Observations on the Audibility of Acoustic Polarity*

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A number of experiments are described which show that absolute acoustic polarity is clearly audible in certain select cases of reproduced sound from acoustical instruments. The nature of the audible differences and the characteristics of the temporal signals which lend themselves to audibility are described. A large double blind listening experiment using varied musical program material is described as well.

0 INTRODUCTION

Since the time of acoustical work of Helmholtz and others there have been discussions and, indeed, heated arguments about the audibility of phase relationships among the components of audio signals and, more recently, about the audibility of absolute inversion of the acoustic polarity of audio signals. These matters are certainly of interest to the professional recordist since initial responsibility for maintaining "correct" polarity rests there.

Considerable agreement is found about the audibility of changed (from the original) phase relationships in audio signals, particularly transient signals. In most cases the phase behavior in a complex recording system is unknown or out of control. Yet great homage is paid to the need for reduced phase shift, phase linearity, minimum phaseness, and the like in audio equipment. Some claim to hear almost unmeasurably small phase distortions. Yet, interestingly enough, one hears among this same group almost random responses on the question of the audibility of acoustic polarity inversion. At this time there is no clear consensus about the audibility of polarity inversion. Professionals vary in opinion from those who simply say the issue is irrelevant to those who carefully keep track of polarity at every turn in the recording chain. The consumer market, on the other hand, can only be characterized as total chaos.

Polarity inversion does not distort the phase and amplitude relationships between the frequency components of a signal, nor does it change the temporal shape of a transient signal. It does, however, present to the ear a fundamentally different signal, that is, compressions are replaced by rarefactions and vice versa. The eardrum at any instant is "pushed" instead of "pulled." Surely this is a fundamental and major change in the acoustical presentation to the listener, and surely it should be readily audible. While acoustical instruments cannot generally be made to produce both normal and inverted acoustic polarity, it is common to reproduce sound from loudspeakers, and these can easily be connected to give both normal and inverted acoustic polarity. Does it matter? Would the kettledrum sound different if struck from the inside rather than the outside? Acoustical instruments, even when played in a steady-state mode, often emit temporal waveforms that are highly asymmetrical. They often have peaks of either compression or rarefaction, and one might assume that these waveforms would sound different to the ear if inverted. Still, very little attention seems to have been paid in actual recording practice to maintaining original polarity. A high quality has been attained in the state of the recording art in recent years, and it is now easy to control and keep track of polarity in the digital domain. It would seem time to determine the contribution that absolute acoustic polarity makes to the accuracy of reproduced sound. Some experiments on the audibility of absolute acoustic polarity are described in this paper. The results are not entirely consistent nor totally definitive. The experiments, while simple in principle, have proved to be surprisingly difficult to carry out and interpret.

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The experiments reported here show that the quest to establish in a convincing way that polarity inversion is audible is complex and also that the issue of polarity in music reproduction should not be cast aside as unimportant in pursuit of the goal to establish accurate reproduction of an acoustic event.

1 BASIC CONSIDERATIONS

When sound is emitted by an acoustical instrument it travels through the air in the form of compressions and rarefactions that are "picked up" by a microphone and turned into an electric signal. The microphone may turn compressions into positive voltages and rarefactions into negative voltages, or vice versa, depending on its design. In a similar manner, when a positive polarity is applied to a loudspeaker, it may move forward and cause a compression at its surface, while a negative polarity causes the loudspeaker to move backward whereupon it generates a rarefaction in the air. Some multiway loudspeaker designs still invert the polarity of one of the drivers in a multiway system in order to achieve flat frequency response [1], [2]. What this does to the matter of maintaining absolute polarity is a nightmare. In order to ensure accurate reproduction, it would seem reasonable that an acoustic wave be reproduced in such a manner that the original compressions should be reproduced as compressions and the rarefactions as rarefactions. We assume this to be a desirable goal and have tried to set up experiments to see whether it matters all that much.

These experiments are designed to determine only the audibility of inversion of the acoustic polarity of the signal as reproduced by a sound system. In the work described here only the polarity of the signal is modified, the temporal shape of the waveform remains constant and unchanged.

It is not possible to make an acoustical instrument such as a trumpet or trombone that can perform acoustic waveform inversion without otherwise changing the sound in an obvious way. However, when reproducing sound with a loudspeaker, it is possible to generate an arbitrary acoustic polarity. The polarity of the acoustic signal from the loudspeaker may agree with the polarity of the signal that reached the microphone (the original signal) or not. Unless great care has been taken to keep track of the acoustic and electric polarity of the signal in the record–reproduction chain, in the sense that an acoustic compression at the microphone generates an acoustic compression at the face of the loudspeaker, any sense of polarity is lost (Fig. 1). The literature is replete with opinions about the audibility of polarity inversion. Most of these opinions are anecdotal or based on uncontrolled and unverifiable individual listening experiences (see Bibliography).

