A Quest Audibility

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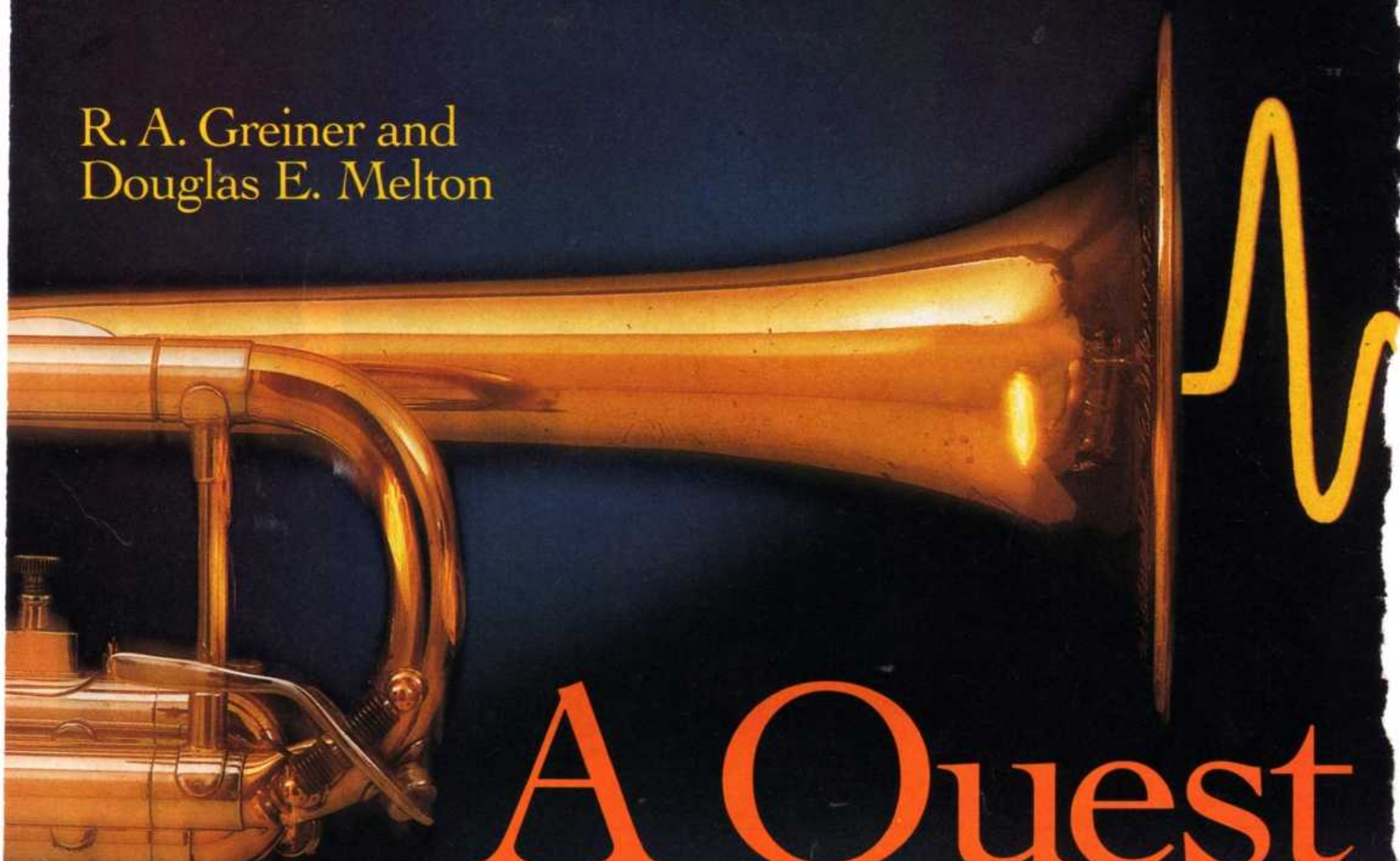
When sound is emitted by an acoustic instrument, it travels through the air in the form of compressions and rarefactions that are "picked up" by a microphone and turned into an electrical signal. The microphone may turn compressions into positive voltages and rarefactions into negative voltages (or vice versa, depending on its design). In a similar manner, when a positive voltage is applied to a loudspeaker, it may move the cone forward and cause a compression at the cone's surface. In this case a negative voltage would move the cone backward, whereupon it generates a rarefaction in the air (or vice versa, again depending on the design). It would seem reasonable that for an original acoustic wave to be "reproduced correctly," the original compressions should be reproduced as compressions and the rarefactions as rarefactions. This does not happen unless care is taken in the recording/reproduction chain to keep track of the polarity of the electrical signal at all stages. It is crucial that a compression at the microphone, which forces the diaphragm inward, result in a forward motion of the loudspeaker piston to cause a compression at the piston's surface. Figure 1 shows this concept in a simple schematic.

