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Phase as the basis for wave vision

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Abstract. The work is devoted to the problem of obtaining images using radio and ultrasonic waves. These waves are not originally carriers of images, unless they carry a phase. In the simplest examples, it is theoretically and experimentally shown that waves with phase can be used to restore images of objects.

1. The method of synthetic aperture as the basis of vision systems

A person has no senses that would allow him to see the world around him in radio or acoustic radiation, and to obtain one, one has to use some technologically advanced devices, this motivates how vision systems arise, which allow using radars and sonar devices to orient in conditions of poor visibility. However, obtaining high-quality images is possible only when using the phase information contained in the radiation. Based on this so-called large aperture synthesis systems [1–10]. We explain its essence.

This can be done, for example, if the transmitter (T) and the receiver (R) are in direct contact, to obtain quadrature components of the scattered signal by the object, the direct heterodyning techniques has been used:

$$I = A \cos \varphi, \quad Q = A \sin \varphi. \quad (1)$$

Amplitude and phase carry all the information necessary for the implementation of the wave vision. It is enough to collect the signal quadrature distribution over a certain aperture (Figure 1). The resulting distribution of the complex amplitude ($E(\mathbf{r}) = I + iQ$) gives an image of the probed object by matched filtering with the hardware function of the system (HFS) $G(\mathbf{r})$, which is the response of the probing system to a single reflector. This filtering is performed by a simple calculation using fast integral convolution algorithms:

$$R(\mathbf{r}) = E(\mathbf{r}) * G^*(\mathbf{r}) \quad (2)$$



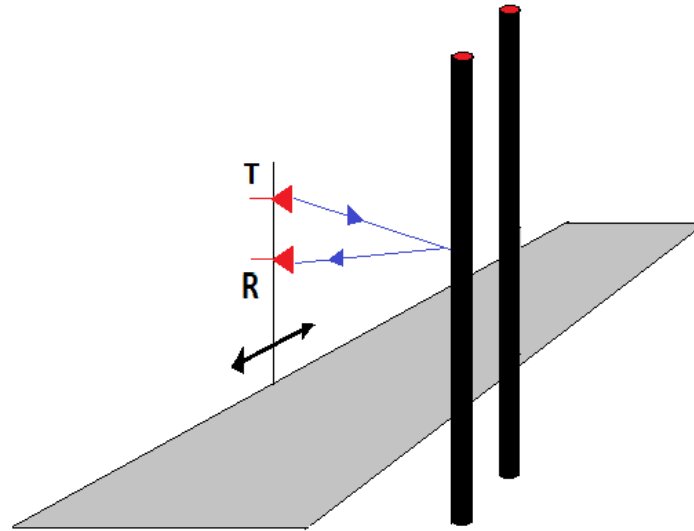


Figure 1. Typical measurement setup.

With a sufficiently large aperture of the probe system, the resulting distribution of the function is an image of the object being probed. Figure 2 shows an example of using the described procedure in the case where the reflector is a point. It is important to emphasize that at each observation point the reflected radiation is recorded taking into account the components of the total complex field, i.e. taking into account both amplitude and phase. This corresponds to coherent tomography or holography. From Figure 2 it can be seen that - the position of the reflector point is restored. Similarly, more complex images are restored.

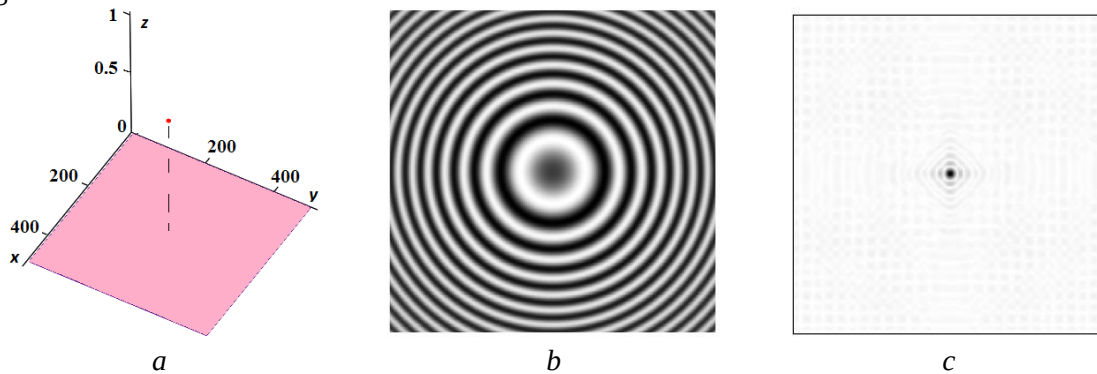


Figure 2. Position of the sensing point (a), the real part of the scattered field (b) and the reconstructed image of the point (c).