The results reported here show that polarity inversion is clearly audible in some circumstances, but that in many situations it is not. In fact, most of the time polarity inversion seems to be inaudible. However, it is audible often enough that it is suggested here that the polarity of the recorded acoustic signal be traced through the entire record–reproduce chain so that the correct polarity can be reproduced at the listeners' loudspeakers.

2 PRELIMINARY LISTENING EXPERIENCES

It is clear from the technical literatue that it is easy for the ear to distinguish the polarity of an acoustic signal, or at least a change in polarity, under certain conditions with specially designed waveforms. The "classic" waveform used to perform this experiment is shown in Fig. 2 [3]. It is a very simple waveform, consisting of a fundamental and the second harmonic of one-half of the amplitude of the fundamental and phase shifted by 90°. Often the audible effect of inverting this waveform is described as a change in pitch or timbre of the signal, with the pitch change being the predominant effect. Generally these experiments are carried out with steady-state tones or repetitive signals and with carefully controlled A/B testing procedures. Our experiments easily verify this result. Before carrying out the large-group listening tests reported on in the next section, a considerable amount of time and effort went into the preparation of the listening venue and in selecting suitable source material. While the preparations for these tests were underway, speculation about the anticipated results were considered and discussed at length among the researchers involved. For example, it was thought from the beginning that acoustic polarity inversion should be quite easily audible and that a normal stereo listening setup should be used. However, in preliminary listening tests done with both headphones and loudspeakers almost none of the listeners could hear any effects of acoustic polarity inversion. With a stereo loudspeaker listening setup and

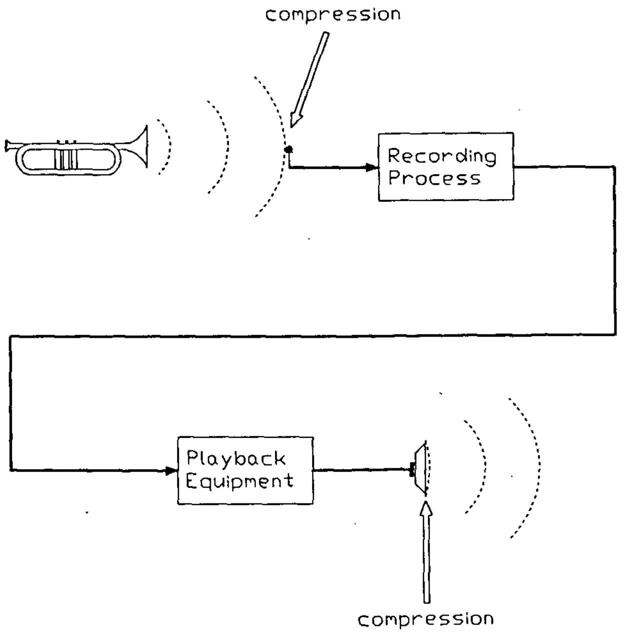

Fig. 1. Record–playback of acoustic waveform showing that a compression at the microphone should be reproduced as a compression at the loudspeaker.

musical program material the listening experience seemed to be far too complex to detect precisely and consistently what turned out to be very subtile effects caused by acoustic polarity inversion. While some persons have reported obvious audible effects under such conditions, we were not able to observe them in our high-quality low-distortion setup.

It was clear that a simpler listening setup was required if polarity inversion was to be detected consistently and reliably. Thus it was decided that the listening tests would be done in a semianechoic room to reduce the complexity of the sound field caused by reflecting room boundaries. Since headphone listening to special test tones demonstrated to everyone that polarity inversion was in fact clearly audible for some conditions, it seemed important to find a demarcation point in either the complexity of the listening setup, the sound field, or the program material for which polarity inversion became more or less detectable. It was found that with a monaural loudspeaker setup in semianechoic conditions and with simple waveforms polarity inversion became as obvious as it was with headphones. The special test signal, reproduced in Fig. 2, clearly showed audible effects in this setup. Both the timbre and pitch of the tone were affected. With this simplified reproduction system and using musical program material, some of the listeners could hear inversion regularly. This final result was encouraging in that it indicated a positive result for the audibility of acoustic polarity using musical program material. With this rather simple listening setup it was expected that a double blind, statistically significant listening test would show that polarity was audible to a significant extent for any program material. In this way the listening venue, the program material selections, and the test methods were carefully prepared, in fact biased, toward making acoustic polarity inversion audible. While tests should have given statistically significant positive results, in fact, the results were not clearly convincing and generated as much confusion as clarification. Nevertheless the results are interesting and suggest how additional experiments might be performed.