This article examines the audibility of changes in the acoustic polarity of musical signals. Discussions about the audibility of an inversion of the polarity of an acoustic signal, or of a change in the phase relationships of the spectral components within a signal, have been going on for about 100



years. Some interesting references from the more recent popular and professional literature are annotated at the end of this article.

Much of the discussion in the past has been about the audibility of changing phase relationships among various components in a signal presented to the ear. This article is not about the audibility of *phase* relationships within a waveform. It is about the audibility of inversion of the acoustic polarity of the signal, as reproduced by a sound system, compared to the original acoustic signal produced by the acoustic instrument. In the work described here, the shape of the waveform remained constant and unchanged; only the polarity of the signal was manipulated—i.e., it was either inverted or noninverted when played back for the listening tests. Polarity inversion is generally not identical to "phase inversion" or "180° phase shift," so terms such as phase are avoided in this discussion.

Experiments were carried out to answer the seemingly simple question: Does an acoustically generated signal sound different to the ear when it is acoustically inverted (i.e., when compressions and rarefactions in the waveform are interchanged)? While this is a "simple" enough question, the answer is actually quite hard to deter-

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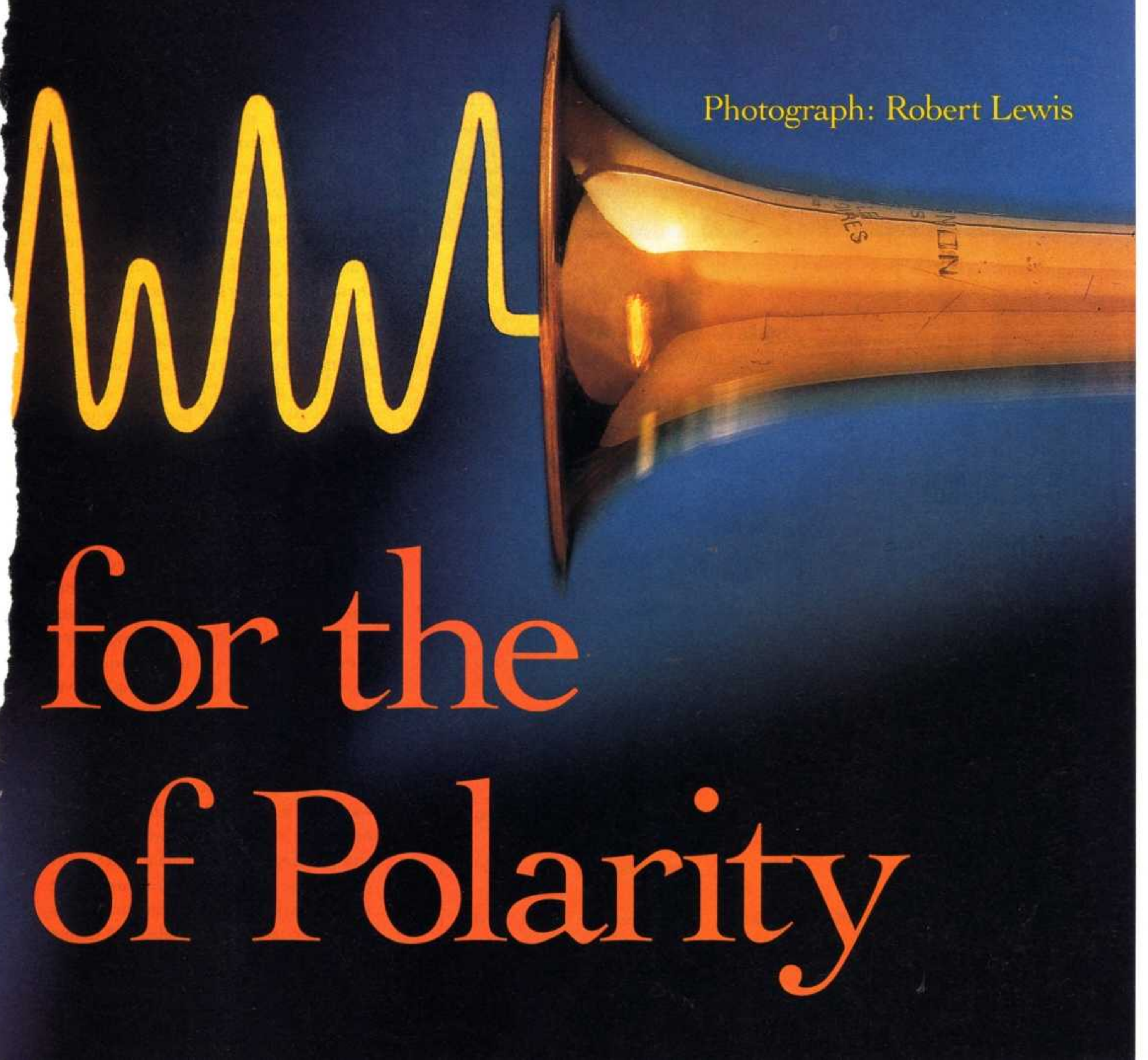

