Detection of Phase Shifts in Harmonically Related Tones*

RICHARD C. CABOT, MICHAEL G. MINO, DOUGLAS A. DORANS, IRA S. TACKEL, AND HENRY E. BREED

Acoustics Research Laboratory, Rensselaer Polytechnic Institute, Troy, NY 12181

The results of tests on the audibility of phase shifts in two component octave complexes are described. The tests were made via headphones with fundamental and third-harmonic signals. The quantitative results were compared with those of previous researchers, and a detailed discussion of the responses of a group of listeners is presented.

INTRODUCTION: The audibility of phase shifts in harmonically related tones has been a topic of discussion for many years. Before the advent of electronic instrumentation, Helmholtz ran crude experiments to show that phase shifts were not audible. Further tests of this were made by Hansen and Madsen [1], Raiford and Schubert [2], Craig and Jeffress [3], and Mathes and Miller [4].

Mathes and Miller [4] used sinusoids of slightly different than harmonic frequency multiples. The quality or tonal character of the sound was judged to change with time as the relative phases of the sinusoidal signals changed. Craig and Jeffress [3] investigated the audibility of phase reversals of the harmonics of a test signal. Their listeners required extensive training sessions, and the resultant accuracy of detection was only slightly better than chance. Raiford and Schubert [2] used a specially designed timing circuit to control the signal presentations. Hansen and Madsen [1] used an entirely different approach to the generation of a test signal, a three-component signal, generated by gating a sine wave.

The testing methods used by previous experimenters do not appear to give the listener the most convenient method of comparison. We felt it would be more informative to allow the listener complete control over all timing of signal presentations. In our approach the listener controlled the audition intervals of both the reference and comparison signals. Careful note was taken of the length and number of audition intervals chosen by listeners, and some interesting trends were noted.

EQUIPMENT

The apparatus used in the experiment is diagrammed in Fig. 1. The Fourier synthesizer produces phase-locked signals in multiples of 400 Hz. The 400-Hz and 1200-Hz outputs are used, with their levels monitored by a Balantine model 320 linear dB-scale voltmeter. The 1200-Hz output is fed to an adjustable passive phase shifter. The phase difference between input and output of the phase shifter is monitored with a phase meter. One channel of a Crown DC-300-A amplifier is fed a mixture of the fundamental (400 Hz) and the third-harmonic (1200 Hz) signals. The other channel is fed with a mixture of the fundamental and the phase-shifted third-harmonic signals.

The outputs of the amplifier are connected via a four-position switch, the relay input selector, to a reed relay. The relay operation is controlled by the listener, allowing him to make $A-B$ comparisons. The signals which the listener received as A or B are shown in Table I for each position of the relay input selector. Fig. 2 shows the appearance of a phase-shifted and unshifted waveform and the definition of the phase shift θ. The signal from the relay input selector is fed to an oscilloscope and an rms voltmeter for monitoring the shape and amplitude of the waveform. The output then goes through the feed switch to a pair of Koss ESP-9 electrostatic headphones.

The 400-Hz fundamental level was adjusted to three times the 1200-Hz third-harmonic level. This relationship was chosen because it is the amplitude ratio of the first two Fourier components of a square wave. The sound pressure level of the signal reaching the listener's ears was 70 dB as computed from the manufacturer's sensitivity specifica-

---

* Presented October 31, 1975, at the 52nd Convention of the

Packard spectrum analyzer and was found to contain less than 0.1% intermodulation and harmonic distortion. More importantly, the distortion content was independent of the relay input selector position or the phase shift selected. The equipment was located in a room adjacent to the listener to avoid distractions.

PROCEDURE

The following procedure for gathering data was chosen for clarity and ease of duplication. The phase of the adjustable composite signal and the position of the relay input selector were set for the first test item. The signal was then applied to the headphones. The listener was allowed to compare the two signal presentations with the *A*–*B* switch until satisfied that a difference was or was not perceived between them. No limit was placed on the time available or the number of *A*–*B* comparisons for the listener to make his decision.

His response, YES or NO, was recorded by the experimenter who then disconnected the signal source from the headphones. The phase of the adjustable signal as well as the position of the relay input selector were then set for the next test item. The composite signal was again connected to the headphones. Thus no signal was present between successive trials.

This procedure was repeated thirty times per experiment for each subject. The range of the phase shift θ was limited to 0°–120° in increments of 30° in the first experiment. It was reduced to 0°–30° in increments of 7.5° in the second experiment. The order of the signal presentations was randomized to prevent biasing of the results. Total experiment time ranged from eight to twenty minutes for the subjects to complete one set of 30 signal pairs.

