CIRCULAR PHASE MEASUREMENT OF THE DIRECTION OF INCOMING WAVE

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1. Introduction

In underwater acoustics the direction of the received wave is usually found with a narrow directive beam. This is, however, not very practical when a distant source of the wave must be found, as it is the case with transponding sonobuoys used in oceanotechnics, high-sea fisheries, etc. and also, /or especially/ when the position of a diver or a caisson fitted with transponder must be swiftly found in emergency operations.

In such cases an all-round measurement of the direction of incoming wave is definitely preferred, and it may be realized with the circular phase measurement.

2. The circular phase

This idea is based on the trigonometric relation /1/:

$$\bar{U}(\sin\vartheta\cos\omega t + \cos\vartheta\sin\omega t) = \bar{U}\sin(\omega t + \vartheta) \qquad /1/$$

where ω is the angular frequency and ϑ is the azimuth of the wave. The left hand side of the relation /1/ represents the sum of two voltages of equal maximum amplitudes $\bar{U}$ and in phase quadrature.

Their maximum amplitudes correspond to the directions of the maxima of the directivity patterns and the actual, or directive amplitudes correspond to the $\sin\vartheta$ and $\cos\vartheta$ values, respectively.

The effect of the summing-up operation is that the phase of the voltage on the right hand side of the relation /1/, relative to the reference phase φ_o is equal to the azimuth of the incoming wave ϑ, relative to the reference direction ϑ_o

$$\vartheta = \varphi \qquad /2/$$

This basic idea is somewhat similar to that used in the omnidirectional direction finder, designed by the author[1], but it can not be directly made use of with the ultrasonic waves, because there is no transducer that has a sinusoidal directivity pattern.

A sinusoidal directivity pattern may be produced with a pair of two non-directional transducers A-B /e.g.tubes/ spaced at a distance l as shown in fig 1 a.

The directivity function of such a pair is:

$$\varkappa = \cos\left(\frac{\Phi}{2} + \frac{\pi l}{\lambda}\sin\vartheta\right) \qquad /3/$$

When the antiphase /e.g. difference/ voltage is taken from the electric terminals of the transducers $\Phi = \pi$ and consequently:

$$\varkappa = \sin\left(\frac{\pi l}{\lambda}\sin\vartheta\right) \qquad /4/$$

When the spacing l is longer then the wave length λ a well known, multilobe directivity pattern is formed.
When the spacing is definitely shorter, $l/\lambda \ll 1$, it may be assumed as

$$\varkappa = \frac{\pi l}{\lambda}\sin\vartheta \qquad /5/$$

1. Jagodziński, Z. Systemy Radionawigacyjne, Warszawa 1961.

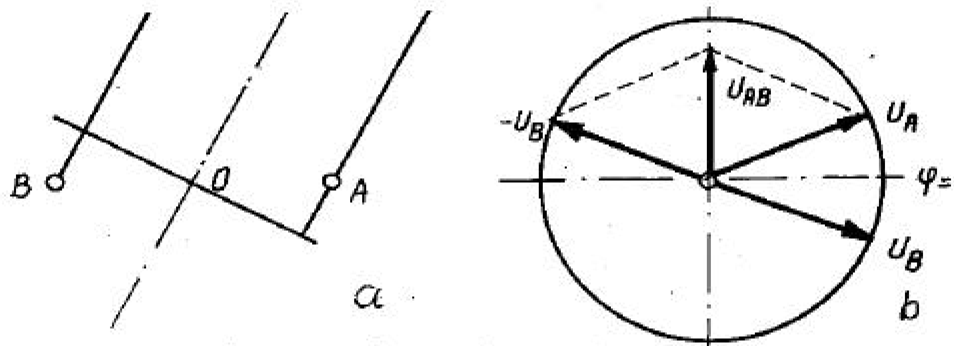

Fig 1. A pair of non-directive transducers

In this way a sinusoidal directivity pattern is formed as needed in relation /1/.

The vector diagram corresponding to the short spacing is shown in fig 2b.-

The constant factor $\frac{\pi l}{\lambda}$ has no technical consequence since the amplitude depends on amplification.