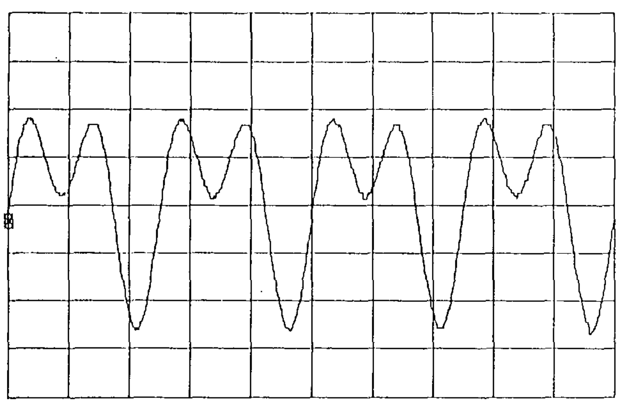

Fig. 2. This simple waveform is often used to demonstrate the audibility of acoustic polarity inversion. In this paper it is called "classic" waveform.

Because of the complex and inconclusive results of the large-group listening test program, additional listening tests were done, in some cases with only a few individuals, aimed at identifying the reasons why music signals and special test tones differ so greatly in generating an audible difference upon inversion. The large-group tests are described first, with a description of the additional tests following.

3 LARGE-GROUP LISTENING RESULTS

Listening tests were carried out using a group of 39 students who were taking a senior-level course in audio system design at the university. Enough individual tests, 10 per student, were evaluated to give good statistical confidence in the results. Listening tests for the large group were done double blind.

For the large-group tests a DAT tape was prepared with 10 examples of music. The musical examples were of a great variety selected from CD sources. Table 1 lists the program material used. Musical examples were purposely selected which had large asymmetries in their waveforms in the time domain. The examples were selected so that a particular instrument was highlighted in a solo passage, although with some background instruments in a few cases. A preliminary casual listening to this program material did not seem to show much audible effect upon acoustic polarity inversion. While this observation suggested that it would be difficult to obtain useful results from a time-consuming set of listening tests, these tests were carried forward. A brief description of the selected musical passages follows. A selection of these waveforms is shown in Figs. 3–8.

Example 1: Vocal. The voice waveform is highly spiked and highly asymmetrical and showed both pos-

Table 1. Program examples used for large-scale listening tests.

	Identification	Artist/Instrument	Track	Start Time	End Time
1	CD13	McBroom/Vocal	3	0:00	1:30
2	CHAN8549	Clarinet	9	0:00	1:30
3	CD-KODO	KODO/Drums	2	2:01	3:33
4	GRP-D-9507	Grusin/Jazz	1	0:00	1:30
5	GPP-D-9503	Mulligan/Sax	3	0:00	1:28
6	CD-80220	Class Brass	1	0:00	1:27
7	417361-2	Bolet/Piano	18	0:00	1:30
8	CD-80134	Romero/Guitar	3	0:00	1:30
9	BIS-CD-258	Trombone	6	0:00	1:29
10	CD5	Grusin/Jazz	2	0:00	1:40

itive and negative spikes (Fig. 3). The audible effects of inversion, if any, were totally obscured by musical factors of vibrato, tremolo, and intonation.

Example 2: Clarinet. No examples of significant asymmetry were found, although the waveform was very complex.

Example 3: Bass Drums. These drums show very complex transients which are highly undamped (Fig. 4). No effects of inversion were audible.

Example 4: Electric Bass. These tones show clear asymmetries in their waveforms. No changes in these musical signals could be heard upon inversion.

Example 5: Saxophone. Considerable spiking and asymmetry are apparent in this saxophone tone (Fig. 5). The musical factors, vibrato and the like, make audible detection of inversion effects impossible.

Example 6: Trumpet. Spiking, but more or less symmetrical spiking, was observed for this trumpet tone (Fig. 6). No highly asymmetrical examples of spiking were found, but this does not mean that they do not exist. This tone showed no audible effects of inversion.

Example 7: Piano. No examples of strong asymmetry were found, although the waveform was very complex and full of transients.

