Audibility of phase distortion

Pulse testing of all-pass phase shift networks, loudspeakers and human heads

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The intense interest aroused in scientific circles by matrix quadraphony has resulted in a careful scrutiny of all its components, most important among them being all-pass phase-shift networks (or "psi-networks" as we like to call them). After presentation of our paper on quadraphony at the Audio Engineering Society Meeting in Rotterdam[1], a discussion was held about wave-shape changes that had been observed in testing psi-networks with square waves. We acknowledged the existence of these changes, but replied that at no time had we noticed audible distortion with psi networks (the results of psychoacoustic testing in which such networks were randomly introduced in paired comparisons being governed strictly by chance [2]), and concluded by stating that square waves did not seem to be useful for testing psi networks (or, for that matter, loudspeakers). This paper expands our views on this subject.

As every electronics engineer knows, psi networks have been used in audio communications for many years without the slightest perceptible ill effect. Traditionally, they have been utilized for production of single sideband modulation; an important application in modern a.m. and f.m. broadcasting technology is for "symmetricizing" speech waves to increase the modulation index — a psi network sold in the U.S.A. under the trade name "Symmetrapeak" is commonly used for this purpose. Also, a widely employed scheme for producing monophonic records from, and for compatible broadcasting of, stereophonic programs utilizes differential psi networks in the two channels of the stereophonic source.

Prior to the introduction of the SQ system by CBS, the action of psi networks was carefully reviewed at our laboratories using music, speech, square waves, triangular waves, and Gaussian noise sources. These were applied to loudspeakers with the psi network in and out of the circuit. At no time have any of our listeners been able to detect the slightest audible difference. These experiments, naturally, did not prove that some all-pass networks might not be capable of altering the quality of sound — they simply meant that the psi networks we designed had not produced such alterations. I presume that similar tests have been performed by Mr Itoh of Sansui[3] and by Drs Cooper and Shiga of Nippon/Columbia[4] with their systems of matrix quadraphony which also use psi networks. Additionally, one should mention the work of Dr Manfred P. Schroeder, who studied psi networks and established criteria for their audible performance[5].

Impulse testing of psi networks

Let us take a typical psi network of the type used for matrix encoding and study its impulse characteristics. As an example, we selected a 10-pole network used in an SQ encoder, with straight-line phase shift versus log-frequency characteristic from 20-20,000 Hz, shown in Fig.1. The sine-wave response of this network is flat within 0.25 dB over the audible range and its harmonic and intermodulation distortions are virtually unmeasurable. However, if a rectangular wave, e.g., of 1ms duration, is applied to it, the output has little resemblance to the input, as seen in Fig. 2. The alteration of shape obviously is caused by differential phase delays.

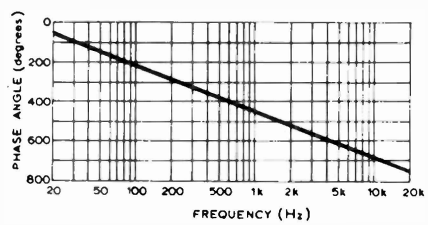

Fig. 1 Typical phase shift function, psi (f) of psi network used in SQ encoders.

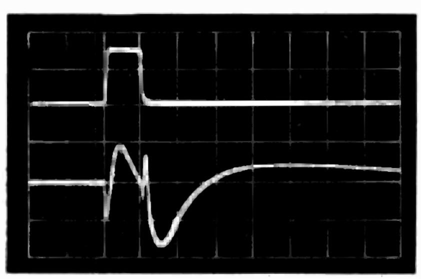

Fig. 2 The response of the psi network of Fig. 1 (lower trace) to a 1 ms rectangular pulse (upper trace).

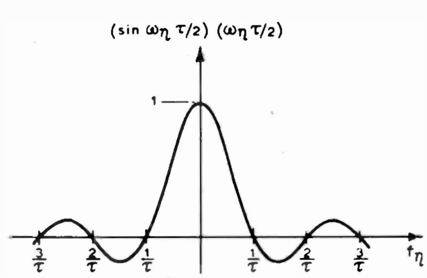

Fig. 3 The plot of $(\sin \omega_\eta \tau/2)/(\omega_\eta \tau/2)$

We know, of course, through the use of the Fourier transform, that a single rectangular pulse may be represented in the frequency domain by a continuum from minus to plus infinity with amplitude distribution following the law $(\sin\omega_\eta\tau/2)/\omega_\eta\tau/2)$ shown in Fig. 3, where ω_η is the angular frequency, $2\ \pi f_\eta$, and τ is the pulse length in seconds, or by an equivalent line structure in the event of periodically generated pulses. With a 1ms-wide pulse, the nulls occur at 1 kHz intervals. Any presumption that such a continuum can fairly be used for visual assessment of the performance of a psi network used for conventional speech and music clearly is unwarranted, especially since the presence or absence of the network does not perceptibly influence the audible quality of sound.

Nevertheless, visual inspection of the effect of psi networks upon pulses is, at times, desirable as when one wishes to measure system overload capability or time delay. Some years ago, while developing tests for loudspeakers, similar consideration led us to search for a pulse which would fairly represent the reaction of an acoustical system to transient signals. Reviewing the available signals, one finds at one extreme the delta pulse of infinitesimal duration which is equivalent, in the frequency domain, to a uniform cophase amplitude distribution extending from minus to plus infinity; and at the other, a continuous sine wave signal extending from minus to plus infinity in the time domain, equivalent to a single line-frequency. Either extreme is obviously uninformative. A limited-frequency continuum appealed to us as a reasonable compromise since the delay characteristics of the waves within such a packet would be more or less uniform. In the time domain the limited-bandwidth pulse resembles a bell-shaped amplitudemodulated sine wave, not unlike the shape of the transient sounds of some musical instruments.