The cosinusoidal pattern that is also needed in the relation /1/ may be obtained with a second, perpendicular pair of transducers.

The approximation /5/ i.e. $\sin x \approx x$ is usually assumed when $\sin x \leq 0.1$ i.e. $x \approx 6^{\circ}$. In this case a less rigrous exigence is sufficient. A more detailed analysis shows that $l \cong 0.1\lambda$ may be accepted as the maximum admissible spacing. The difference voltage is then $0{,}314\,\bar{U}$.

As mentioned, the cosine, difference component is produced with a perpendicular, symmetrical pair of transducers.

3. Symmetric lay-out

The requirements of the relation /1/ are fulfilled with an array /or rather array of arrays/ of five transducers shown in fig 2 in which the transducers A, B, C and D form two perpendicular, symmetrical pairs, producing two difference voltages U_{AB} and U_{CD}. The transducer O, placed in the center of the array is the source of the reference phase

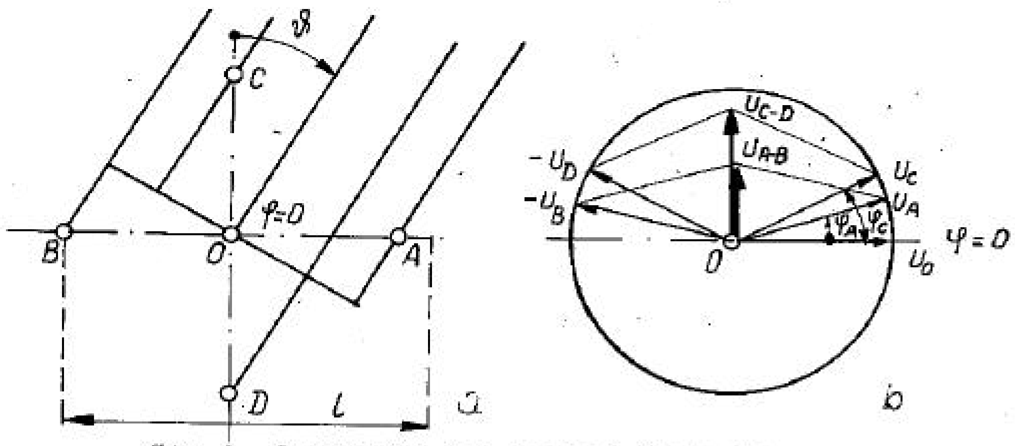

Fig 2. Symmetric lay-out of transducers.

When the wave is received from the direction ϑ, the phases of the voltages produced in each transducer are shifted, relative to the reference phase, as shown in fig 2b. The phases are shifted due to the difference of distance between the transducer and the plane wave passing through reference phase, central transducer. The vector diagram is symmetric and the difference voltages U_{A-B} and U_{C-D} are in line and perpendicular to the reference voltage U_0. When the phase of one of the difference voltages is shifted at $\frac{\pi}{2}$ in accordance with the notation $\sin\omega t$ and $\cos\omega t$ in the relation /1/, a vector diagram shown in fig 3 is produced, in which the two component vectors U_{A-B} and U_{C-D} have a $\frac{\pi}{2}$ phase difference and their sum produces a resultant vector U_ϑ that possesses the circular phase φ equal to the azimuth ϑ, as required in the relation 2.

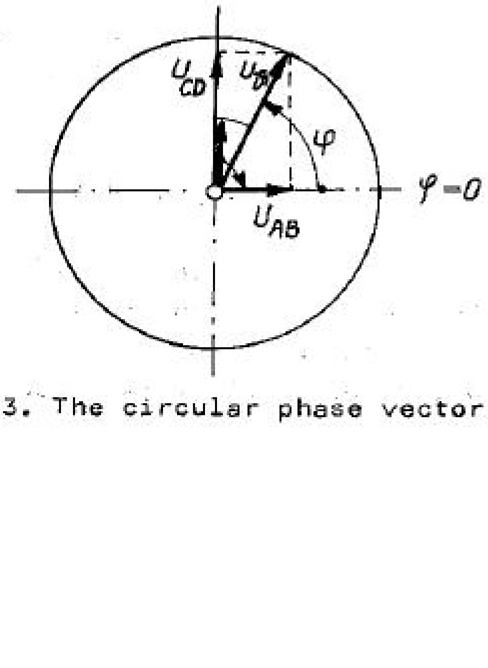

Fig 3. The circular phase vector.