Photograph: Robert Lewis

for the

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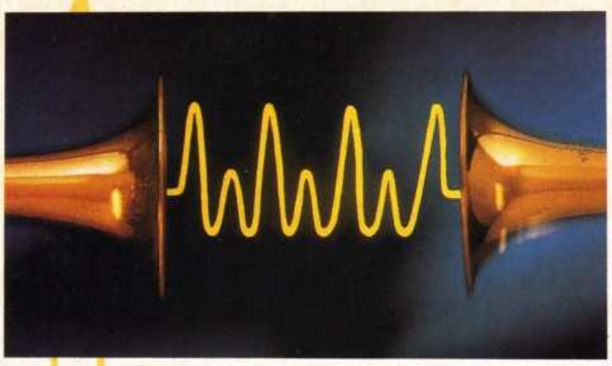


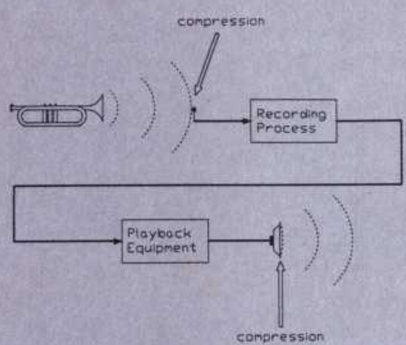


Fig. 1—Record/playback of an acoustic waveform.

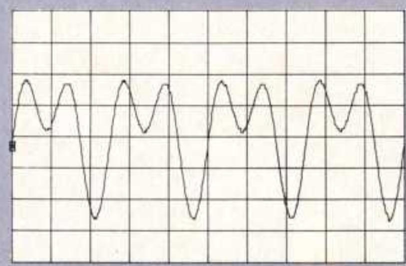


Fig. 2—Simple waveform often used in demonstrating audibility of polarity inversion.

mine. It is not possible to make an acoustic instrument perform this inversion without otherwise changing the sound in an obvious way. However, when reproducing sound with a loudspeaker, it is not only possible but usual to have an arbitrary polarity of the acoustical signal from the loudspeaker. We know that two loudspeakers, as in a stereo system, must be in correct polarity with each other for proper stereophonic sound, but this does not imply that they are in polarity agreement with the original acoustical sound wave picked up by the microphone. The speaker signals may or may not agree with the polarity of the original. Unless great care has been taken to keep track of the acoustical and electrical polarity of the signal in the reproduction chain—in the sense that an acoustical compression at the mike generates an acoustical compression at the face of the speaker—any sense of polarity is lost. While some standards exist in current practice, they are not uniformly followed.

