Reduction of Feedthrough in Audio Switching

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Feedthrough of signal through a supposedly open circuit can be reduced by splitting the load

Feedthrough may be defined, at least for the purpose of this article, as the undesired passage of a signal or other alternating emf through a supposedly open circuit. It has long been a problem in the switching of audio signals. In communications work, it can cause cross-talk between the various lines being switched. In those electronic organs where keying is done in the signal line, it can be responsible for an extremely annoying high pitched whine, which is most evident when no keys are depressed.

Feedthrough is a function of three factors: The generator resistance, the load resistance, and the capacitance of the switching mechanism. *Figure* 1 shows a simple switched circuit where E_g is open-circuit generator voltage, R_g is the generator resistance (including any isolating or other resistors between the generator and the switch), R_L is the load resistance, and C_s is the capacitance of the switch. The output emf with the switch closed is

$$E_L = E_g\left(\frac{R_L}{R_g + R_L}\right) \quad Eq. (1)$$

When the switch is opened, the output emf becomes

$$E_L = E_g\left(\frac{R_L}{R_g + R_L - jX_c}\right) \quad Eq. (2)$$

where $X = 1/\omega C_s$, the reactance of the switch capacitance. For calculation purposes, this reactance should be taken at the highest frequency to be passed by the switch. If the reactance at this frequency is more than about eight times the value of $R_g + R_L$, *Eq. 2* may be simplified with negligible error (less than one per cent) to

$$E_L = \frac{E_g \cdot R_L}{X_c} \quad Eq. (2a)$$

Then, the feedthrough, expressed as a fraction of the signal output with the switch closed, becomes

$$F = \frac{R_g + R_L}{X_c} \quad Eq. (3)$$

which is *Eq.* (*2a*) divided by *Eq.* (*1*).

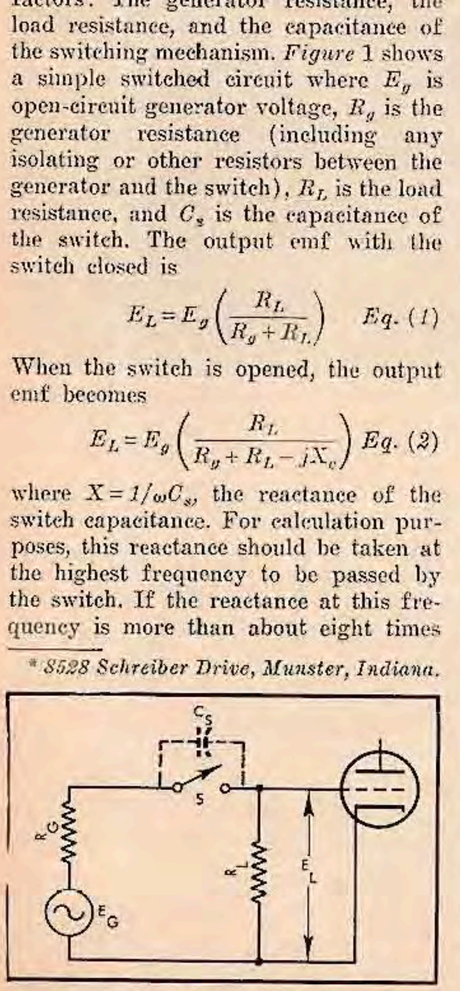

Fig. 1. Simple switched circuit.

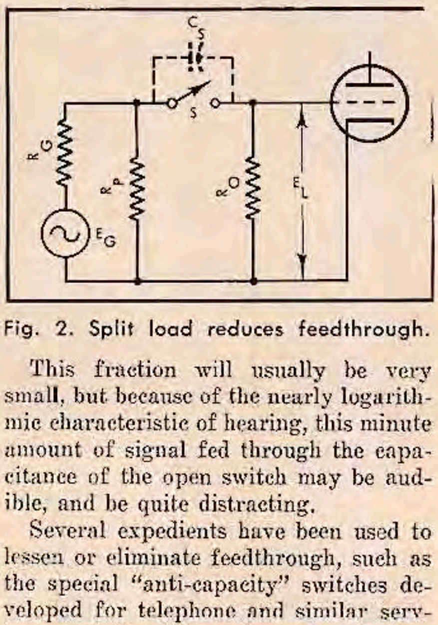

Fig. 2. Split load reduces feedthrough.

This fraction will usually be very small, but because of the nearly logarithmic characteristic of hearing, this minute amount of signal fed through the capacitance of the open switch may be audible, and be quite distracting.

