Phonograph Preamplifier Design Criteria: An Update*

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A systems approach is used to develop criteria for phonograph preamplifier design in order to better align results with real-world considerations. Specially cut test disks have been prepared and analyzed with various playback systems for symmetry, speed, and distortion. Low-frequency stability requirements are analyzed in light of the infrasonic warp content of records. RFI performance is given special attention.

0 INTRODUCTION

The need exists for a transient test signal for RIAA equalized preamplifiers which lies within the capabilities of modern cutting and playback equipment. Such a signal should take into account the dominant high-frequency overload mechanism (curvature overload of the playback stylus), thus reducing the need for extreme power bandwidth (and slew rate) in the phonograph preamplifier. The previously proposed test [1] was an RIAA-preemphasized 1-kHz square wave with a single-pole rolloff at 30 kHz. Such a test demands a flat power response out to the limit of the rolloff filter, and a power response corresponding with the rolloff of the filter beyond. This is so since the falloff of the square-wave spectrum with ascending frequency is essentially canceled by the preemphasis. The test was criticized for its excessive peak-to-average level ratio, thus stimulating both symmetrical and asymmetrical clipping and slew-rate limiting, which were unlikely with any real cartridge [2].

In order to set reasonable criteria for phonograph preamplifiers, then, the dynamic range capability of the medium versus frequency must be known. Two methods were used to evaluate the potential of the medium. The first was to study the previously published information about the velocity versus frequency characteristics of records [3], and the second involves original research which will be reported here.

* Based on a paper entitled "Phonograph Preamplifier Design Criteria Arising from System Measurements," by T. Holman and Frank Kampmann; revised 1980 Jan. 21.

In any study of such requirements, real-world considerations intrude which must be accounted for so that the results have universal application. The warp content of records combined with the transfer function of the tone-arm/cartridge combination yield potentially large infrasonic components which the preamplifier must handle linearly. The effect of high-frequency ringing on transients may exceed the normal curvature overload limit of the stylus. And radio frequency interference (RFI) from broadcast stations, CB sets, refrigerators, and heating systems, etc., also forms a potential input to phonograph preamplifiers which must be eliminated without audible consequences.

1 CAPSULE REVIEW OF EARLIER PUBLICATION [3]

In a previous paper, signals available from records were studied in each frequency band. In the infrasonic region the effect of warped records combined with a variety of playback systems was documented. In the low-frequency sonic region, the displacement capability of the cutter head limits the output capability. Starting at mid-audio frequencies, a velocity limit is imposed by the shape of the cutting stylus. In playback another limit is imposed, since the contact area of the playback stylus forms a scanning aperture which limits the output with a characteristic high-frequency rolloff.

For the combination of a highest output playback system with good trackability and nominal preamplifier gain, the worst case analysis of Fig. 1 applies. Fig. 1 gives two curves in the infrasonic region, which correspond to the required output limits referenced to the output of the preamplifier with (2) and without (1) a three-pole Butterworth filter at 15 Hz. The necessity for such a filter was demonstrated in the paper by studying the consequences of *not* filtering on the power output capability of the system and on the distortion generation in loudspeakers [3]:

> The curve in Fig. 1 then gives the sine-wave low-distortion power response of the cutter head and cutting stylus, cartridge, preamplifier combination. That is, no single-frequency component of the program material may exceed the limits for low reproduced distortion. But because overload is a peak phenomenon for which all frequency components instantaneously add, the actual spectral output of the preamplifier must run substantially below the sine-wave limit line. The amount below is determined by the frequency and phase characteristics of the program material. Since the energy distribution of orchestral music falls off with increasing frequency, it is less likely to produce high-frequency overload than modern popular or jazz recordings, with their increased high-frequency energy content.

