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PHASE: A PRIMER

Improve almost everything you record by mastering this vital concept

Part 1: What Is Phase?

By Eric Ferguson

It all comes back to phase. Whether you are attempting to record, mix, reinforce, or simply understand sound, phase is a central and unavoidable phenomenon. Unfortunately, although its ramifications are everywhere in audio, phase is a complex and often misunderstood topic.

This is most likely because the human hearing mechanism does not directly discern phase. We can clearly note a change in loudness or frequency, but a change in phase is usually unnoticeable until multiple sources, offset in time, are mixed. Most audio engineers learn phase on an intuitive level, and collect tricks to overcome its destructive tendencies.

While there is nothing wrong with fixing phase issues with just your ears, understanding the physics can open you up to more complex solutions. Part 1 of this series will discuss the fundamentals of phase and introduce comb filtering. Later parts will look deeper into combing and discuss multiple situations in which phase affects sound quality.

Frequency, period, and wavelength

Sound is typically transmitted through the jostling of air molecules. This jostling is created when an object, such as a string, drum, or vocal cord, pushes air molecules in one direction and then immediately pulls them back in the opposite direction. When measured at one location, these movements create a cycle of rising and falling variations in air pressure.

Frequency, the rate of a sound's pressure oscillations, is measured in Hertz (Hz). 1 Hz is one full waveform cycle (pressure rises, then falls, and back) every second. The higher the frequency, the higher the perceived pitch of the sound. The range of human hearing is typically stated as 20 to 20,000 Hz. When a sound has only a single frequency, its pressure variations can be graphed as a sine wave (see Figure 1).

Looking at Figure 1's sine wave, it is easy to see that it repeats in a pattern. Imagine a flute, producing a 1,000 Hz sine wave. The pressure wave, repeating at a specific frequency, takes time to complete its full up/down cycle. The term *period* is used to define the amount of time it takes a wave to complete its over and under pressure cycle.

A 1000 Hz tone, for example, oscillates 1000 times per second, so its period is one thousandth of a second. If the flute were to play a note an octave lower, at 500 Hz, the pressure oscillations would be twice as slow, and thus the period twice as long. The period of 500 Hz is therefore two milliseconds, or two thousandths of a second. This illuminates the most crucial concept to understand about period: *as frequency rises, period gets shorter.*

We usually hear sound in air, and it takes time for sound to travel through the air from source to listener. When a flute plays a note, it moves away from the instrument and its sine wave cycle of pressure variations is stretched across physical space. The period of the note's frequency can thus be converted into distance. *Wavelength* is a term used to define the physical distance a frequency requires to complete its over and under pressure oscillation. The math is simple: *wavelength times frequency equals the speed of sound.*

Using 1129 feet per second as our speed-of-sound reference, 1000 Hz has a wavelength of 1.3 feet. Since the speed of sound is the same for all frequencies, 500 Hz, twice as long in period, requires twice the distance to complete its wave cycle. The wavelength of 500 Hz is thus 2.6 feet. The crucial concept to understand is that *as frequency rises, wavelength, like period, gets shorter.*

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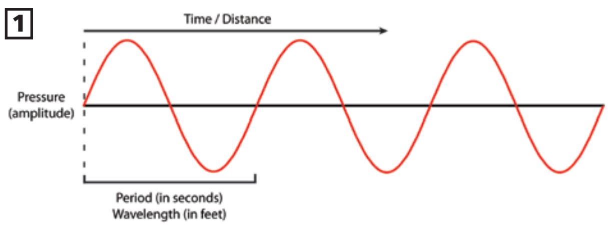

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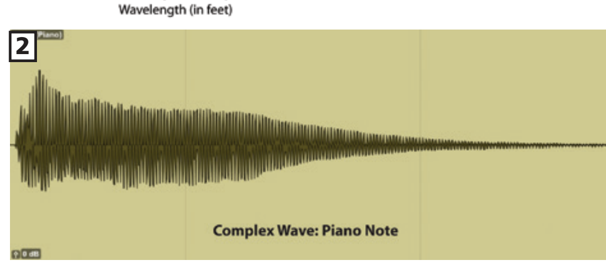

