase shift at this particular frequency but it does alter the over-all attenuation at the 6-db-per-octave slope point.

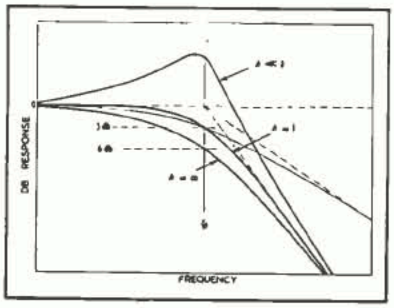

Fig. 4. Variation in response with value of the interaction factor, k, for values of n = 1. This combination can never be represented by real values in the form of (B) in Fig. 3.

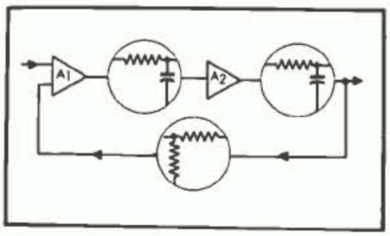

Fig. 5. When single reactance rolloffs are separated by amplifier stages so as not to interact in simple amplification, the addition of feedback causes interaction, and modifies the response in a manner somewhat similar to the circuit of (A) in Fig. 3.

Inductance and Capacitance

If we next apply this concept to the signal coupling network represented in *Fig.* 3 which has both inductance and capacitance in the same circuit we shall find that a similar method can be applied.

First consider some effects of different combinations of values. If L in (A) is made negligible in effect compared to the other components, C would then be shunting a virtual source consisting of the two resistance components in parallel. On the other hand, if L becomes relatively large, so as to isolate r from C, the effect of C in producing a rolloff could be considered as acting solely upon R.

A similar comparison can be made by considering C to be negligible so that L is acting in series with both the resistors. In this case the effective resistance to be compared with L will be the combined value of the two in series. On the other hand, if C exercises considerable shunting effect upon R, L can be regarded as producing an increased series reactance compared only with r.

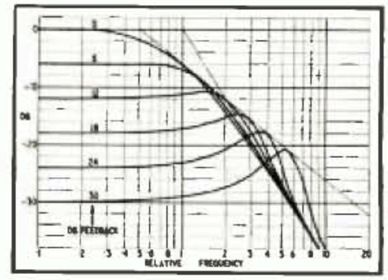

Fig 6. Showing the effect of different amounts of negative feedback on the response of the arrangement of Fig. 5, in the particular case when n = 1. Other cases follow the same pattern from a different starting point.

This being the case the time constant or rolloff comparisons which we make will take a mean position between the two extremes: the time constant for L combined with the resistance will be taken as a mean between r and the combination of the two resistors in series; the time constant for C will be taken as a combination with the mean value of R and the parallel combination of the two.

The equivalent non-interacting network is shown at (B) in *Fig.* 3 using L' and R' where R' is the mean value just described as combined with L; and r' and C' where r' is similarly the mean value combined with C.

Sometimes the equivalent can be expressed in terms of real components but this is not always possible.

First we will consider the special case where the effective time constant of both arrangements is the same. In other words following the nomenclature of *Fig.* 2, $n = 1$. This is shown at *Fig.* 4. Notice that we still have an interaction factor, similar to that used in the arrangement of *Fig.* 1, of $k = r/R$. For any particular case (value of n) the value of k will determine the attenuation at the mean frequency, which is still the frequency

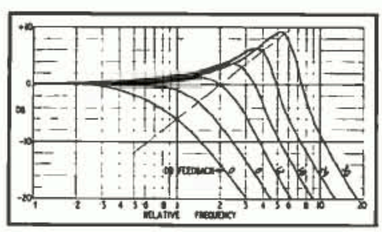

Fig.7. The curves of Fig. 6 replotted to the same zero reference, so the effect of feedback on the over-all response can be better seen.

where the attenuation slope is 6 db per octave and the transfer phase shift 90 deg.