Several expedients have been used to lessen or eliminate feedthrough, such as the special "anti-capacity" switches developed for telephone and similar services, and the "Crossed-wire" switching contacts used in several electronic organs. However, these switches are expensive, and the crossed-wire designs require precision shop work far beyond the scope of most non-professional shops to insure positive switching, combined with easy keying. Other organ designers have bypassed this particular problem completely by keying their oscillator plate supply circuits instead of the signal circuits. Of course, this introduces other problems, affecting the whole philosophy of organ design, but these are beyond the scope of this article.

A limited degree of improvement can be had by making the load impedance as low as possible, consistent with adequate signal output when the switch is closed. The limiting factor here is apt to be the generator impedance. As may be seen from *Eq.* (*3*), the theoretical maximum improvement in feedthrough-to-signal ratio would only be 6 db if the load resistor were reduced from the value of the generator impedance all the way to zero. Doing this, however, would lose the signal too.

There is another method of decreasing the feedthrough-to-signal ratio, which can give improvements of 20 db or even more over the simple circuit of *Fig.* 1. Unfortunately, it is not universally applicable, because for every 2 db reduction in feedthrough, about 1 db of signal is lost. Where sufficient signal strength is available, or where the loss can be made up readily by an extra stage of amplification, a great improvement in the feedthrough-to-signal ratio can be obtained.

Briefly, this expedient consists of splitting the load resistance, as seen by the generator, into two equal or nearly equal sections. They are in parallel when the switch is closed and form the shunt arms of a two step attenuator when the switch is open, as shown in *Fig.* 2.

The improvement in the feedthrough ratio obtained by this arrangement is a function of the load seen by the generator and of the ratio of the two resistances, R_p and R_o, which make up R_L, as well as the reactance of the switch capacitance. When the switch is closed, the output is the same as *Eq.* (*1*) with the exception that R_L is now the parallel resistance of R_p and R_o. When the switch is opened, the output (or feedthrough) becomes

$$E_L' = E_g\left(\frac{R_p R_o}{R_g(R_p + R_o - jX_c) + R_p(R_o - jX_c)}\right) \quad Eq. (4)$$

If X_c is at least ten times the value of R_g, this equation can also be simplified with negligible error to

$$E_L' = E_g\left(\frac{R_p R_o}{X_c(R_p + R_g)}\right) \quad Eq. (4a)$$

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and the feedthrough, expressed as a fraction of the signal output (*Eq.* (*4a*) divided by *Eq.* (*1*)) is

$$F' = \frac{R_p R_o (R_L + R_g)}{R_L X_c (R_p + R_g)} \quad Eq.\ (5)$$

For any given values of R_g, R_L, and X_c there will be an optimum ratio of R_p to R_o, which may be found by expressing R_o and R_p in terms of their ratio (K) and R_L: $R_p = R_L(K+1)$ and $R_o = R_L (K+1)/K$. Then the feedthrough becomes

$$F' = \frac{R_L(K+1)^2 (R_L + R_g)}{X_c K (R_L + R_g + KR_1)} \quad Eq.\ (6)$$

Differentiating with respect to K, and equating to zero, gives

$$K\ (optimum) = \frac{R_g + R_L}{R_g - R_L} \quad Eq.\ (7)$$

It has been found that the feedthrough ratio (F) varies so slowly as K is varied in the neighborhood of the optimum value that K can range from 1.0 to 1.5 for any value of R_L lower than 0.2 R_g with no significant change in the feedthrough ratio. Therefore, the remainder of this discussion is based on $K = 1.0$, or $R_p = R_o = 2R_L$.

The improvement in feedthrough suppression obtained by splitting the load may be readily illustrated by taking the ratio of the feedthrough with the single load (*Eq. 3*) to that with the split load (*Eq. 6*):

$$\text{Improvement ratio} = \frac{R_g + 2R_L}{4R_L} \quad Eq.\ (8)$$

Equation (*8*) shows that the equivalent load must be much smaller than the generator resistance to obtain any significant improvement over the simple load arrangement, as shown in *Fig.* 1. In fact, when K (*Eq. 6*) is set at 1.0, there is more feedthrough with the split load than with the simple one, if R_L is greater than 0.5 R_g. However, as the equivalent R_L is decreased with respect to R_g, the relative improvement in feedthrough is increased, almost in direct proportion.