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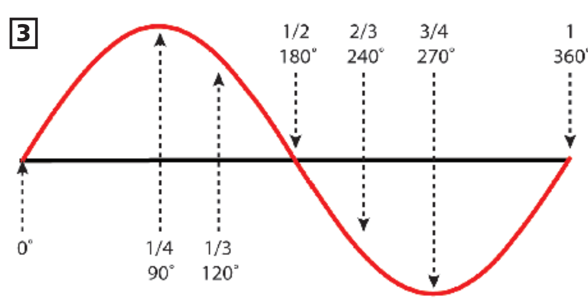

Phase is Measured in Phase Angle

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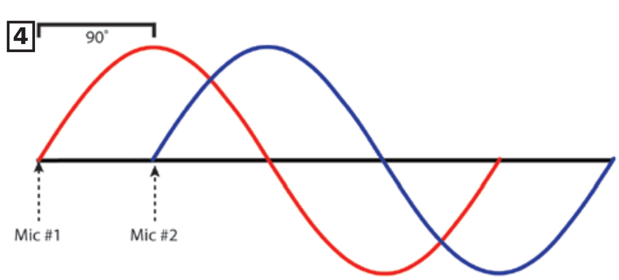

The phase difference of 281 Hz is 90˚ when two microphones are spaced one foot apart.

PHASE: A PRIMER

If you are new to the wavelength concept, it may help to visualize it for a few specific frequencies. The low frequency 100 Hz has a wavelength of 11.29 feet, which just so happens to be about the length of a Mini Cooper automobile. As stated a moment ago, the midrange frequency 1000 Hz has a wavelength of just over one foot, or as I like to imagine, a tasty foot-long Italian deli sandwich. 10000 Hz, a high frequency, has a much smaller wavelength of 1.35 inches, or about half the length of your little finger.

Beyond the sine wave—introducing phase

Up until now, we have been discussing single-frequency sine waves. Most sounds, however, produce a much more complex wave built from multiple frequencies. Look at Figure 2, a waveform of a piano note. It's hard to visualize, but the erratic wave is actually made from a combination of many sine waves, all oscillating at different frequencies. The loudest frequency in this particular wave (the *fundamental*) is at 440 Hz, but the addition of harmonics and transient artifacts make the sound complex in both waveform and timbre.

Here's the important idea: a sound may contain many frequencies, but all of them travel from the instrument to the listener at the same speed. Within this traveling sound, different frequencies each have different periods and wavelengths. This is an important concept to grasp. *All frequencies travel together across space at the same speed, but each frequency requires a different distance and time to complete each full cycle.*

With this in mind we can visualize a complex sound departing from a piano and traveling across the room toward a microphone. When the mic captures the sound, each frequency in it is at a different place in its waveform—some rising, some falling. The word for that "different place" is *phase*. Phase is a measurement of where in its cycle a specific frequency is located at a particular moment or location. Put simply, *phase is the position of a wave in its cycle.*

To our ears, these phase variations between frequencies are totally invisible and not a problem. We are not sensitive to phase in this manner, and the piano sounds normal. If we put up a second microphone, however, audible phase issues arise.

Measuring phase

To help understand the ugly side of phase, it helps to learn to measure it. As shown in Figure 3, phase is measured in *phase angle,* and a wave is quantified into 360˚ increments. This allows us to locate where in the wave we are at any distance or time from the sound source. We might be near a wave's start, or 0˚, near its middle, which is 180˚, or near its end, which is 360˚ (which is 0° for the next cycle).

As said a moment ago, it doesn't matter what the phase of each frequency is when we capture sound with a single mic. When a second mic is added at another location, problems can arise because both mics will inherently be at different distances from the piano, and both will capture each frequency in the sound at different phases. This means that every frequency will have its own unique phase angle at each microphone. Thus a per-frequency *phase difference* exists between the mics. Figure 4 demonstrates a frequency with 90˚ phase difference.