For large values of k when $n=1$, as represented in Eq. (*13*) in the appendix, the attenuation at the 6-db-slope point approaches 6 db. This is when r is large compared with R, and L and C have values such that the time constants, represented by a and b in Eq. (*8*) are both at the same frequency.

As k is reduced to the point where it has unity value the maximal flatness curve is reached, in which the 6-db-per-octave slope point is at an attenuation of 3 db. Further reduction in the value of k below unity produces a kind of interaction that causes the response to go into peaking. This is shown in *Fig.* 4.

In this case the whole range of values of k produces an equivalent that cannot be represented by separate networks as at (B) in *Fig.* 3. Only when the two frequencies are divergent, that is, n is greater than *1*, can any values of k exert an influence pulling the two frequencies together (instead of separating them as represented in *Fig.* 2) in the range where the attenuation at the 6-db-per-octave slope point is greater than 6 db. From the 6 db point upwards it is not possible to represent the arrangement by real non-interacting networks as at (B) in *Fig.* 3.

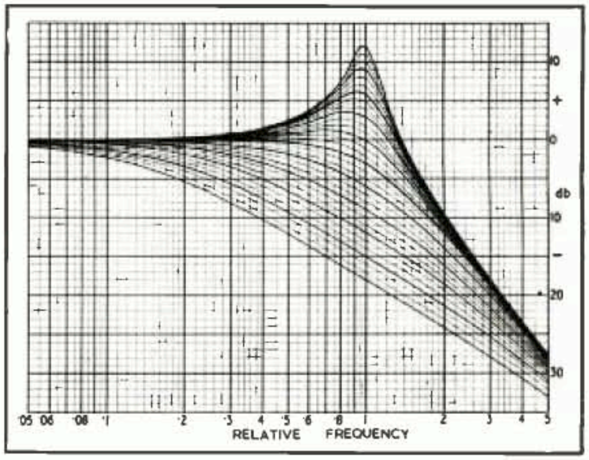

Fig. 9. Family of response curves applicable to two stage arrangements of Fig. 1, or 5, using f_0 as the reference frequency. The value of this frequency, and the required curve, can be identified from Fig. 8.

From the foregoing then we can see that the coupling together of two networks producing a rolloff in the same direction and employing the same kind of reactance (in the example given both were capacitance) the effect of interaction is to spread the equivalent contributing rolloffs to frequencies further apart; but when two different reactances are combined so as to produce a rolloff at the same end of the frequency response the effect of the interaction by coupling them into the same circuit is to pull the equivalent rolloff frequencies together, until the point is reached where the response is 6 db down at the 6-db-slope point; after which the equivalent pairs have imaginary values and the shape of the resultant response goes first to the maximal flatness curve and thereafter into peaking.