Our search for a meaningful transient test is limited by these factors. Not only must the spectrum of the test signal fall under the sine-wave limit line, it also must be analyzed in the time domain for peak level, since the phase characteristics of the test signal constituents are important. At first glance the spectrum of a square-wave test signal does not seem unreasonable, since the natural rolloff of the spectrum is approximately canceled by the RIAA equalization to yield a requirement for flat power response in the preamplifier out to the limit imposed by a low-pass filter, and a power response which follows the filter characteristics thereafter. But the phase characteristic of the square wave yields a very high peak-to-average ratio in a preemphasized signal. (Perhaps a square wave with the phase made random might be a good candidate for a test signal.)

The earlier publication [3] also outlined the fact that records may be cut beyond the geometric limits of low distortion. Criteria for preamplifier design could be based on the capabilities of the playback system ("trackability"), but more conservative designs should be able to handle all the signals present on records, even though they cannot be tracked.

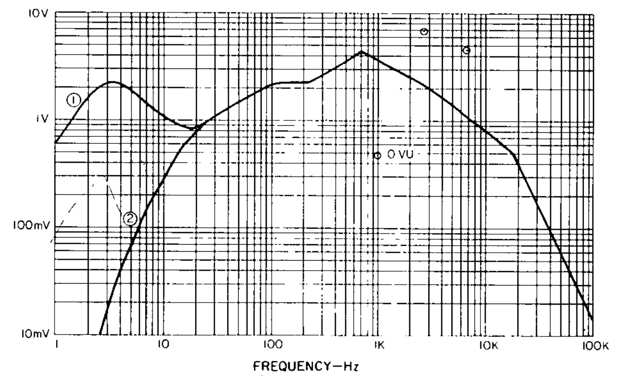

Fig. 1. Power response versus frequency of a high-output system. Curve 1—without an infrasonic filter; curve 2—with a three-pole 15-Hz infrasonic filter. The two plotted points above the curve represent the highest peak velocities known on records. Cartridge sensitivity—0.3 mV/cm·s; transformer turns ratio—1:7; preamplifier gain at 1 kHz—36 dB; worst case combination of tone-arm resonant frequencies and Q_s playing worst warped records which fall under NAB warp guidelines; voltage levels related to output of phono preamplifier stage.

2 MEASUREMENT OF CONTEMPORARY SYSTEMS

In order to be able to state with confidence that the manufactured test signal could be available from records played by cartridges, the maximum output level and slew rate available, if all steps in the process are pushed to the limit, still needed to be established. Test records with square waves were insufficient for our purpose, since we did not know the background behind them in adequate detail (such as full- or half-speed cutting, how symmetrical was the source generator, etc.). Thus a square wave of known high purity was applied to the Neumann cutting system at one of the country's best disk-cutting facilities. It was recorded at both full and half speed in separate tests, each at a level such that the 1-kHz component was at +3 dB re 354 mm/s.

Playback of this recorded test signal was made with a variety of equipment in order to select the playback system that produces the highest stress on the preamplifier due to combined high sensitivity and fast speed. This playback system turned out to be a moving-coil cartridge of the high-output variety combined with a step-up transformer. Both measured within ±2 dB from 1 kHz to 50 kHz. The time-domain output of this combination is given in Fig. 2. The transient "spike" reveals the nature of the preemphasis; it is like differentiation over a limited bandwidth. Other important features are the peak level of about 50 mV peak to peak (0–100%) and the amount of high-frequency ringing present. This ringing is partly an artifact of cutting and partly a playback phenomenon—from comparisons of full- and half-speed cutting with various playback systems (half-speed cutting with less ringing was shown), and from observation of the groove wall through the cutter microscope. Fig. 3 is a "mixed sweep" portrayal where the sweep rate changes at midscreen in order to show the transient. After RIAA deemphasis and amplification in a wideband phonograph preamplifier the same waveform at the input produces the waveform of Fig. 4 at the output. Fig. 5 shows more detail; the high-frequency ringing is considerably attenuated by the RIAA deemphasis. The output slew rate also looks slower than the input slew rate relative to the