Example 8: Classical Guitar. Plucked tones, such as the guitar tone, do not have a very asymmetrical waveform, nor do they show spiked compressions or rarefactions. This seems contrary to what one would expect from a highly transient tone. However, the design of the tonal radiating surface of the instrument is complex so that the radiation from the plucking of the string may not predominate. No tones from plucked or struck instruments were found that gave anything like steady-state spiked waveforms.

Example 9: Trombone. While quite asymmetrical, sustained tones, these musically played notes were not audibly changed by inversion (Fig. 7). This is probably because the musicality of the played note introduces pitch and timbre changes which overwhelm those due to inversion.

Example 10: Kick Drum. While the kick drum shows a very sharp transient waveform that is clearly asymmetrical, it is not possible to hear the effect of inversion (Fig. 8).

Since the examples were taken from actual recorded performances, all show musical characteristics and are thus not purely steady, sustained tones. They have strong transient behavior and variations in pitch and timbre which greatly obscure the effects of polarity inversion.

The musical passages described were presented through a single large multiway loudspeaker of high quality in a monaural mode. The room, about 20 by 20 ft (6 by 6m) in size with a 12-ft (4-m) ceiling, was very dead and in fact nearly anechoic above 250 Hz. All surfaces of the room except the floor were covered with 3-in (76-mm) SONEX. The floor was heavily pad-

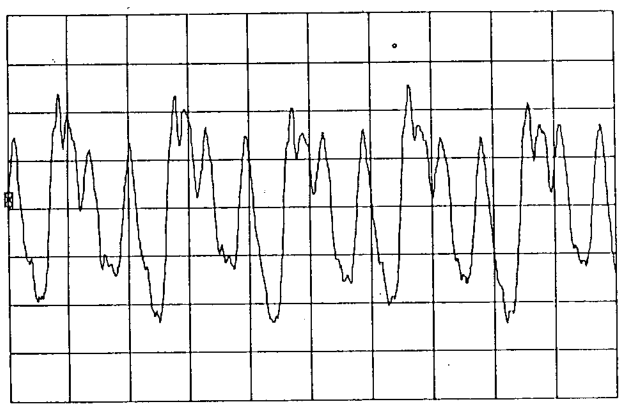

Fig. 3. Waveform from example 1, vocal.

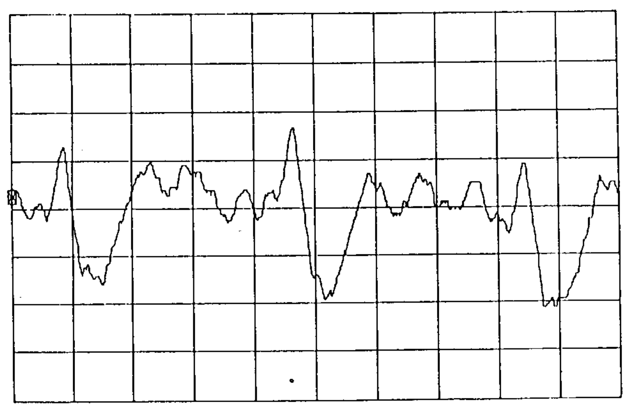

Fig. 5. Waveform from example 5, saxophone.

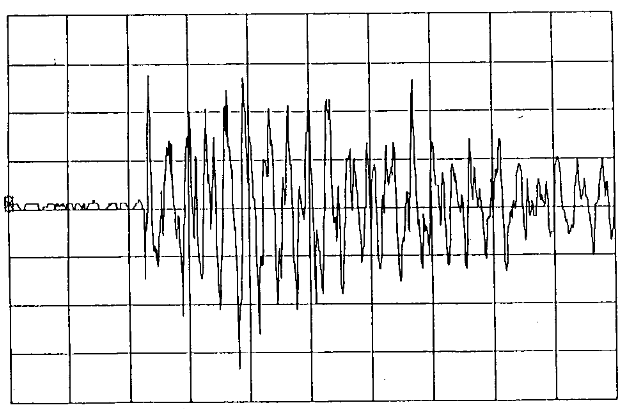

Fig. 4. Waveform from example 3, bass drum.