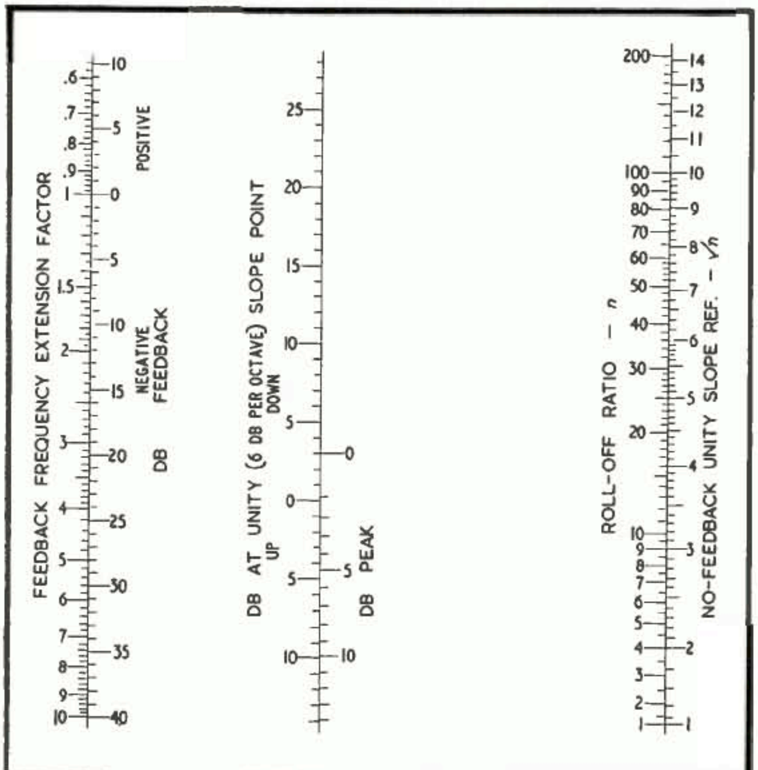

Fig. 8. Chart giving all the essential data to predict the response of a two-stage feedback loop. The frequency extension scale at the left of the left scale shows the ratio by which the unity slope frequency is extended. Ratio n is the ratio between the times constants or rolloffs of the two stages. The square root scale on the right of the right scale facilitates calculation of the unity slope point in the absence of feedback.

INTERACTION DUE TO FEEDBACK

Now we come to the form of interaction which is of particular concern in this article—the one in which amplification is used and the loop is completed producing feedback.

Two-Stage Case

Take first the case of an amplifier in which there are two reactances in the loop, contributing to high-frequency rolloff represented emblematically at *Fig.* 5. As shown by the theoretical treatment in the appendix, application of feedback over these two similar networks produces a variation in response very similar to that of the second case considered in *Fig.* 3. Interaction caused by the application of a specified amount of feedback pulls the equivalent rolloff frequencies together; but it also moves them both further out in the frequency scale. *Figure* 6 shows the effective variation as increasing amount of feedback is applied, taking into account the reduction in gain caused by the feedback interaction. It will be noticed that the 6-db-slope point may be considered as sliding down a line at a slope of 6 db per octave. The ultimate 12-db-per-octave slope is

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the same for all amounts of feedback. This is shown by the dot and dash construction line in *Fig.* 6.

Figure 7 shows the same family of curves normalized to the same level. This gives a better idea how the addition of feedback over a two stage amplifier will vary the response. The curves in *Fig.* 6 and *Fig.* 7 are for the special case where *n* is unity, or the rolloff point of the two networks identical.

In cases where they are divergent to begin with, some feedback is necessary to bring the 6-db-slope point up to a level of 6 db attenuation. This follows the same general pattern shown in *Fig.* 6

and a relatively simple abac, shown in *Fig.* 8, tells the whole story of interaction for the two-stage case. For this particular case the variation in response shaping can be shown quite simply by using the 6-db-slope point as a reference frequency. It follows a family of curves given at 1 db intervals in the chart of *Fig.* 9.

This is the variation of response shape for the case where both rolloffs are in the

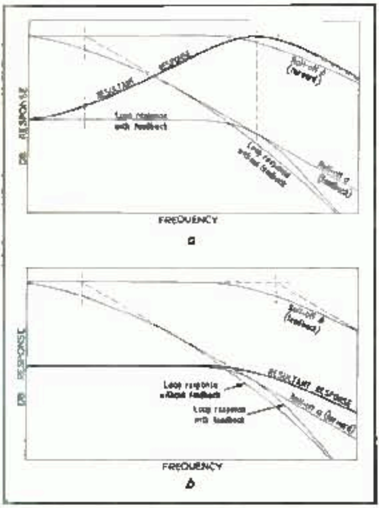

Fig. 10. How to compute the response when one of the rolloffs is in the feedback path. Both cases illustrate the rolloff ratio and amount of feedback, but at (A) the early rolloff is the feedback one, while at (B) it is the remote rolloff.

forward part of the circuit, as represented in *Fig.* 5. In some circuits however, one of the rolloffs may be in the return or feedback path. This means that the over-all loop response can be obtained from the family shown in *Fig.* 9, but the resultant forward gain must be further deduced by subtracting the rolloff in the feedback path from this curve. The method of doing this is illustrated for two cases in *Fig.* 10.