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 can only be characterized as totally chaotic. In common practice, the polarity of the signal throughout a reproduction system is not likely to be maintained and in consumer products is often considered of little importance.

The technical literature shows that the ear can easily detect polarity changes with special signals.

It is clear from the technical literature that the ear's ability to distinguish the polarity of an acoustic signal, or at least a change in polarity, is very good under certain conditions and with specially designed waveforms. There is no longer argument about this fact. The "classic" waveform used to perform this experiment is shown in Fig. 2. It is a very simple waveform, consisting of a fundamental and second harmonic of one-half 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 under carefully controlled A/B testing procedures.

TABLE I—*Musical program examples used for the large-scale listening tests.*

NO.	DISC ID	ARTIST/ INSTRUMENT	TRACK	START TIME	END TIME
1	SHEFFIELD CD13	McBroom/Vocal	3	0:00	1:30
2	CHANDOS CHAN8549	Clarinet	9	0:00	1:30
3	SHEFFIELD CD-KODO	KODO/Drums	2	2:01	3:33
4	GRP GRP-D-9507	Grusin/Jazz	1	0:00	1:30
5	GRP GRP-D-9503	Mulligan/Sax	3	0:00	1:28
6	TELARC CD-80220	Class Brass	1	0:00	1:27
7	LONDON 417361-2	Bolet/Piano	18	0:00	1:30
8	TELARC CD-80134	Romero/Guitar	3	0:00	1:30
9	BIS BIS-CD-258	Trombone	6	0:00	1:29
10	SHEFFIELD CD5	Grusin/Jazz	2	0:00	1:40

In light of these facts, it would be easy to argue that since polarity can be heard in some cases, why not just keep track of polarity and "have done with it"? Unfortunately it is cumbersome to keep track of polarity throughout the record/playback system, given use of multimike sound pickup arrays, multitrack mixing, and the whole complex chain of electronic control. Even if this were achieved on the recording end of the system, the consumer electronics end of the playback chain would undoubtedly remain unpredictable. Concern about absolute polarity among consumers and makers of electronic equipment is evidenced by an increasing number of components that include a polarity-inversion switch. With these components, the consumer can choose for himself which polarity gives the best perceived sound, although such a switch often seems to the listener to do nothing at all to the sound. The literature is replete with opinion about the audibility of polarity inversion; most of this opinion is anecdotal or based on uncontrolled and unverifiable individual listening experiences. The experiments reported here not only show that the quest to convincingly establish that the audibility of polarity inversion is complex, but 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.

The reported results will show that polarity inversion is clearly audible in some circumstances but in many situations is not audible at all. In fact, most of the time polarity inversion is not audible. However, it is audible often enough that we suggest that the polarity of the recorded acoustical signal be traced through the entire record/reproduce chain so that the correct polarity can be reproduced at the listeners' loudspeakers. Perhaps with the advent of completely digital processing from the microphone to the listeners' loudspeakers, it will be possible to keep track of polarity easily. This has not been done with analog recording, where practice seems to be totally helter-skelter.

The Experiments

In carrying out the listening experiments, a considerable amount of time and effort went into the preparation of the listening environment and of suitable source material. This work was done between fall of 1989 and late spring of 1990. While the preparations for the tests were underway, some speculations about the anticipated results were considered and discussed at length among the researchers involved. For example, it was first thought that normal stereo listening should be used. However, in preliminary tests none of the listeners could hear the effects of polarity inversion with complex program material in normal stereo. The listening experience seemed to be far too complex to let listeners precisely and consistently identify the very subtle effects of acoustical polarity inversion.

It was clear that a simpler setup was required if polarity was to be detected consistently and reliably. With a monaural loudspeaker setup, polarity inversion became obvious when the special test signal shown in Fig. 2 was used. The clear audibility of inversion for this signal agrees with results reported in the literature. This result was obtained for headphone audition as well as for loudspeaker audition. The test signal was an asymmetrical but simple tone that is easily recognized as different when inverted, especially in an A/B testing routine. Both timbre and pitch are affected. With musical program material, preliminary tests indicated that some of the listeners could hear inversion some of the time. Both of these results were encouraging, so a monaural loudspeaker arrangement was used for the final large-group listening experiment. It was expected that a double-blind listening test would show that polarity was audible to a statistically significant extent with this experimental setup. This expectation was not fully supported, as will be described below.