The previous paragraph is very important and worth rephrasing. When two spaced microphones capture the same sound, each individual frequency will have its own unique phase difference between the two mics. Put in common audio engineering language, when the two mics are mixed together, each frequency will be *out of phase* by a different amount. The mics themselves do not share one phase difference. Instead, when comparing the mics, each frequency has its own phase difference, because each frequency has its own period/wavelength and the distance between the mics affects each frequency differently.

Phase differences across frequencies

How out-of-phase each frequency is when compared to another is determined by relative wavelength. Since higher frequencies have shorter wavelengths, the distance difference between the two mics will have greater impact on the phase of highs than lows. To demonstrate this, let's imagine that the first microphone is one foot closer to the piano than the second. We can draw a graph charting the phase difference between the mics across frequency, based on this equation:

Phase Difference = Offset Distance x Frequency x 360 / Speed-of-Sound

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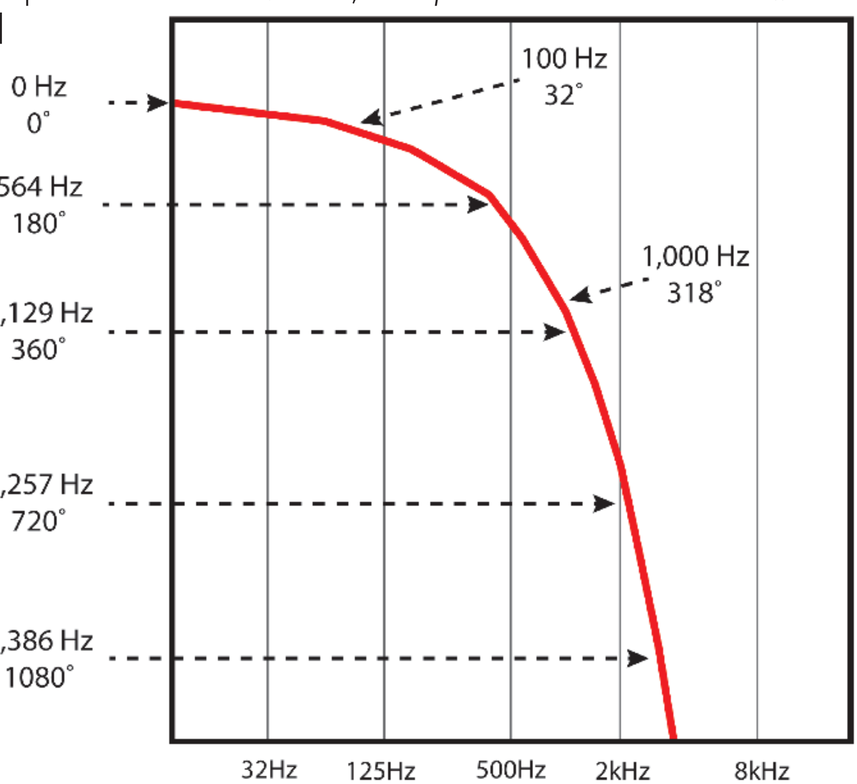

Phase Difference Across Frequency with a 1 Foot Offset

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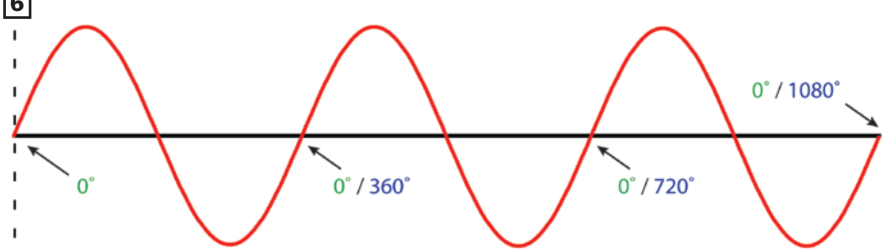

Measuring Phase: 0-360˚ Scale vs. Infinite

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Figure 5 demonstrates per-frequency phase difference between two mics spaced 1 foot (0.9 milliseconds) away from each other. As you can see, higher frequencies exhibit progressively greater phase difference. This is because the 1 foot of distance between the mics is small compared to the wavelengths of low frequencies (remember, 100 Hz is as long as a Mini Cooper).