Prior to initiating the set of trials for each subject, a signal pair with the third harmonic shifted 0° and 120° was presented to the subject for comparison. He was simultaneously shown an oscilloscope presentation of the signal he had selected. This was intended to acquaint the subject with the subtlety of the differences to be detected. The subject was not allowed to see the oscilloscope during the remainder of the experiment. The subjects tested were college students, male and female, ranging in age from 18 to 25 years.

ANALYSIS

In order to determine the ability of the subjects to discern phase distortion and place a measure on the threshold of phase discrimination, a means of analyzing the YES and NO responses is needed. The authors chose to use a method first used by Blackwell [5].

It has been found that when subjects are asked to make a YES–NO discrimination of any test stimulus, they may respond YES in the absence of any actual difference. The subject is in effect giving a false positive response or what we shall term a false alarm. To obtain a measure of this tendency, stimulus pairs of identical composition (equal or zero phase shift in the third harmonic of both signals *A* and *B*) were included at random in the experiment. These presentations are commonly known as ''blanks'' or ''duds'' and a YES response to these is termed a false alarm.

The observed YES responses may then be due to both a perceived difference and the random error represented by the false alarm rate. Denoting the probability of a false alarm as P_{fa} and the probability of an observed YES response by P_0, we may write (see [5])

$$P_0 = P_{\text{fa}} + P\,(1 - P_{\text{fa}}) \tag{1}$$

where P is the probability of a perceived difference by a

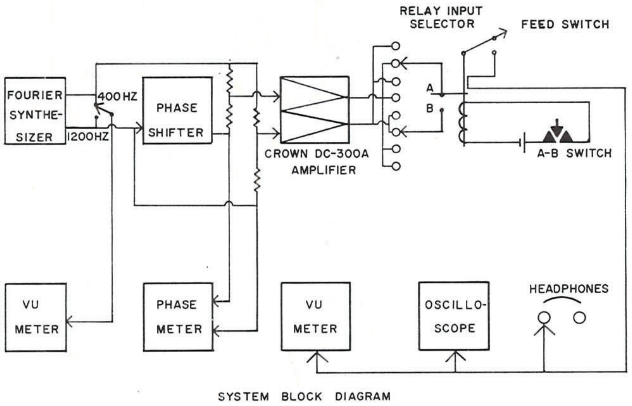

Fig. 1. Schematic block diagram.

Table I. Function of the relay input selector.

Switch Position	Composite Signal Pair	
	*A**	*B**
1	$400+1200 \angle 0^\circ$	$400+1200 \angle 0^\circ$
2	$400+1200 \angle \theta^\circ$	$400+1200 \angle 0^\circ$
3	$400+1200 \angle 0^\circ$	$400+1200 \angle \theta^\circ$
4	$400+1200 \angle \theta^\circ$	$400+1200 \angle \theta^\circ$

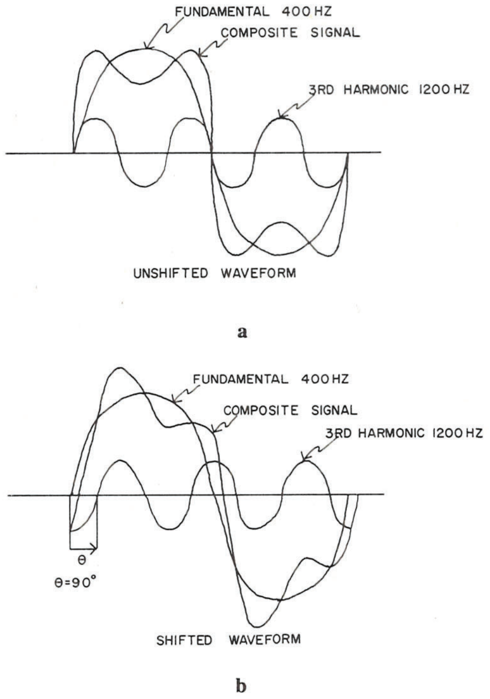

Fig. 2. Appearance of phase-shifted and unshifted waveform.

subject with zero false alarm rate. The data are grouped into classes for each particular phase shift. Values of P_0 were computed for each class by dividing the total number of YES responses for all subjects in that class by the total number of responses.

The values of P_{fa} for each phase shift were computed by dividing the number of YES responses to pairs of equal phase shift by the number of such pairs. By rearranging Eq. (1) P may be found in terms of P_0 and P_{fa}:

$$P = (P_0 - P_{fa})/(1 - P_{fa}). \qquad (2)$$

The values of P, P_0, and P_{fa} are given in Table II for each value of phase shift. The computed values of the probability of a perceived difference are graphed as a function of θ in Fig. 3. The $P(\theta)$ points for θ less than thirty degrees are circles to indicate that they were derived in a separate experiment.