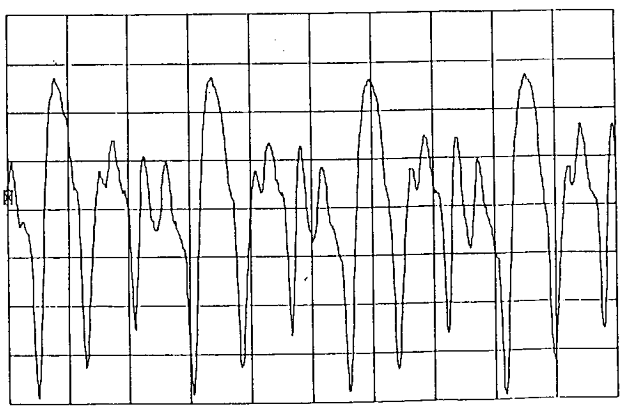

Fig. 6. Waveform from example 6, trumpet.

ded and carpeted. The loudspeaker was quad amplified, and levels were adjusted so as to make the system quite uniform in frequency response at the listening position. Because of the size of the system and the relatively modest loudness levels at which the system was operated, very low distortion levels existed in the reproduced sound. It was hoped that any nonlinear effects would not bias the acoustic polarity changes. It was very clear that several special test tones played at varying levels all clearly showed the audible affects of acoustic polarity inversion described in the preceding.

It was felt that this listening setup was suitably minimalist so that the listeners could concentrate on the tonality and timbre of the sound without confusion from stereo imaging effects and reflections from room boundaries. This, it was hoped, would optimize the audibility of the subtile effects of polarity inversion. All equipment and operating personnel were in an adjacent room. Inverting circuits were inserted in the signal path so that inverted or noninverted reproduction could be selected by successive pushes of a hand-held button, depending on the setting of a master decision-making control. Each musical selection of about 1½ min length was randomly selected to be unchanged or inverted each time the control button was pressed.

Of the 390 tests conducted, 227 responses correctly identified whether a change in polarity occurred when the control button was pressed. Using confidence interval analysis for large-sample binomial experiments, several confidence intervals were generated to estimate the true rate of correct identification. The confidence intervals determine an upper and lower limit of the true identification rate. The large-group listening test results are given in Table 2. The confidence intervals show that the correct response ratio may be very close to 0.5 if a high level of confidence is required. In this type of test, significant results are obtained when the correct response ratio deviates from 50%.

The results were also analyzed for each individual musical example. The ratio of correct to incorrect responses for each example is given in Table 3. While all of the ratios are greater than 0.5, indicating a slight ability to detect if a change in polarity occurred, the piano (7) and the classical guitar (8) tracks yielded significantly higher correct responses.

Thus it seems that this attempt to show the audibility of polarity inversion in a relatively well designed experiment gives a result with a slight positive bias. It seems fair to say that the inversion of an acoustic signal is not distinctly audible in most cases. This conclusion, it must be remembered, is for the particular program material, the particular room (semianechoic), and the particular loudspeaker system (multiway very low distortion). Because this result is in some ways disappointing in that it seems more reasonable that acoustic polarity inversion, which is a very large physical change in the acoustic presentation to the ear, should be more clearly audible, further study of these effects is required.

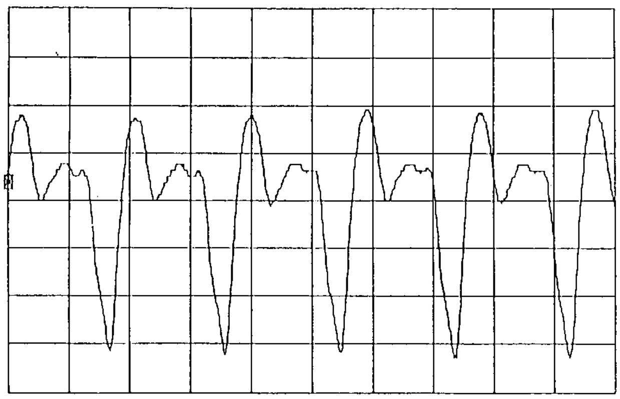

Fig. 7. Waveform from example 9, trombone.

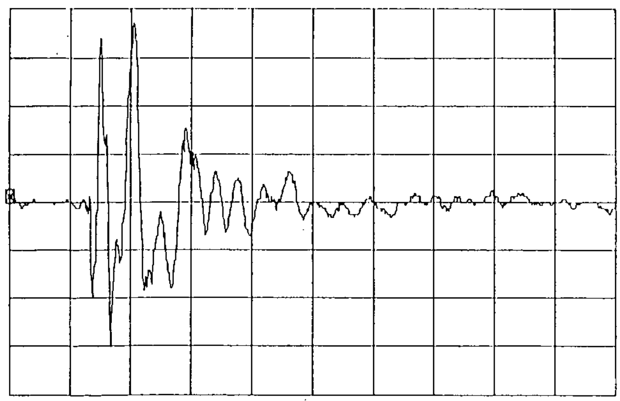

Fig. 8. Waveform from example 10, kick drum.