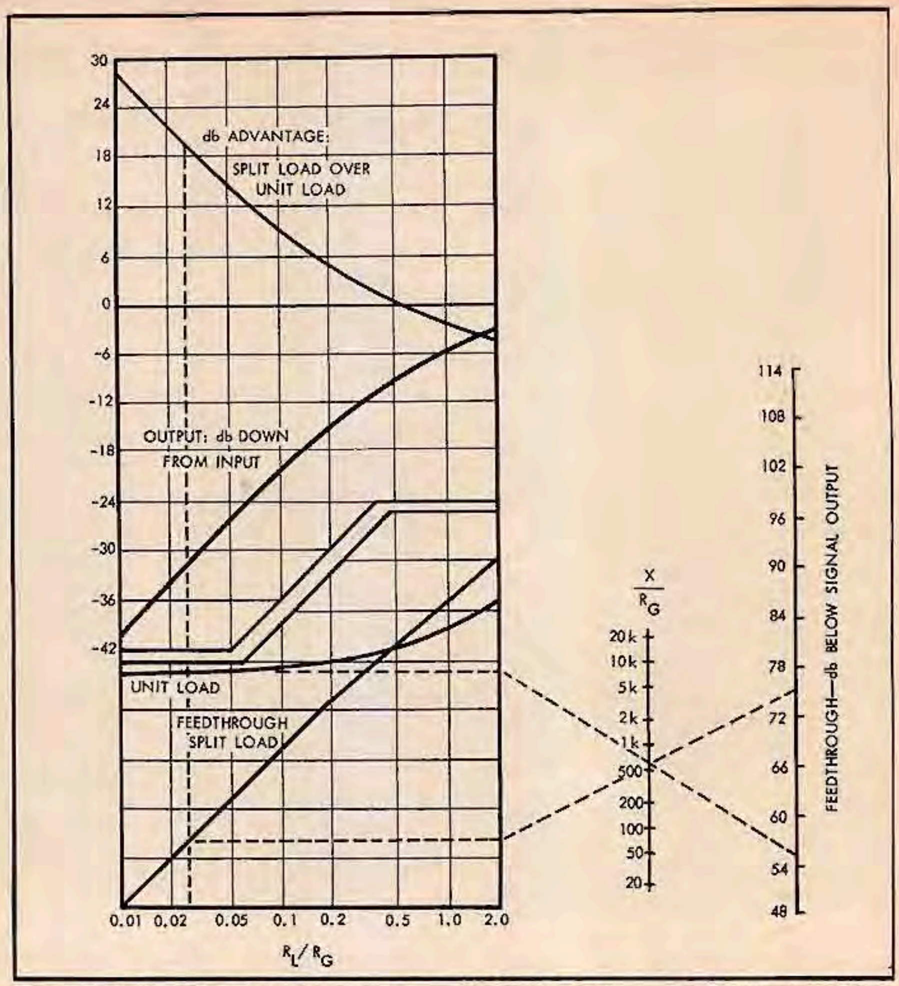

Figure 3 shows graphically the effects of the various factors involved. The load resistance, whether single or split, and the switch reactance are both shown in terms of their ratio to the generator resistance, and feedthrough is expressed as db below the signal output.

As an example of the use of this circuit, an electronic organ keying circuit is fed a one volt signal from generators with 10,000 ohm equivalent resistance (which includes isolating resistors). Keying is done by leaf switches which have a capacitance of 6.3 pf. The highest frequency to be passed is 4200 cps, giving a reactance at this frequency of 6 megohms. The load resistance is not critical, and may be varied over a wide range.

If the load resistance is now set at 265 ohms (0.0265 R_g), the closed circuit output is 0.0256 volts, or 31.8 db under the one volt input. This, and the following values, can be calculated from the preceding equations, or may be read off approximately on *Fig.* 3. For a unit load (as in *Fig.* 1), the feedthrough voltage is 0.0000438 (87.1 db below one volt), or 55.3 db below the closed circuit output. Splitting the load into two 530 ohm resistors (R_p and R_o in *Fig.* 2) does not alter the closed circuit output, but cuts the feedthrough voltage to 0.00000459 (107.8 db below one volt), which is 76.0 db below the signal output. Thus, splitting the load has resulted in a 20.7 db improvement in the signal-to-feedthrough ratio, with a 31.8 db loss in the signal. A greater improvement in the feedthrough ratio could have been obtained, but at the cost of a lower signal output. Conversely, as may be seen from *Fig.* 3, if more signal output is needed, a portion of the advantage of the split load arrangement must be sacrificed. Æ