4. Circular phase with ultrasonic waves

Realization of the relation /1/ in the way described here, derectly with the ultrasonic waves, as it is done with the electromagnetic waves in marine direction finders, is not possible.

In sonar and transponders where the wave lengths about 1 - 10 cm are used the spacing l should be, in accordance with /5/ no more then few milimeters and the receiving faces of the transducers no greater than about one milimeter. This does not seem reasonable and the realization of an array as in fig 2 would be extremely difficult if ever possible.

This problem may be overcome with the use of modulated waves. The kind of modulation is not essential provided it is a sinusoidal modulation.

Then, after demodulation in each receiving channel a sine wave is obtained and the time delays respective to the central transducer correspond to the phase shifts of the modulating frequency in the same way as described above, in fig 2, for a high frequency and all relations remain valid.

The spacing l is definitely longer and tube transducers may be used. The design of the equipment is more "elastic" since both the spacing and modulation frequency may be chosen according to actual needs.

To avoid transients and to average the phase fluctuations, the response pulse length of the transponder should be long enough so that it contains about 10 periods of the modulating frequency. The design of a suitable transponder is not a problem.

In this way an all-round measurement of the direction of incoming wave may be performed with an accuracy of about 1 - 3 degrees.

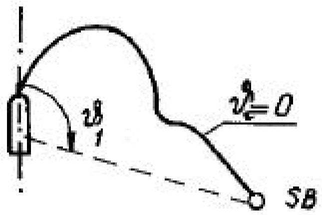

Fig 4. The homing manoeuwre.

5. Asymmetric lay-out

In practice a good, all-round accuracy of direction finding is seldom needed, for instance in underwater navigation and positioning in oceanotechnical operations. In many /if not most/ practical applications a direction finding equipment is used for "homing navigation" that is to find and approach the transmitting source of the wave - e.g. a sonobuoy or a diver in emergency.

Two manoeuvring stages are performed. First, the transponder response is used only to get a crude information about the direction of the received wave. It is enough to make a suitable circulation so that the ship's course is nearer and nearer to the reference direction ϑ_c . Then, in the second stage, accurate indication on or near the reference direction is needed to lead the ship exactly to the source of the transmitted wave.

For this purpose the full, five-channel circular phase system may be simplified to a three-channel asymmetric lay out shown in fig 5a.

The three transducers are positioned in triangle configuration, one of them /A/ being common to both pairs of the difference voltage and used as the source of the reference phase.

The vector diagram, corresponding to the asymmetric lay-out is shown in fig 5b.

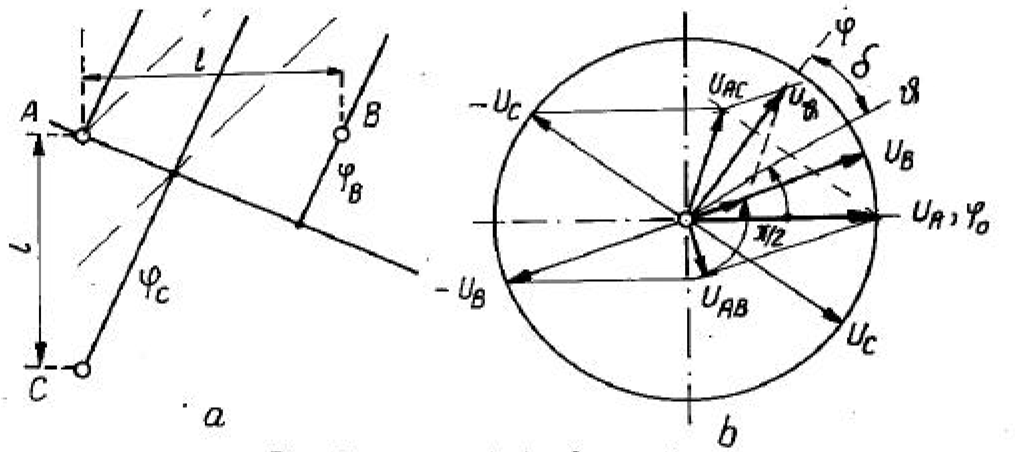

Fig 5. Asymmetric lay-out.