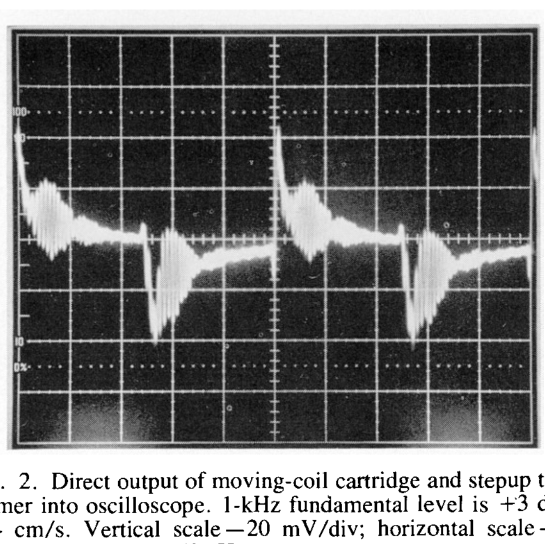

Fig. 2. Direct output of moving-coil cartridge and stepup transformer into oscilloscope. 1-kHz fundamental level is +3 dB re 354 cm/s. Vertical scale—20 mV/div; horizontal scale—0.2 ms/div. Ringing is at 60 kHz.

peak level of the signal. This is because the RIAA deemphasis looks like an integration function —this is *not* nonlinear slew rate limiting; it is caused by the linear process of equalization, which is used to fit the dynamic range of the program material to that of the medium.

This difference between input and output waveforms and slew rates must be accounted for in equalized preamplifiers. Such a complication does not exist with linear flat amplifiers.

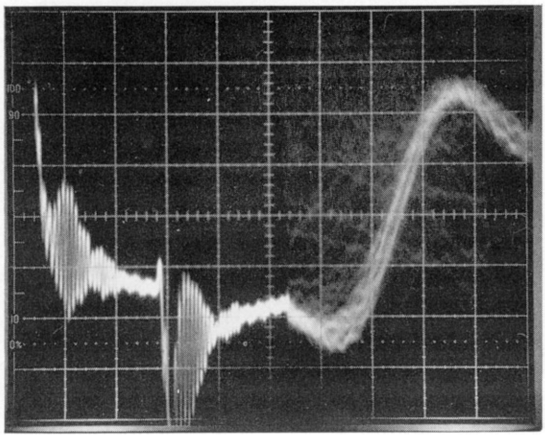

Fig. 3. Same as Fig. 2, except for vertical scale—10 mV/div; horizontal sweep is mixed—left half at 0.2 ms/div, right half at 5 μs/div.

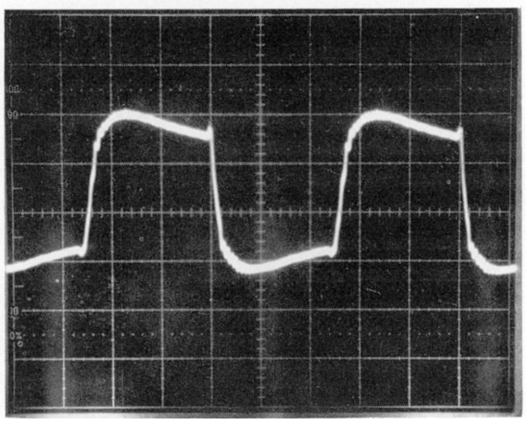

Fig. 4. Same input as Fig. 1, only referenced to output of preamplifier. Vertical scale—50 mV/div; horizontal scale—0.2 ms/div.

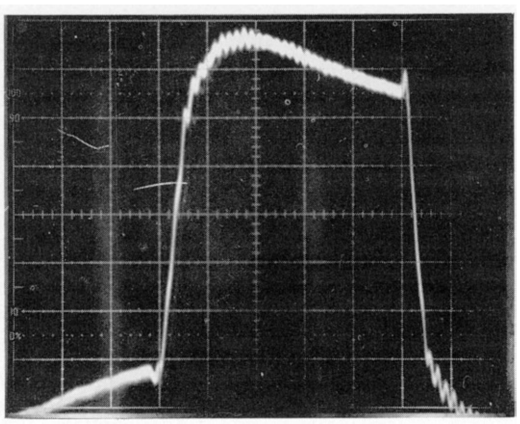

Fig. 5. Same as Fig. 3, except for vertical scale—20 mV/div; horizontal scale—0.1 ms/div.