Two types of listening tests were performed. The first sets of tests were performed with large groups and gave slightly positive results. The second sets of tests were done with only a few individuals, and were aimed at identifying the reasons why musical signals differ so greatly from special test tones in generating an audible difference upon inversion.

Initial listening tests were carried out using a group of about 50 students who were taking a course in audio system design at the senior university level. Enough individual tests were evaluated to assure good statistical confidence in the results. Listening tests for the large group were done double-blind.

For the large-group tests, a DAT cassette was prepared with 10 examples of music. The selections were of a great variety of music recorded from CD sources. Table I lists the program material used. The musical examples were selected because they had large asymmetries in their waveforms in the time domain, and were selected so as to highlight a particular instrument in a semi-solo passage. A preliminary, casual listening to these waveforms did not seem to show much audible effect on acoustic polarity inversion. This observation suggested that it would be difficult to obtain useful results from a time-consuming set of listening tests. A brief description of the selected musical passages follows; a selection of their waveforms is shown in Figs. 3 through 8.

Example 1, vocal. The voice waveform was highly spiked and highly asymmetrical, and showed both positive and negative spikes. The audible effects of inversion, if any, were totally obscured by musical factors of vibrato, tremolo, and intonation.

Example 2, clarinet. No examples of asymmetry were found, though the waveform was very complex.

Example 3, bass drums. These drums showed very complex transients that were highly undamped. No effects of inversion were audible.

Example 4, electric bass. These tones showed clear asymmetries in their waveforms. No changes in these musical signals could be heard upon inversion.

Example 5, saxophone. Considerable spiking and asymmetry were apparent in this saxophone tone. The musical factors, vibrato and the like, made audible detection of inversion effects impossible.

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

Example 7, piano. No examples of asymmetry were found, despite the fact that the waveform was very complex and full of transients.

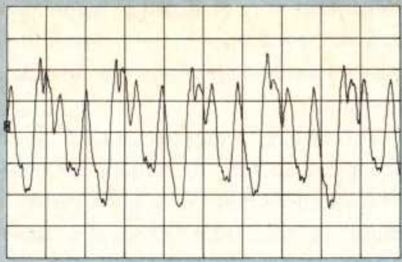


Fig. 3—Waveform from example 1, vocal.

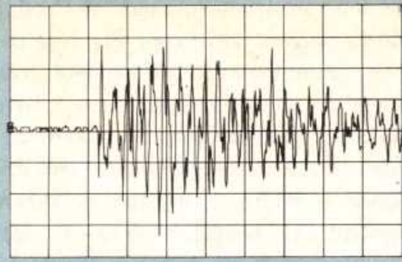


Fig. 4—Waveform from example 3, bass drum.

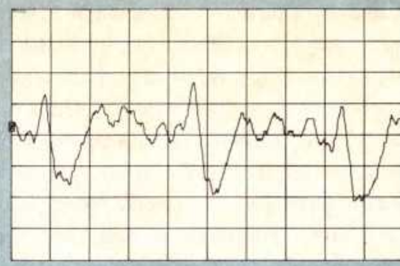


Fig. 5—Waveform from example 5, saxophone.

Example 8, classical guitar. Plucked tones, such as the guitar tone used in the experiments, neither have a very asymmetrical waveform nor show spiked compressions or rarefactions. This seems contrary to what one would expect from a highly transient tone. However, because the design of the instrument's tonal radiating surface is complex, the radiation from the plucking of a string may not predominate in the overall sound. 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. This is probably because the musicality of the played note introduces pitch and timbre changes that overwhelm those due to inversion.

Example 10, kick drum. Although the kick drum showed a very sharp transient waveform that was clearly asymmetrical, it was not possible to hear the effect of polarity inversion.