An easy way to obtain the desired function is to pass a 100 μs or shorter pulse through a 1/3-octave bandpass filter. Fig. 4 shows what happens when such a test signal produced through a filter with a mid-frequency of 1000 Hz (top curve), is passed through the psi network (bottom curve). We note that the packet of waves passes through the network with practically no change in the shape of the envelope, albeit the phase relationship at midpoint, predictable from the curve in Fig 1, is modulo 360°, or 450° — 360° = 90°.

Impulse performance of loudspeakers

Since we commonly use loudspeakers to judge sound quality, the performance of loudspeakers with impulsive sounds becomes a matter of interest. Fig 5 shows the response of a high-quality monitor loudspeaker to the 1μs rectangular pulse. A small microphone with flat frequency response placed approximately 18in from the loudspeaker grille picks up the reproduced pulse. The time delay, (1 μ per division), clearly corresponds to the transit time from the loudspeaker to the microphone, plus a small delay within the loudspeaker proper. The reproduced pulse is quite similar to that exhibited by the psi networks but with some added perturbations.

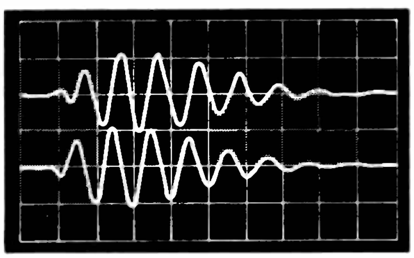

Fig. 4 A bandpass-filtered delta pulse (lower trace) with the bandpass-filtered delta pulse passed through the psi network (upper trace).

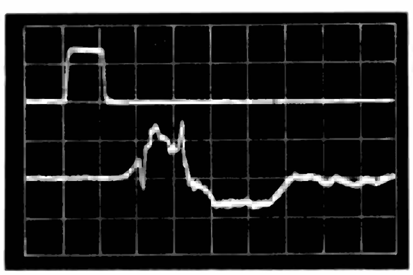

Fig. 5 The response of a high quality loudspeaker (lower trace) to a lms rectangular pulse (upper trace).

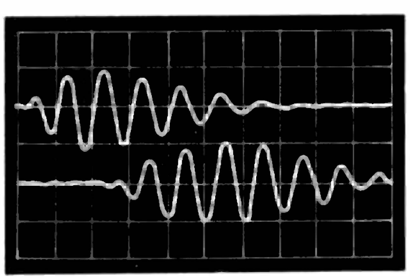

Fig. 6 The bandpass-filtered delta pulse (upper trace) compared with the response of a high quality loudspeaker to the same pulse (lower trace).

By applying the 1000-Hz centred 1/3-octave filtered packet of waves to the loudspeaker, the result shown in Fig 6 becomes similar to that obtained with the psi network, except that the envelope delay corresponding to the microphone-speaker distance again is noted. The response curve of this particular loudspeaker exhibits a slight hangover, suggesting a somewhat underdamped condition. In CBS Laboratories' high fidelity components testing programme, such 1/3-octave band-limited pulses are regularly used for loudspeaker testing[6]. Comparing the shapes of the input and output pulses allows us to study such diverse factors as magnetic dissymmetries, mechanical nonlinearities, acoustical reflections, etc. which otherwise would be difficult to detect.

Having established that psi networks and loudspeakers share similarities with respect to impulsive sounds, one is led to conjecture whether there might not exist an opportunity for improving the performance of both classes of devices. Here we open the door to a debate which probably will continue for a long time to the delight of hi-fi enthusiasts and magazine editors alike.

Will the ultimate perfection of psi networks and loudspeakers, if it were theoretically possible, lead to significant improvements in fidelity? Even to conjecture about this question requ we define what is meant by audible fidelity in the reproduction of impulsive sounds. Some years ago we measured the interaural delays caused by the human head as a function of frequency and azimuth of sound arrival[7]. The delays were calculated from phase measurements at the ear canal entrances at low frequency, but high-frequency measurements were difficult to perform because of rapid phase changes caused by minuscule head motions, also exhibiting inconsistencies which probably were related to differences between phase and group velocities. Later we attempted to use acoustical pulses with the thought of obtaining group delay characteristics. The results were similar to those exhibited by the psi networks and loudspeakers. Thus, even if one were able to design these latter components to transmit visually unaltered rectangular pulses, the diffraction around the head might prevent the audible effect of such change from being significant, except possibly at very low frequencies.

Conclusion

In conclusion, careful auditing of speech, music, impulsive repetitive sounds and Gaussian noises reproduced with and without psi networks through high quality loudspeakers convinced us that the types of networks we use are not a cause of discernible changes in quality. With respect to distortions occasionally reported by some observers, one is tempted to wonder if an unrelated factor such as a change in frequency response, amplifier overload, etc., might not in fact have been the assignable cause. The phase shifts or time delays exhibited by our psi networks simply have turned out to be inaudible.

Presumably, we should be grateful to Messrs. G. S. Ohm and H. L. F. Helmholtz who discovered that phase does not influence timbre[8]. even if a number of distinguished investigators have described subsequent experiments designed to demonstrate that phase changes can result in alterations of timbre[9]. Shroeder[10] maintains that small or no subjective changes will be produced by variations of phase spectrum which leave the envelope of the stimulus invariant. The latter condition is attained with the impulse we used in testing psi networks as demonstrated by Figs 4 and 6, and which we believe fairly represents the impulsive sounds of speech and music. But even the timbre of square waves is unaltered with our psi networks, we conjecture, because loudspeakers and human heads introduce similar differential delays in the path of the signal. Evidently more research into this problem is needed.

References

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