Note that to restore the image is fundamentally important to measure the phase structure of the scattered field. From a physical point of view, obtaining an image is equivalent to focusing a field when a scattered field distributed in space (Figure 2b) is assembled at a point (Figure 2c). Only in this case, the observed interference pattern is compressed in this case to a point. This happens when the field is fully coherent when the phase of the field is written through quadrature's.

2. Other methods for measuring the quadrature's of the scattered field

In some cases, to measure the quadrature, it can be used not full, but partial, with a decrease in frequency to a level where direct digitization of the signal is already possible. This happens, for example, when using ultrasonic sounding at a frequency of $f_1 = 41$ kHz. If you select a heterodyne signal equal to $f_0 = 40$ kHz, the difference frequency is equal to $\Delta f = f_1 - f_0 = 1$ kHz, which already makes it possible to

use almost any analog-to-digital converters (ADC) for digitizing signals (Figure 3). This is important when creating multi-touch measuring systems, for example, when probing pavements.

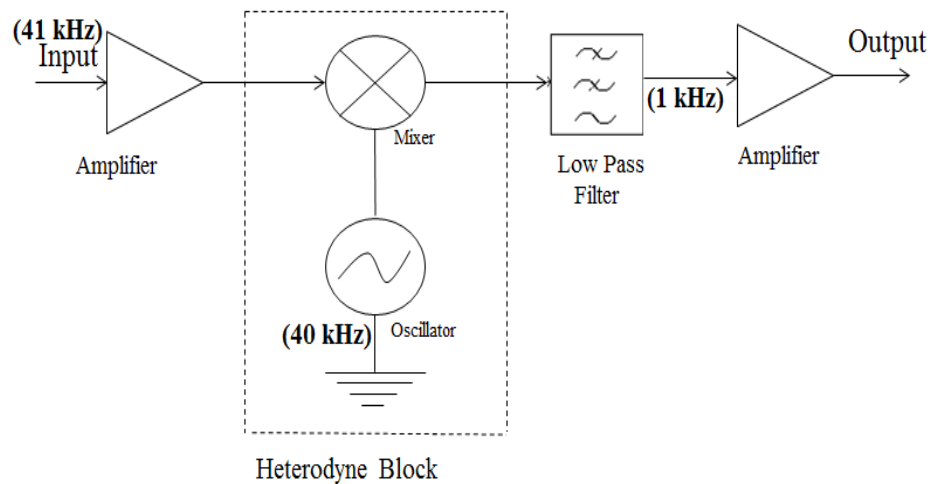


Figure 3. Receiver Schematic circuit Diagram.

After digitization, further selection of the complex amplitude or quadrature's of the signal is performed by digital heterodyning. The effectiveness of this procedure is illustrated in Figure 4, which shows the experimental result of reconstructing the image of a single pipe with a diameter of 1.5 cm. Here are the results of a 4-fold scan of the same pipe.

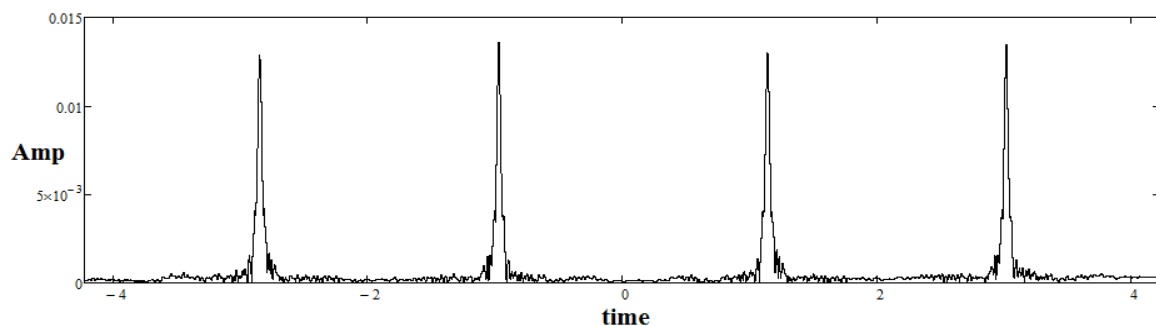


Figure 4. Image of 4 times sounding a single pipe (*time in sec*).

For comparison in Figure 5 shows a similar result of scanning two tubes located at a distance of 5.5 cm between them.