The musical passages were presented through one large multiway loudspeaker of high quality, in monaural mode. The room, about 20 × 20 feet, was very dead and, in fact, nearly anechoic above 250 Hz. The loudspeaker was quad-amplified, and levels were adjusted to make the system quite uniform in frequency response at the listening position. Because of the size of the loudspeaker system and the relatively modest loudness levels at which it was driven, very low distortion levels existed in the reproduced sound.

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

Of the 390 tests conducted, 227 of the responses were correct in identifying whether a change in polarity occurred when the control button was pressed. With the use of 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 results for the large-group listening tests are given in Table II. 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 is given in Table III. While all of the mean scores are greater than 0.5, indicating a slight ability to detect a change in polarity, the tracks of piano (example 7) and classical guitar (example 8) yielded significantly higher correct responses.

Thus, this attempt to define the audibility of acoustic polarity inversion gives a modestly positive result. However, it is also clear that polarity inversion, which seems like a drastic modification of the signal physically, does not stand out with great audibility in most cases, i.e., "like a sore thumb."

Fig. 9—Waveform of trombone-like tone synthesized from three components.

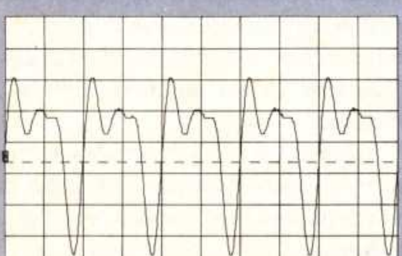


Fig. 10—Waveform of trombone-like tone synthesized from four components.

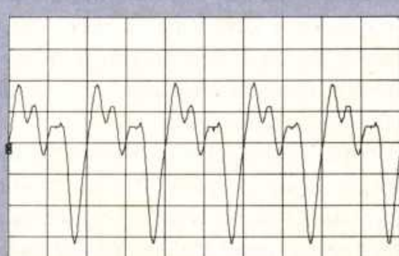
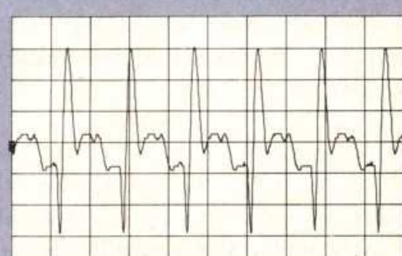


Fig. 11—Waveform of loud but relatively symmetrical tone from an acoustical trombone.



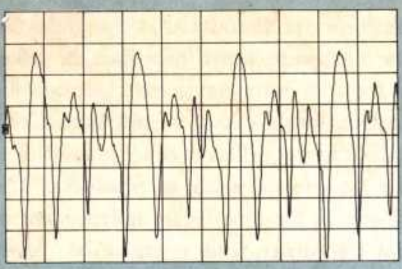


Fig. 6—Waveform from example 6, trumpet.

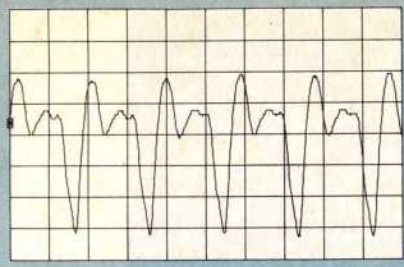


Fig. 7—Waveform from example 9, trombone.

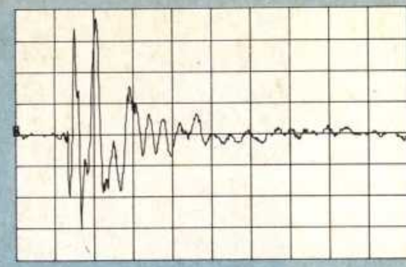


Fig. 8—Waveform from example 10, kick drum.

Since simple test waveforms demonstrated clearly audible effects when inverted while the more complex musical signals did not, several further listening tests were undertaken. The double-blind technique was not used, since in most cases polarity inversion was so obvious that there was no question it was recognized by all of the listeners. These tests were done mainly in an attempt to discover what properties of a signal make it inversion-sensitive.