The two difference voltages, U_{AB} and U_{AC} are not in line, and when one of them is shifted at $\frac{\pi}{2}$ the resultant voltage U_{ϑ} has a phase that differs considerably from the correct value of $\varphi = \vartheta$. A more detailed examination of the vector diagram shows, that on some directions with $l = 0.1\lambda$ the deviation $\hat{\delta}$ exceeds 20°.

There is one direction only $\vartheta = 45^{\circ}$ /or its opposite 135°/ where there is no deviation, $\hat{\delta} = 0$. This is the case when the wave front lies on the bisecting line of the triangle BAC /fig 6/. Relative to this line, and to the corner transducer the phase shifts in the B and C transducers are numerically equal and have opposite signs. The vector diagram is symmetric and the resultant phase has the correct value . This direction should be used for homing navigation.

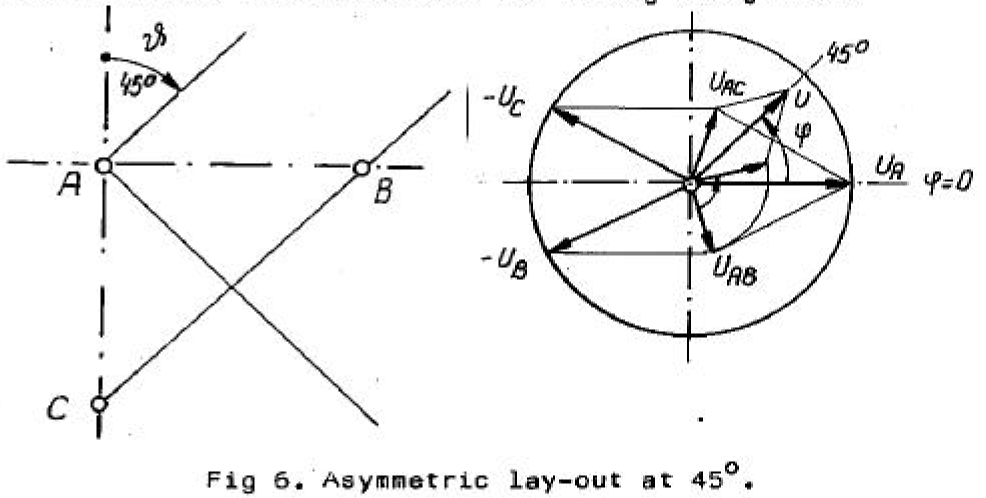

Fig 6. Asymmetric lay-out at 45°.

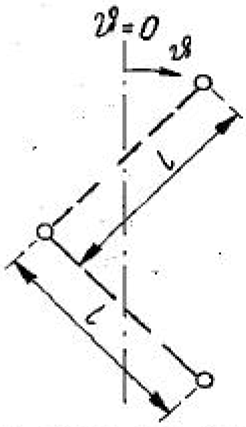

Fig 7. Transducer array for homing navigation.

Accordingly, relative to the lay-out shown in fig 6, the transducer array must be rotated at 45° as shown in fig 7, and the reference phase voltage from the corner transducer A shifted at 45° too. In this way accurate indication is obtained for homing navigation. On other directions there are deviations shown in fig 6.

Therefore one may ask why to use a circular phase system instead of a simple directive transducer. The answer is simple. To have the first stage, crude information over the circular azimuth either a rotating transducer or an array of at least four transducers and a corresponding number of response pulses are needed.

Also, a pair of transducers as used in some oceanographic short-base system gives ambiguous information. To resolve this ambiguity - right or left, and front or back a more elaborated system, containing two pairs or three transducers is needed.

If so, the circular phase concept in its asymmetric version is simpler in design and easier to operate.