4 FURTHER LISTENING TESTS

Since simple test waveforms demonstrated clearly audible effects when inverted while the more complex music signals did not, several additional listening tests were undertaken. These tests were done by the authors and their colleagues, with and without the benefit of double blind techniques, the latter applying mainly in cases where polarity inversion was so obvious that there was no question that it could be recognized all of the

Table 2. Summary of statistical analysis results for large-group listening tests.

Experiment set: 39 listeners, 10 individual tests per listener	
Administered test: Ratio of # of tests with polarity inversion to # of tests with no polarity inversion	192/390 = 0.4923
Listener responses: Ratio of "changed" responses to "unchanged" responses	115/390 = 0.2949
Correct responses: Ratio of correct to incorrect responses	227/390 = 0.5821
Confidence intervals for true ratio of correct to incorrect responses*	0.5410–0.6231 90% confidence
	0.5331–0.6310 95% confidence
	0.5177–0.6464 99% confidence

* Given an infinite sample of experiments.

time by almost any listener. These tests were done in an attempt to discover what properties of a signal make it subject to inversion sensitivity.

It was very clear, in listening tests, that the waveform shown in Fig. 9 was audibly altered when inverted. While the timbre of the tone changes somewhat, it is very clear that an apparent pitch change dominates. Yet the tone, inverted or not, obviously maintains the same frequency. In order to determine which waveforms were most sensitive to inversion, several waveforms were generated with a set of oscillators. In addition, live acoustic test tones were generated in one case with a trombone and in another case with a harmonica.

Three synthesized tones used are shown: the "classic" tone (Fig. 2), a three-tone signal made to look something like an acoustical trombone tone (Fig. 9), a four-tone signal made to look even more like a complex trombone tone (Fig. 10). (Figs. 7, 11, and 12 show real trombone tones.) The idea was to make more and more complex tones to find the point at which complexity overcomes the ability to hear inversion effects as found in simple tones. This quest was only partially successful, but yielded some useful clues about the relationship between steady tones, musical tones, and inversion sensitivity.

With synthesized tones such as those in Figs. 9 and 10 it was always easy to hear the effects of inverting the acoustic polarity of the signal so long as there was a very substantial asymmetry in the signal. This was true for headphones and loudspeakers and at all loudness levels. These tones were of course perfectly cyclical in time since they were generated by high-precision synchronized oscillators.

The next step was to use an acoustically generated real instrumental tone. An asymmetrical tone generated by a trombone is shown in Fig. 11. This tone was generated live by playing a trombone in a semianechoic room and recording it directly to the DAT machine. The tone was a sustained note played as uniformly as possible for as long a time as possible. Two notes were recorded. One, shown in Fig. 11, was a loud 280-Hz tone. The tone had to be loud in order to generate spiking in the waveform. Soft tones were more symmetrical and smooth. Even the loud tone showed spikes of compression and rarefaction that were relatively symmetrical. This tone did not change in perceived sound when the polarity was inverted. The second tone was a 320-Hz harsh sounding note. The harshness of this tone can be seen in the very sharp spikes and great asymmetry of the waveform in Fig. 12.

When the harsh tone is presented to the ear in a polarity inversion test, it clearly takes on both a changed timbre and pitch, depending on whether the spikes are compressions or rarefactions. When the spikes are reproduced as compressions, the pitch seems lower, and when the spikes are reproduced as rarefactions (acoustically inverted for the case of the trombone), the pitch seems higher. This is the case regardless of the other properties of the waveform such as loudness. It is also independent of the transducer and could be clearly heard on headphones or loudspeakers. While the effect is small, it is very clear and practically everyone could hear it. Thus it appears, tentatively, that asymmetry of the signal is a property necessary to make a difference in perception of an acoustical inversion of the signal.

Since many acoustical instruments, in this case a trombone, yield sharp spikes of compression when played so as to generate a rather harsh tone, it would seem logical to retain the polarity of the acoustic signal in reproduction and present spikes of compression from the loudspeaker to the listener as well.

A second acoustical instrument, the harmonica, was used to test and verify some of the observations described. Waveforms for two harmonica notes are shown in Figs. 13 and 14. The one in Fig. 13 is an "out" note, one in Fig. 14 an "in" note. These waveforms are strikingly complex, showing both spikes and asymmetry. When the acoustic polarity of either of these signals was inverted, the tone changed distinctly. Both the timbre and the pitch of the tones were affected. When the tone was acoustically inverted from normal, it sounded higher in apparent pitch. This is interesting since the "in" and "out" notes have spikes of compression and rarefaction, respectively. Thus for both the trombone and the harmonica notes inversion of the correct acoustic polarity seems to yield higher pitch regardless of the polarity of the spikes.