It was very clear, in the listening tests, that the waveform shown in Fig. 9 was audibly altered when inverted. The timbre of the tone changes to some extent. There is also an "apparent change" in the *pitch* of the tone. The tone, inverted or not, clearly maintains the same *frequency*, since frequency is a physical phenomenon. The pitch, however, is a psychoacoustic, hearing-related phenomenon and may very well change. It is well known that pitch and timbre depend on both the intensity of the tone and its waveform. Thus, it should be no surprise that pitch and timbre are sometimes affected when a tone is inverted in polarity. In order to determine which of the waveforms were most sensitive to inversion, several waveforms were generated with a set of oscillators. Additionally, live acoustic test tones were generated, in one case with a trombone and in another with a harmonica.

Three synthesized tones were used: The "classic" tone shown in Fig. 2, a three-tone signal made to look something like an acoustical trombone (Fig. 9), and a four-tone signal made to look even more like a complex trombone tone and shown in Fig. 10. (Figures 11 and 12 show real trombone tones.) It is relatively easy to hear inversion effects in simple tones. Thus, the goal of these experiments was to create successively more complex tones with the hope of finding a point at which complexity of the tone would overcome the ability to hear inversion effects clearly. While this quest was only partially successful, it yielded some useful clues about the relationship between simple tones, more complex tones, and real musical tones and about how complexity does indeed strongly affect the audibility of polarity inversion.

With synthesized tones, such as those in Figs. 9 and 10, it was always easy to hear the effects of inverting the acoustical 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 and of constant frequency, 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 semi-anechoic room and recording it directly to a DAT machine. The tone was a sustained note played as uniformly as possible for as long as possible. (The human lungs have limitations, and trombones take a lot of air.) 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. Its harshness 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 test of polarity inversion, it clearly changes in both timbre and pitch. The character of this change depends on whether the spikes are reproduced as compressions or rarefactions. When the spikes for

Fig. 12—Waveform of loud, harsh-sounding tone from an acoustical trombone; the tone is spiked and asymmetrical.

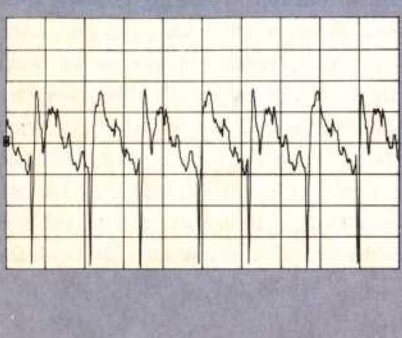


Fig. 13—Waveform of "out" harmonica note; the tone is highly spiked and somewhat asymmetrical.

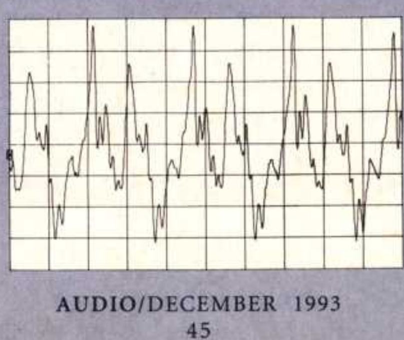
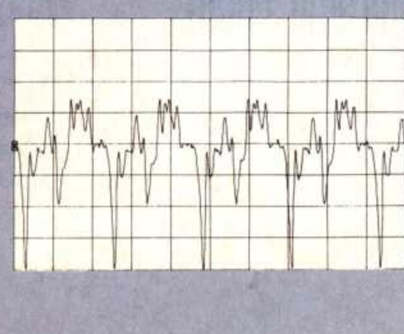


Fig. 14—Waveform of "in" harmonica note; the tone is highly spiked and quite asymmetrical.