3 A NEW SET OF TRANSIENT TEST SIGNALS

Fig. 1 indicates that the curvature overload function may be characterized by a two-pole low-pass filter. Other information in [3] shows that the break frequency associated with curvature overload depends on the type of playback stylus, since the radius of the stylus along the length of the groove wall forms an aperture. For a 1-kHz square-wave spectrum where the 1 kHz fundamental is adjusted to be equal to the "0 VU" velocity of 354 mm/s peak lateral velocity per channel played with a cartridge with a sensitivity of 1 mV/cm·s, the break frequency for the filter is 20 kHz. An appropriate test signal is thus a pure 1-kHz square-wave spectrum preemphasized by the RIAA record function and filtered by a 20-kHz two-pole low-pass filter representing the curvature overload limit. In the time domain this signal is shown in Fig. 6; the peak level is 42 mV. The small overshoot at the trailing edge of the transient spike is due to the non-phase-linear characteristics of the low-pass filter. Fig. 7 shows the spectrum of this test signal.

This signal clearly must be handled linearly. But program material is often accompanied by either or both warp and high-frequency ringing. So a battery of tests was devised to cover the variety of situations expected. The first test consists of applying the test signal spectrum at a level corresponding to an average warp played by a peaked tone-arm/cartridge system; the level was 10 mV rms. For this test not only must the resultant spectrum be examined in general for deviation from the input spectrum, but it also must be examined in detail, looking for any 10-Hz sidebands on midrange spectral lines. In a third test an ultrasonic sine wave was added to the basic test signal to determine whether the presence of high-frequency ringing would cause any intermodulation within the audible spectrum. The frequency and level were chosen, after examination of Fig. 2, to be 50 kHz at 15 mV rms. The fourth test raises the level of the test signal to correspond with the highest level signals available from disks for simultaneously stressing both level and slew rate abilities.

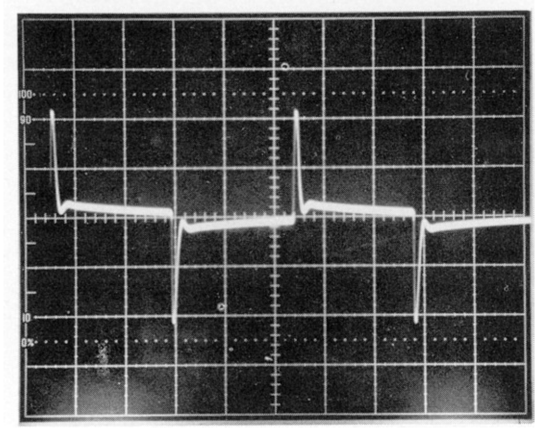

Fig. 6. Test signal for transient tests. Vertical scale—20 mV/div; horizontal scale—0.2 ms/div. Various other sine waveforms were added to this one for testing of response to warp, ultrasonic ringing, and symmetrical TIM (10 Hz, 10 mV rms; 50 kHz, 15 mV rms; 15 kHz, 4:1 peak-to-peak amplitude ratio). The small overshoot at the end of the transient spike is result of the nonlinear phase characteristics of the curvature overload filter.

4 RESULTS WITH THE NEW TEST SIGNALS

The preamplifiers which performed both well and poorly on the previous transient test were still available; so they were tested with the new set of tests. Other preamplifiers with poor reputations were chosen to widen the scope of the survey. In all, three "good" and three "bad" preamplifiers were submitted to the set of four tests. The output spectrum of the preamplifier under test was compared to the expected result with a perfect playback system.

Under this set of test conditions, which could be characterized as transient in nature without stressing nonlinear regions of peak clipping or slew rate limiting, all the preamplifiers performed well and equally. The fourth test of the survey was made with the transient signal plus the signals corresponding to warp and ringing. The maximum peak level was adjusted to be equal to the highest peak level observed from a commercial record played with a high-output moving-coil cartridge with a step-up transformer. (The record was ECM 1060 and the level was 100 mV peak). Even under this combination of stressful conditions all six preamplifiers performed well. The output was indistinguishable from the properly deemphasized signal. This makes good common sense if one remembers what we are trying to do: to get electrons to follow faithfully the motion of a diamond driven by the groove wall.