OBSERVATIONS AND DISCUSSION

The described experimental results were obtained after modifications to the test procedure and equipment were made. Initially the experiment was conducted with a medium-power switching relay used after the relay input selector. The switching of the relay controlled by the subject caused an audible transient in the signal perceived and a brief interval of silence. This was found to confuse the listener and make it impossible to discriminate the intended stimulus better than predicted by the false alarm probability calculated. Whether this was due to the switching transient or the silent interval was not determined. This would seem to indicate that the listener's memory of the first presentation is either destroyed by the transient or lost during the interval of silence.

The relay was then replaced with a reed delay and the experiment was repeated. The problems described with the original relay were considerably reduced, as was the difficulty in making accurate judgments by the listener. The subjects, initially, had difficulty in determining what it was they were listening for. The first subjects refused to believe that there was a difference until they were shown traces of the signals on an oscilloscope. After this it became standard practice to present the subject with a 0°–120° phase-shifted pair at the beginning of the experiment and allow him to view the signal on the oscilloscope. The oscilloscope was not available to be viewed for the remainder of the experiment.

The listeners had complete control of the length of time each signal in the A–B pair was presented. They were told to operate the A–B switch as often and as long as they desired. A pattern seemed to develop whereby the subjects listened to the first signal of the pair for a comparatively long time, then depressed the A–B switch for a relatively short time and released it again to listen to the original. This was repeated about twice for each signal pair. This pattern correlates with some previous experiments in detecting phase shifts using similar techniques. Craig and Jeffress [3] presented their subjects with similar A and B signals for relatively long preset durations of each. They reported that their listeners were unable to detect a 180° phase shift in this same–different test arrangement. Raiford and Schubert [2] were able to obtain reliable data by using a special timing arrangement. The reference was presented for a relatively long time, followed by the second signal for a short time, and then the reference was presented again. The timing of the on–off periods was not under the listener's control, but was preset by the experimenter. Nixon, Raiford, and Schubert [6] had reported in an earlier paper their discovery of the optimum timing used in their experiment and its usefulness in allowing phase shift detection. It is interesting to note that the timing chosen by our listeners and that selected by Raiford and Schubert were very similar.

The experiment shows phase shifts of harmonic complexes to be detectable, but judging from the difficulty experienced by the subjects, the effect appear to be small. For the frequencies and level used, the ear is incapable of detecting less than about 15° of phase shift. This correlates well with the results of Hansen and Madsen for the same frequencies and level. Considering different test methods used, this fact supports the reliability of both experiments. The experiment was performed for phase-shift increments of 30°, and it was found that a 30° shift was still fairly well recognized. The experiment was then repeated with phase-shift increments of 7.5° ranging from zero to 30°. The data

Table II. Test data.

Phase Shift θ (degrees)	Dectection Rate P_0 (%)	False Alarm Rate P_{fa} (%)	Corrected Rate P (%)
Experiment 1, 15 Subjects			
0	23	23	0
30	83	33	75
60	92	27	89
90	85	23	81
120	92	27	89
Experiment 2, 5 Subjects			
0	55	55	0
7.5	53	52	2
15	80	63	46
22.5	83	58	60

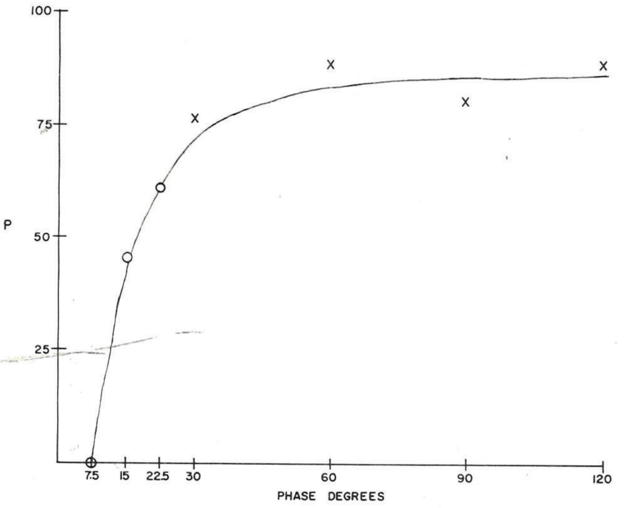

Fig. 3. Computed values of the probability of a perceived

from the two experiments were then combined to obtain the final graph. Not as many subjects were tested for the second experiment because we were already satisfied that a difference could be reliably perceived, and we did not feel it was necessary to use as large a sample. The false alarm rate for the second experiment was much higher than that of the first experiment. This may be attributed to a smaller sample and confusion of the subject in attempting to make a finer discrimination. The signal pairs presented were much more alike, and detecting a difference was more difficult. Thus the resulting confusion may have led to more guessing.