5 CONCLUSIONS

If asymmetry of the waveform is important in relation to hearing polarity inversion, then several precautions and warnings about loudspeaker systems are in order. High values of even-order distortion, that is, second, fourth, etc., in a sound system might make polarity

Table 3. Analysis of large-group listening tests for individual musical examples.

#	Artist/Instrument	Mean	95% Confidence Interval
1	McBroom/Vocal	0.6154	0.4627–0.7681
2	Clarinet	0.5385	0.3820–0.6949
3	KODO/Drums	0.5897	0.4354–0.7441
4	Grusin/Jazz	0.5385	0.3820–0.6949
5	Mulligan/Sax	0.5385	0.3820–0.6949
6	Class Brass	0.5128	0.3559–0.6697
7	Bolet/Piano	0.6923	0.5474–0.8372
8	Romero/Guitar	0.6667	0.5187–0.8146
9	Trombone	0.5385	0.3820–0.6949
10	Grusin/Jazz	0.5897	0.4354–0.7441

inversion more audible than it would be with a system that has low values of distortion. Such effects have been mentioned in the literature. If nonlinear distortion is a problem with a loudspeaker, it could sound very much different at higher as compared to lower sound pressure levels, depending on the polarity of the signal. If a system shows great sensitivity to polarity inversion with normal program material, there might be a problem with distortion in the system. However, even in a very low distortion system, acoustic polarity inversion is audible with relatively simple waveforms.

What reduces the ability to hear acoustic polarity inversion as the music signal becomes more complex? One factor is simply the complexity of the music itself. There is often too much going on to allow human concentration on subtle effects. Since the perception of inversion seems to manifest itself through changes in both timbre and pitch, the normal musical playing of a note, such as vibrato, tremolo, and instrumental filigree, may significantly obscure the inversion effects

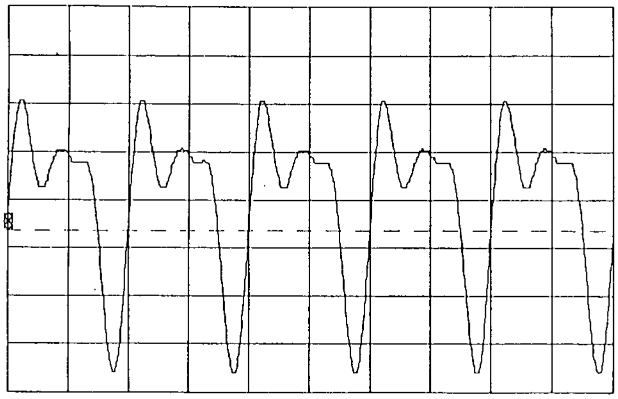

Fig. 9. Three-tone synthesized tone; trombonelike tone.

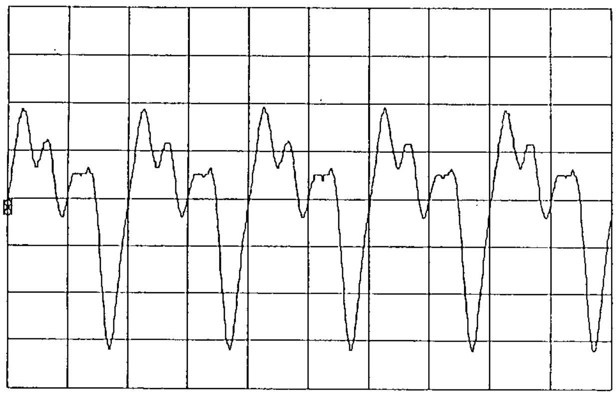

Fig. 10. Four-component synthesized tone; trombonelike tone.

Fig. 11. Acoustical trombone tone—loud but relatively symmetrical tone.

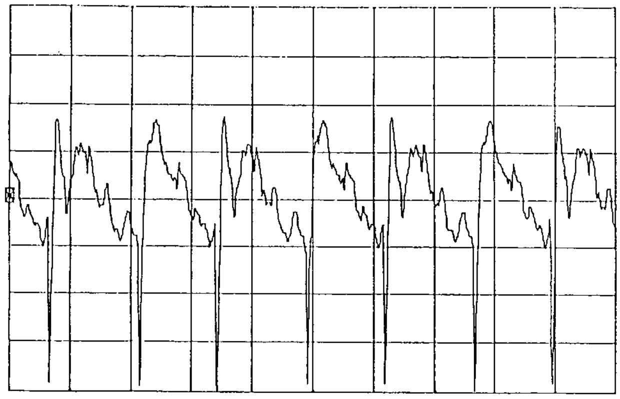

Fig. 12. Acoustical trombone tone—harsh sounding and loud trombone note, very spiked and asymmetrical.