For higher frequencies, 1 foot is a much bigger percentage of wavelength. At 1000 Hz, which is 1.3 feet long, a 1-foot offset creates 318˚ of phase shift, just shy of a complete wavelength. At 10000 Hz, a very high frequency about a half-pinkie in length, 1 foot equates to an off-the-chart 3186˚ of phase difference, or about 9 wavelengths in length. *Highs see more shift than lows for the same distance offset.*

Glancing at Figure 5, we see that 1,129 Hz is 360˚ offset in phase between the two microphones. Rising in frequency, 2,257 Hz experiences 720˚ of shift and 3,386 Hz is offset by 1080˚. These frequencies are each 360˚ apart in phase and all three mark the beginning of another wave cycle. Since sine waves are *periodic*, i.e. they repeat in shape every 360˚, we have two options when measuring phase differences greater than one wavelength. The first method is to measure infinitely upwards, as shown in Figure 5. The second approach is to mark phase differences on a 0˚ to 360˚ scale, starting over at 0° for every new cycle of a wave. When we compare relative phase between two sources (or two mics on one source), this tells us all we need and keeps the numbers manageable. A phase difference of 90° sounds the same as a phase difference of 90° + 360°, or 90° + 720°, etc. See Figure 6 for both possible numbering systems.

Phase interaction

So what happens when the two spaced piano mics are mixed together in a console? Each frequency in the sound experiences its own unique amount of *cancellation* or *summation* determined by its phase difference.

This is easiest to understand at the extremes. Two waves 180˚ out of phase to each other are exact mirror opposites, and when mixed together their contrary positive and negative pressure changes cancel each other out, rendering the frequency silent. Oppositely, two waves 360˚ offset from each other are identical in wave shape and thus sum together, doubling in amplitude, and creating a +6 dB increase in level for that frequency. Since all frequencies posses their own unique phase difference, each experiences a unique amplitude change somewhere between total cancellation and +6 dB summation. Figure 7 demonstrates several key phase differences and their associated amplitude changes.

Remember, every frequency has a unique phase difference between our two spaced mics, so each frequency will have its own level change when the mics are mixed together. From this we can make a bold summarizing statement: *When two mics at different distances from a source are mixed together, every frequency will change in level by a different amount.* This makes for a very erratic (not flat) frequency response.

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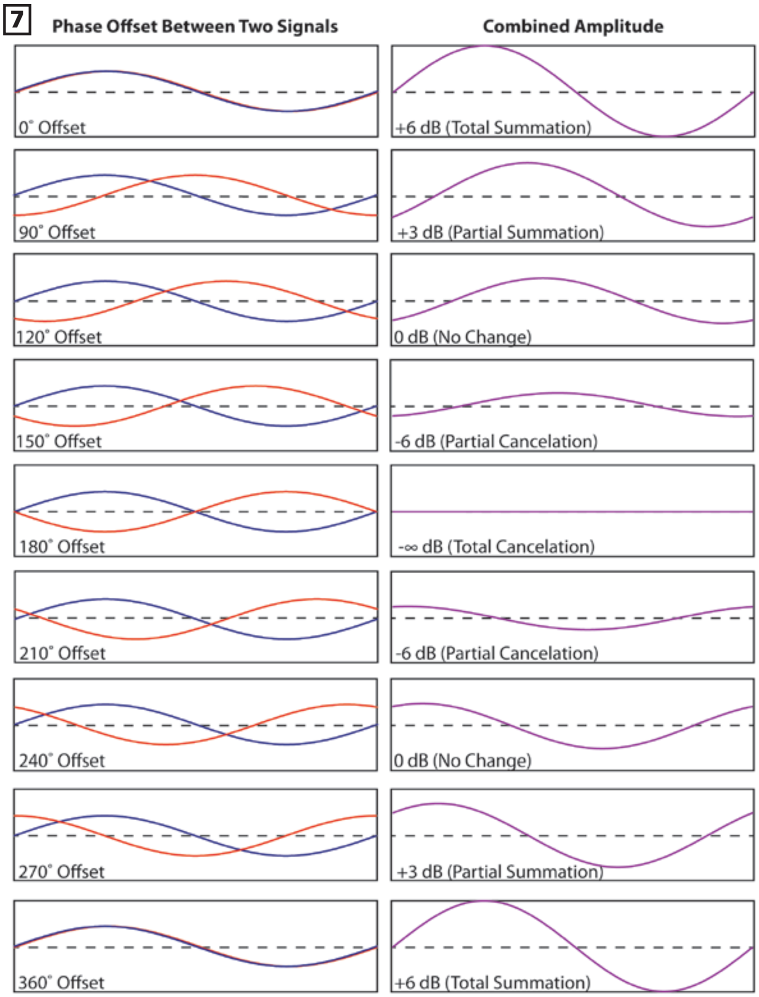