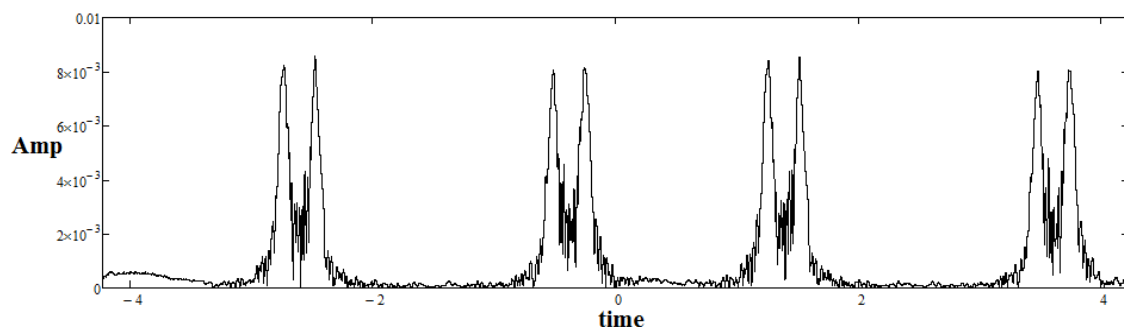


Figure 5. Image of 4 times sounding of two parallel tubes (*time in sec*).

Let us consider another variant of phase measurements, when, for one reason or another, the direct signal necessary for heterodyning at the receiving point is not available. This situation arises, for example, when using small unmanned aerial vehicles (UAVS) for sensing the earth, when placing on board a powerful coherent generator requires significant energy costs. A fairly simple solution is to use only one receiver, which registers only the amplitude of the signal reflected from the ground. At the same time, stealth and autonomy of the UAV is ensured. But what about the phase information necessary to obtain an image?

The output is when the radiation scattered by the earth is a mixture with external (reflective) coherent radiation. The intensity of the received radiation is estimated as

$$I = |E_0 + E_1|^2 = A_0^2 + A_1^2 + 2A_0A_1 \cos(\varphi_1 - \varphi_0), \quad (3)$$

Where $\varphi = \varphi_1 - \varphi_0 = 2k|\mathbf{r}_1 - \mathbf{r}_0|$ is the phase difference between the object and reference waves. It is assumed that $E_0 = A_0 \exp\{i\varphi_0\}$ - the reference wave, $E_1 = A_1 \exp\{i\varphi_1\}$ - the subject wave. We assume that the amplitudes of the waves are as $A_0 \approx A_1$. Then for a variable part of the intensity of the total field you can write

$$\Delta A^2 = I^2 - \langle I^2 \rangle = 2A_0A_1 \cos(\varphi). \quad (4)$$

It is important that this expression, up to a constant factor, coincides with one of the quadrature's scattered field, which is necessary to reconstruct the image using the technology of synthesizing a large aperture. To illustrate the applicability of the proposed approach, we consider the case of three objects whose image should be obtained (Figure 6). It is seen that the image of all objects using the described procedure is surely restored.

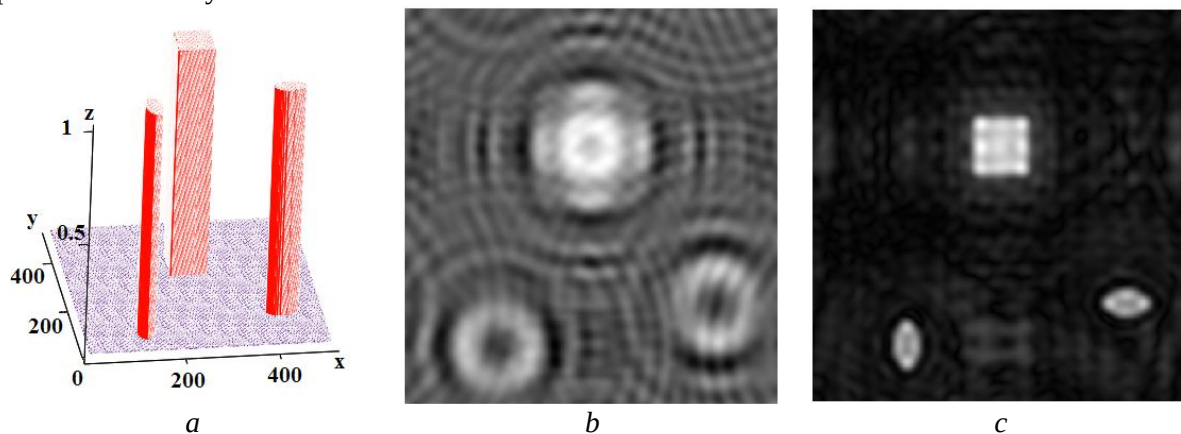


Figure 6. The position of the three objects (a), the intensity distribution of the recorded interference field (b) and the reconstructed image of the objects (c).

4. Summary

The restoration of images using wave radiation, one way or another, requires the preservation of phase information about the scattered field. Without using this information, focusing of images is impossible. Three different ways of extracting this information are considered; direct heterodyning, analog-digital heterodyning, and incoherent heterodyning mixed with a reference wave. In all cases, the images are well restored in the presence of phase information.

Acknowledgments

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