5 RELATIONSHIP WITH OTALA'S TIM TEST

Otala has pointed out [4] that a test employing only a square wave is adequate for asymmetrical transient intermodulation distortion (TIM), but it does not test for symmetrical TIM. This point is valid because symmetrical TIM would not generate even harmonics; it would only slightly change the level of the odd harmonics. To overcome this difficulty with the method, Otala superimposes a 15-kHz sine wave on a 3.18-kHz square wave as a test signal. For an equalized preamplifier one would then apply appropriate preemphasis and a single-pole rolloff filter at either 30 kHz (TIM 30) or 100 kHz (TIM 100). But the difficulty with this test is the same as in the original test: the preemphasis yields an unrealistic peak level.

A procedure modified to accommodate these difficulties employs a test signal with a 3.18-kHz square wave with a 15-kHz sine wave added at 4:1 peak-to-peak amplitude ratio, low-pass filtered by a two-pole 20-kHz filter. The level into the preamplifier was adjusted to be 100 mV peak, which is the highest level observed with the moving-coil cartridge and transformer combination.

None of the test preamplifiers altered the input spectrum measurably (residual less than 0.01%). An appropriate name for this test is "TIM 20 for phono preamplifiers."

6 CONSEQUENCES OF RC COUPLING AND BOOTSTRAP CAPACITORS

In the course of the survey some interesting phenomena showed up when the various preamplifiers were overloaded with test signals. One preamplifier, when clipped with a 50-kHz signal, went into a severe 8-Hz nonsinusoidal oscillation. Another "motorboated" when clipped in the midrange. These effects are due to the fact that when a stage driving a coupling, bootstrap, or, for example, an emitter bypass capacitor is driven into clipping, the capacitor begins to take on a net charge. When the signal then reverses state so that the overload condition should cease immediately, it does not, since the accumulated charge continues to misbias the surrounding stages. Overload recovery becomes a lengthy process because the charge on the capacitor must reequilibrate. If there should be a feedback loop around this process, either within the amplifier or around it because of common power supply impedances, the amplifier may oscillate (motorboat) at some infrasonic rate.

There are two ways to avoid this instability. One is to make certain that under no set of conditions the amplifier could ever be overloaded; the other is to design circuits that are free from such effects by eliminating internal RC coupling and bootstrap and gain-increasing emitter (or cathode or source) bypass capacitors. This consideration becomes more important in light of the large infrasonic content present in record playing systems, as shown in Fig. 1. A design should account for the simultaneous application of audio, warp, ultrasonic ringing, and RFI, since it is certain that some time in the life of a product all will be present simultaneously.

As time goes by, more and more circuits are made in the form of a dc-coupled operational amplifier. One reason has been the ease of integrating such circuits, but they also have an important advantage in overload recovery, since there are generally no storage elements to take on charge during overload. Although it is possible to make such circuits misbehave through feedback in common power supply impedances, operational amplifier circuits are fairly insensitive to these problems.

7 RFI CONSIDERATIONS

A test of 21 midpriced receivers conducted by Consumer Union showed that the phono stage of these units was the most often and most severely affected of the various parts of a receiver. Since this is apparently an increasingly important problem and since it may become subject to government regulation, designers must be aware of the tradeoffs involved. Proper impedance termination for phonograph cartridges has previously been seen to be one of the largest areas of difference among various designs. Attempts to control RFI by means of RF bypass capacitors around the first stage of a phonograph preamplifier must be examined for causing frequency response errors. The typical moving-magnet cartridge has a source impedance that goes up with ascending frequency, which makes the cartridge response increasingly load dependent at higher frequencies. Cartridge designers employ this fact and optimize the electrical circuit consisting of the cartridge and its load to provide a complementary response to the response of the mechanical system for best overall flatness. Thus preamplifiers may not have arbitrary input impedance but should provide the cartridge with its optimum load (after subtracting cable capacitance).