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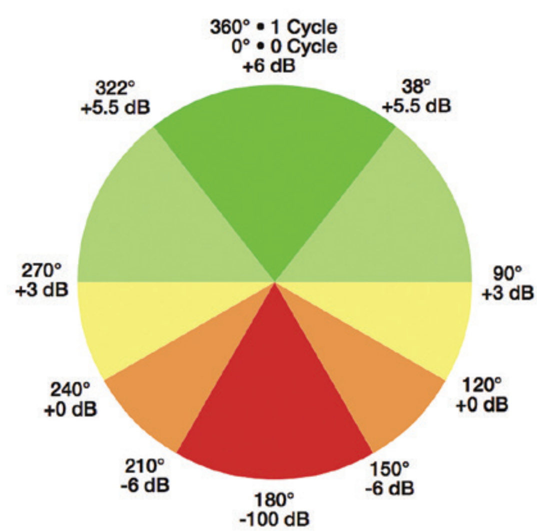

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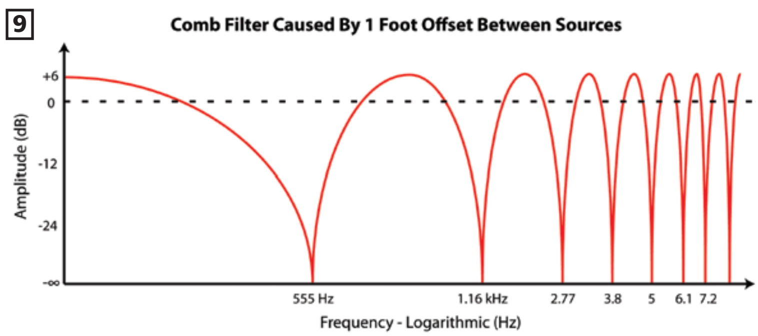

Comb filtering

Phase difference and associated level change is often pictured on a wheel. Figure 8, courtesy of Mauricio Ramírez and Meyer Sound, demonstrates the cyclical nature of phase interaction and its associated amplitude change. Using the wheel you can easily calculate the per-frequency level change when offset sources are mixed. For example, frequencies close to 90˚ offset see approximately a +3 dB level change, while frequencies shifted by about 150˚ see around a –6 dB change. Frequencies experiencing close to 180˚ of phase difference almost completely cancel, but as shift increases further, the wheel moves from cancellation back to summation. Frequencies with close to 210˚ of shift see only –6 dB of reduction, and those 270˚ off see +3 dB.

Although its ramifications are everywhere in audio, phase is a complex and often misunderstood topic.

This circle illuminates the cyclical nature of phase. In Figure 5, we saw that phase difference steadily increases as frequency rises. When converted into a 0˚ to 360˚ scale, phase difference (and associated level change when mixed) continually circles the phase wheel as frequency rises. This means that when we mix our two mics together, their combined amplitude response slides up and down across the frequency spectrum, reflecting the change from complete cancellation to perfect summation. The effect is commonly called a *comb filter*, since its amplitude response looks like the teeth of a comb when graphed linearly across frequency. Figure 9 illustrates the comb filtering present between our spaced piano mics.

Next time, we will continue this discussion of phase, focusing on comb filtering and common situations in which the effect can be sonically undesirable. See you then!

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