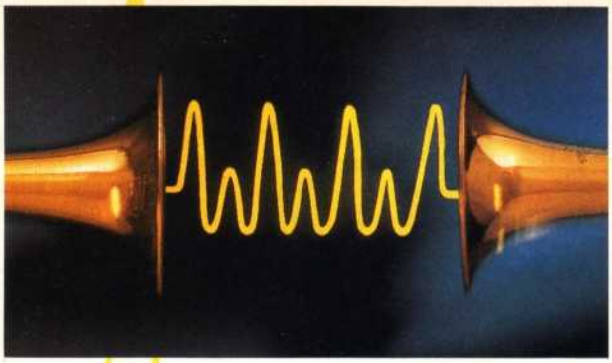


TABLE II—*Summary of statistical analysis results for the large-group listening tests.*

EXPERIMENT SET: 39 listeners, 10 individual tests per listener		
ADMINISTERED TEST: Ratio of no. of tests with polarity inversion to no. 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 the true ratio of correct to incorrect responses (given an infinite sample of experiments)	0.5410 0.6231	90% Confidence
	0.5331 0.6310	95% Confidence
	0.5177 0.6464	99% Confidence

TABLE III—*Analysis of large-group listening tests for individual musical examples.*

NO.	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

Inverted polarity is audible often enough that it should be traced through the entire recording chain.

this tone are reproduced as compressions, the pitch seems lower than when the spikes are reproduced as rarefactions (acoustically inverted for the case of the trombone). This is the case regardless of other properties of the waveform, such as loudness. The change in the tone is also independent of the transducer, and it could be clearly heard on both headphones and loudspeakers. While the effect was small, it was very clear and practically everyone could hear it. Therefore, it appears that asymmetry of the signal is one property that makes a difference in the perception of the tone when it is acoustically inverted.

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 acoustical 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 above observations. Waveforms for two harmonic notes are shown in Figs. 13 and 14. The waveform in Fig. 13 is of an "out" note, while the waveform in Fig. 14 is of an "in" note. These waveforms are strikingly complex, having 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 harmonica tones, inversion of the correct acoustic polarity seems to yield higher pitch regardless of the polarity of the spikes.

Conclusions

If asymmetry of the waveform is important in relation to hearing polarity inversion, then several precautions and warnings about speaker systems are in order. High levels of even-order distortion (second, fourth, etc.) in a sound system might make polarity inversion more audible than it would be with a system that has low levels 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 sound pressure levels than at lower SPLs, depending on the polarity of the signal. If a system shows great sensitivity to polarity inversion with normal program material, there might possibly be a problem with distortion in the system.

What reduces the ability to hear acoustic polarity inversion as the musical signal becomes more complex? One factor is, simply, the complexity of the music itself. There is often too much going on musically to allow a listener to concentrate on a very subtle effect. Since the perception of inversion seems to be detectable through both changes in timbre and pitch, the normal musical playing of a note—i.e., vibrato, tremolo, and instrumental filigree—will probably totally obscure the inversion effects in most cases. It is incredibly difficult to separate out the many variables involved with actual musical signals.

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 produced large audible effects with inversion, even though they were originally selected because of their substantial asymmetry. However, instruments that had modest asymmetry, the piano and guitar (examples 7 and 8), were somewhat better identified in these tests. This suggests that asymmetry alone may not be the decisive factor in generating audible inversion effects. Most likely there are still other psychoacoustic effects, caused by attack and decay of the signal, that help the ear identify the signal's correct (real) acoustic polarity. More detailed experiments need to be done to ferret out these cause and effect relationships.

Only a small 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 observed effects were an artifact of the record/reproduce system because of the considerable care taken to eliminate distortion and 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 insure the most accurate possible reproduction of the original acoustic waveform. A

Authors' Addendum: The work presented here was done in 1991. (It is now September 1993.) Since then, there has been some, but not much, progress made in establishing polarity standards in the recording industry. This work is continuing at the present time. There has been some discussion in hi-fi publications and much anecdotal reporting, in various publications, on the audibility of acoustical polarity inversion. There has been nothing noteworthy in the professional literature, however, that clarifies the issue or "proves" that audibility of polarity inversion is a major factor in listening enjoyment. While it is not clear why this is the case, several factors might be: The difficulty of doing the experiments in a controlled way, as evidenced by this work; the fact that the effect of polarity inversion is small in most program material, or the fact that the effect seems to be small compared to the many other variables in the recording/reproduction processes (microphone use, room acoustics, electronic processing, and the like). Nevertheless, it seems reasonable that at some point another step toward achieving greater audio fidelity will be maintaining polarity of the signals throughout the record/reproduction chain.

References

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