Beyond considerations of the proper input impedance for a phonograph preamplifier lie three useful facts in dealing with RFI:

1) All other things being equal, the preamplifier with the larger power bandwidth will be less susceptible to RFI than the ones with smaller power bandwidth.

2) All other things being equal, the preamplifier with the more linear input stage will be less susceptible to RFI than the ones with smaller power bandwidth.

3) The proper combination of input resistance and capacitance *must* appear only in the audio band; above audio the input impedance is unimportant, but it is critically important in-band, implying that little useful filtering can be accomplished at AM radio frequencies without very sophisticated filter networks.

Figs. 8 and 9 show the output of two different preamplifiers driven with a 500-kHz, 50-mV rms input signal. Fig. 8 clearly shows slew-rate limiting of the signal. Slew-rate limiting or another nonlinear distortion of the signal acts as a detector to demodulate the audio information impressed on the carrier and reflects a portion of the audio signal down into the audible range (usually distortedly). The preamplifier of Fig. 9 shows no such important nonlinearity. These two preamplifiers are quite different in their susceptibility to RFI from AM and other radio signals. Therefore a wide power bandwidth is desirable in phonograph preamplifiers, not as a requirement for the audio signal, but for minimum detection of RFI through nonlinearities. Of course, this process must have a limit. It is simply unreasonable to build gigahertz power bandwidth phono preamplifiers, but small AM radio signals would seem to require linear operation.

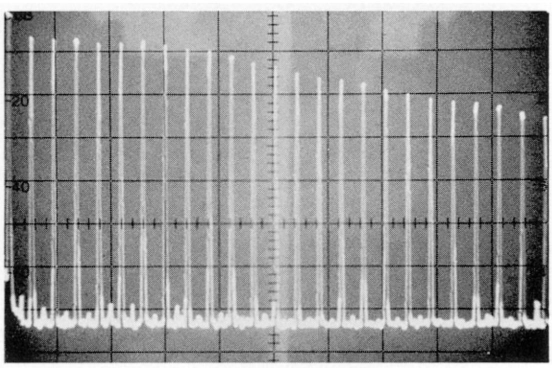

Fig. 7. Spectrum of test pulse at input terminals of preamplifier. Vertical scale —10 dB/div; horizontal scale —5 kHz/div.

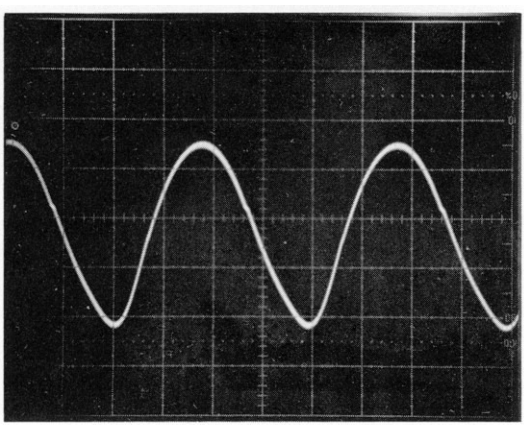

Fig. 8. Output of a preamplifier driven by a 500-kHz, 50-mV rms sine wave. Vertical scale —0.1 V/div; horizontal scale —0.5 μs/div.

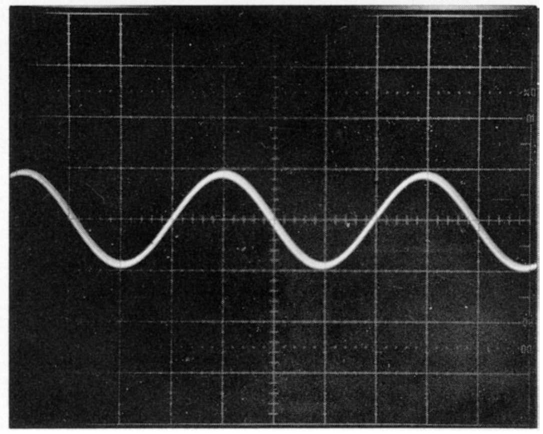

Fig. 9. Same as Fig. 8, but with a different preamplifier.