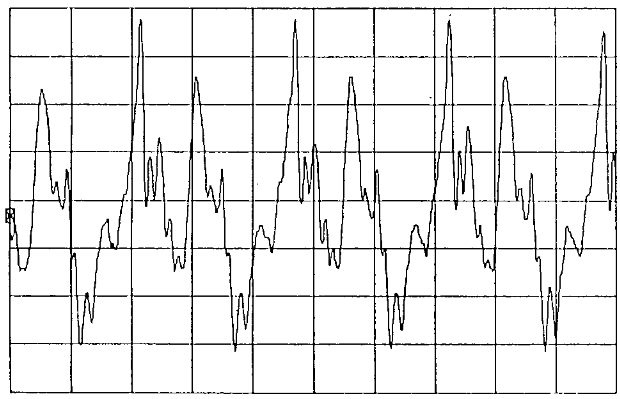

Fig. 13. Waveform for harmonica "out" note. Waveform is highly spiked and somewhat asymmetrical.

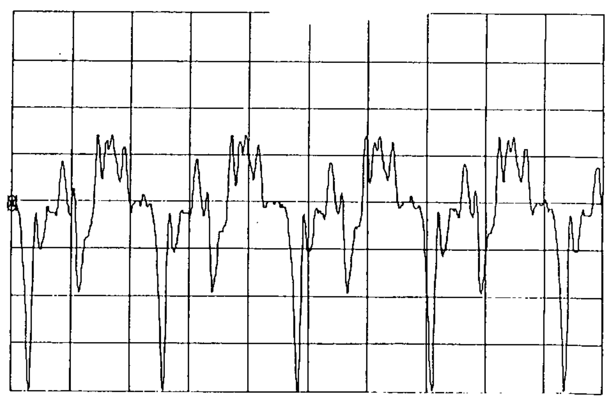

Fig. 14. Waveform for harmonica "in" note. Waveform is quite spiked and quite asymmetrical.

in most cases. It would be of great interest to have reports and analyses on other acoustical instruments played in different manners and then reproduced with and without inversion.

As some may have noted, there is a gap in understanding the listening tests described here. Few of the signals in the large-group listening tests showed audible effects with inversion, even though they were originally selected to have substantial asymmetry. However, instruments that show little asymmetry, namely, the piano and guitar (examples 7 and 8), were marginally better identified in these tests. These instruments have notably strong transient properties. This suggests that asymmetry may not be the decisive factor in generating audible inversion effects. Most likely there are still other psychoacoustic effects caused by the attack and decay properties of the signal that help the ear identify the correct acoustic polarity of the signal. More detailed experiments need to be done to ferret out these cause-and-effect relationships.

Only a tiny sampling of signals was evaluated in this work. However, it is certain from our listening tests that inversion of acoustic polarity is clearly audible for some instruments played in some styles and for some listening situations. It is not likely that the effects observed in this work were an artifact of the record–reproduce system because of the considerable care taken to maintain waveform integrity.

While polarity inversion is not easily heard with normal complex musical program material, as our large-scale listening tests showed, it is audible in many select and simplified musical settings. Thus it would seem sensible to keep track of polarity and to play the signal back with the correct polarity to ensure the most accurate reproduction of the original acoustic waveform.

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"Stereophile, Absolute Phase: Fact or Fallacy?," *Stereophile*, vol. 4, pp. 4–6 (1980 Oct.). This is an article which describes some listening tests designed to determine the audibility of polarity inversion. The article concludes that audibility of polarity inversion is largely due to loudspeaker nonlinearities. This is possible but not always a factor.

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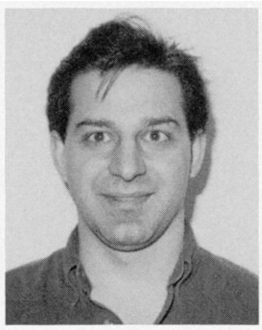

D. E. Melton

Richard A. Greiner is professor of electrical and computer engineering at the University of Wisconsin, Madison, WI. He received B.S. and M.S. degrees in physics in 1954 and 1955, respectively. His doctoral research was in the area of semiconductors and resulted in a Ph.D. degree from the University of Wisconsin

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