CONCLUSIONS

A measurement of the audibility of phase shifts in harmonic complexes has been presented. The results, both quantitative and qualitative, correlate well with those of previous researchers using both similar and very different experimental techniques. Although differences were detectable, they were subtle. This raises the question of its audibility compared to the more familiar forms of distortion.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Crown International Radio and Electronics for their generosity in supplying equipment used in the experiments. They wish to thank Dr. G. Kandel of the RPI Psychology Department for many helpful suggestions on analyzing the data. They would also like to thank Dr. A. Bruce Carlson and Dr. Thomas Shannon for the loan of equipment from their departments.

REFERENCES

[1] V. Hansen and E. R. Madsen, "On Aural Phase Detection: Parts 1 and 2," *J. Audio Eng. Soc.*, vol. 22, pp. 10-14 (Jan./Feb. 1974); pp. 783-788 (Dec. 1974).

[2] C. A. Raiford and E. D. Schuberts, "Recognition of Phase Changes in Octave Complexes," *J. Acous. Soc. Am.*, vol. 50, pp. 559-567, (1971).

[3] J. H. Craig and L. A. Jeffress, "Effect of Phase on the Quality of a Two Component Tone," *J. Acoust. Soc. Am.*, vol. 34, pp. 1752-1760 (1962).

[4] R. C. Mathes and R. L. Miller, "Phase Effects in Monaural Perception," *J. Acoust. Soc. Am.*, vol. 19, pp. 780-797 (1947).

[5] H. R. Blackwell, "Nerval Theories of Simple Visual Discrimination," *J. Opt. Soc. Am.*, vol. 53, pp. 129-160 (1963).

[6] J. C. Nixon, C. A. Raiford, and E. D. Schubert, "Technique for Investigating Monaural Phase Effects," *J. Acoust. Soc. Am.*, vol. 48, pp. 554-556 (1970).

[7] J. H. Craig and L. A. Jeffress, "Why Helmholtz Couldn't Hear Monaural Phase Effects," *J. Acoust. Soc. Am.*, vol. 32, pp. 884-885 (1960).

[8] R. Plomp and H. J. M. Steeneken, "Effect of Phase on the Timbre of Complex Tones," *J. Acoust. Soc. Am.*, vol. 46, pp. 409-421 (1969).

THE AUTHORS

Richard C. Cabot was born in Newark, N.J., in 1955. He received the B.S. degree (cum laude) and the M. Eng. degree in electrical engineering from Rensselaer Polytechnic Institute, Troy, N.Y., in 1975. In 1976 he received the M.S degree in mechanics also from Rensselaer Polytechnic Institute. He has completed all course requirements for a Ph.D. degree in electrical engineering and is currently engaged in thesis research for that degree.

Mr. Cabot is a student member of the Audio Engineering Society, S.B.E., I.S.A., and I.E.E.E. He is a member of Tau Beta Pi and Eta Kappa Nu and an associate member of Sigma Xi. He is currently chairman of the Rensselaer Polytechnic Institute student section of the I.E.E.E. and vice-president of the Rensselaer Polytechnic Institute chapter of Eta Kappa Nu.

•

Michael G. Mino was born in Hamburg, New York, in 1954 and received the B.S. degree (cum laude) in electrical engineering from Rensselaer Polytechnic Institute, Troy, N.Y., in 1975. He received the M. Eng. degree in electrical engineering from Rensselaer Polytechnic Institute in 1976 and is currently employed by Kodak Corporation in Rochester, N.Y.

Mr. Mino is a member of Tau Beta Pi and Eta Kappa Nu.

Douglas A. Dorans was born in Staten Island, N.Y., in 1954 and received the B.S. degree in civil engineering from Rensselaer Polytechnic Institute, Troy, N.Y., in 1976. He is pursuing an M. Eng. degree in civil engineering at Rensselaer Polytechnic Institute.

Mr. Dorans is a member of Chi Epsilon and is currently chairman of the Rensselaer Union Programming Board.

•

Ira S. Tackel was born in 1954 and received the B.S. degree in biomedical engineering from Rensselaer Polytechnic Institute, Troy, N.Y., in 1956. He is presently pursuing an M. Eng. degree in biomedical engineering at that Institute.

•

Henry E. Breed received the Ph.D. degree from Rensselaer Polytechnic Institute, Troy, N.Y., in 1955, and has since been on the staff of the Department of Physics there. His major field of activity has been physical optics, but he has been interested in acoustics. He has played cello in the Schenectady Symphony Orchestra.

Dr. Breed is a member of the Audio Engineering Society, the Optical Society of America, the American Institute of Physics, the American Association of Physics Teachers, and Sigma Xi.