Above the frequency at which the feedback loop is effective because of falling open-loop gain, the input characteristics of the first stage become important. If the first stage detects the RFI, the audio product of the detection will be amplified by the full gain of the amplifier. The degree of detection will depend on the curvature of the transfer function of the input stage device. The exponential base-emitter junction relation of a bipolar transistor is considerably less linear than the square-law characteristic of a field-effect transistor when each is biased appropriately for a phono preamplifier input stage. This implies that FET-input preamplifiers, all other things being equal, should be less susceptible to RFI. Although the finding is empirical, many thousands of installations in the field have proved the efficacy of this approach.

At first glance one might think that FM band RFI would not be detected since the signal, not generally varying in amplitude, would not stimulate an amplitude-dependent detection. However, FM RFI may become amplitude modulation through slope detection. If the gain of the preamplifier has a tilt through the bandwidth of the FM source, the tilt will turn frequency modulation into amplitude modulation, which will then be detected in the level-dependent nonlinearity of the input stage.

Input attenuation filters for CB and other high-frequency interference are also a possibility. Considerations for these filters include adequate loss at the interfering frequency as well as a defined capacitive input impedance in the audio band.

8 CONCLUSIONS

Transient distortion effects in phonograph preamplifiers are unlikely to be stimulated by real-world sources. Overload in preamplifiers is a peak detection phenomenon. It too is unlikely in well-designed preamplifiers which account for infrasonic and ultrasonic inputs as well as the audio band input.

Large capacitors must be examined for their behavior under asymmetrical and clipped signal conditions.

RFI in phono stages is a prominent problem on which there has been little discussion in the literature. Guidelines have been presented which will tend to make preamplifiers less susceptible without causing audible input impedance interactions; other good practice should include good grounding and shielding effective at frequencies that are likely to cause interference.

9 ACKNOWLEDGMENTS

Nathan Sokal of Design Automation, Lexington, Massachusetts, was very helpful in discussions related to the RFI section of this paper. Robert Ludwig at Master Disc in New York cut the special test disks.

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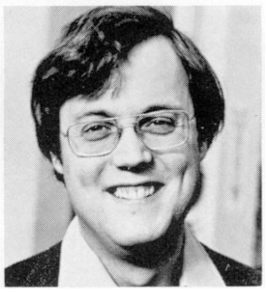
THE AUTHOR



Tomlinson Holman grew up in Illinois and attended the University of Illinois, graduating in 1968. As an undergraduate, he studied engineering and communications and held assistantships in theater and music. As a graduate student in communications, he continued work in the technical aspects of theater, opera, television, and film production. From 1968 to 1973 he worked as sound mixer in the University's Motion Picture Production Center and operated a custom audio business.

In 1973 he left Illinois to join Advent Corporation of Cambridge, Massachusetts, as audio design engineer, and in 1975 became chief electrical engineer. While at Advent, under Henry Kloss, he was responsible for all audio design which led to two U.S. patents and for supervising engineering of the Advent CR70 prerecorded tape program. In 1977 he became a founder of Apt Corporation, where he is director of engineering.

Mr. Holman's musical training at the university included work in Lejaren Hiller's Experimental Music Studio, with Jaap Spek (an engineering associate of Karlheinz Stockhausen) at the Krannert Center for the Performing Arts, with Ludwig Zirner in the university's opera workshop, on Gunther Schuller's *The Visitation*, and in making numerous music recordings. He has continued recording with Russell Sherman, Malcolm Bilson, and others for Advent and various record labels. He was the engineer for the Handel and Haydn Society's recording of *The Messiah*, and serves as audio consultant to the society.

He is a member of the Audio Engineering Society and serves on the review board of its *Journal*. He is also a member of the IEEE. He has published several articles, and taught a course on "The Art of High Fidelity" for the Cambridge Center for Adult Education.