GYROTROPIC MODELS OF SEDIMENTARY ROCKS:
PHYSICAL MODELLING STUDIES

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ABSTRACT


To find out the nature of gyrotropic properties of sedimentary rocks, physical modelling has been applied to test some hypotheses on possible causes for seismic gyrotropy. The objects of investigation are artificial models of sedimentary rocks, constructed on the principle of "azimuthal turn plus translation", which, from Curie's symmetry principle, creates the preconditions for elastic gyrotropy, namely such a property as the ability to rotate the polarization plane of shear waves. This ability, referred to in optics and acoustics as natural activity, its occurrence or absence, was checked. For laboratory experiments, we used piezoceramic transducers with a frequency of 100 kHz as source and two-component receivers. Polarization of shear waves propagating along a symmetry axis in the models of VTI symmetry was studied with the use of the following three models: the cement block with embedded turning sand strips, the cement block with embedded aluminum-foil turning strips, and a collection of turning fiber-glass plastic plates glued together. All three models appear to be gyrotropic. The polarization processing of the two-component records has shown a turn of polarization plane of shear waves, and the turn value, at prevailing frequencies of spectra, was proportional to the frequencies of oscillations; besides, the rotation was right-handed at right-hand turning of strips, and it was left-handed at left-hand turning. The determined quantitative characteristics of gyrotropy appeared to be in good agreement with the expected ones.

KEY WORDS: gyrotropy, shear waves, physical model, Curie's symmetry principle.

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INTRODUCTION

The present work pursues two goals. The main goal is to prove experimentally, by means of controlled laboratory experiment, that seismic gyrotropy does exist. The other goal is connected with the first one. If seismic gyrotropy may really occur, then there is a practical need to know how to recognize it in PS data which are nowadays widely acquired in surface and VSP surveys. The appearance of the second goal results from a similarity of two phenomena which take place in anisotropic media of two kinds: non-gyrotropic HTI and gyrotropic VTI.

The first phenomenon is a well-known shear-wave splitting due to anisotropy. Propagation of shear waves along a vertical path in an elastic HTI or orthorhombic medium exhibits the presence of two shear waves \( S_1, S_2 \), having different velocities and mutually orthogonal linear polarizations. At X-source (X is any arbitrary direction in a horizontal plane), one observes S-wave at two \( (x, y) \) components: at \( x \)-component, S-wave is a vector sum of displacements in the waves \( S_1 \) and \( S_2 \), one arriving faster than the other, and at \( y \)-component, S-wave is a vector difference of displacements in the waves \( S_1 \) and \( S_2 \). When the axes \( x, y \) of acquisition system coincide with the axes \( x', y' \) of natural coordinate system, one observes pure \( S_1 \), \( S_2 \)-waves at \( x' \), \( y' \)-directions. In general, the axes \( x, y \) and \( x', y' \) do not coincide, and pure \( S_1 \), \( S_2 \)-waves are obtained by means of rotation of acquisition coordinate system into the position of natural coordinate system. The procedures of rotation (the most popular of them is the Alford rotation) are of great importance for seismic exploration, because of the fact that occurrence of shear-wave splitting points to vertical fracturing of rocks while found directions of oscillations in the two shear waves indicate azimuthal orientations of vertical planes containing fractures or/and cracks which may be bearing hydrocarbons.

A phenomenon similar to the above-mentioned, at least in its external manifestation, is inherent to a gyrotropic medium with natural activity, i.e., with a so-called ability to rotate S-wave polarization plane while propagating along a symmetry axis of elastic VTI medium (or, in general, along a symmetry axis of three-fold and higher). In this case, S-wave exists as a wave with linear polarization and is seen at two \( (x, y) \) components, though it was, for example, of \( x \)-polarization before entering the gyrotropic medium. Really, the S-wave is a vector sum of two shear waves \( S_1, S_2 \), having different velocities, as in the above event with propagation in HTI medium, but circular polarizations with opposite directions of circulation. The rotation angle is proportional to gyration constant, frequency, length of the path and in inverse ratio to the squared \( V_S \)-velocity. An inverse proportionality to \( V_S \) squared motivates the gyrotropy to be inherent predominantly to the uppermost part of the subsurface. In a sense, gyrotropy and near-surface heterogeneity have much in common.
Since signatures of shear-wave propagation along a vertical path in non-gyrotropic HTI medium and in gyrotropic VTI closely resemble each other, a need arises to distinguish these two cases. This may be helpful to avoid false detection of fractured reservoirs.

The idea of seismic gyrotropy has first been suggested by Obo lentseva (1988); thereafter the concept of seismic gyrotropy has been developed in Obo lentseva (1992; 1996). Various aspects of gyrotropy are elucidated in a collection of papers (Chichinina, 1992; Obo lentseva, 1993) and other work. Of these, Obo lentseva (1993; 2003) are devoted to theoretical problems; in Obo lentseva and Grechka (1989), one chapter contains ray-method algorithms and codes for computing elastic waves in gyrotropic media; Obo lentseva et al. (2000) present acoustic log data which enable to determine gyrotropic parameters of the upper part of the subsurface at depths up to 18 m. Since real media are attenuative, data on shear-wave polarization have been interpreted with accounting for attenuation. The algorithm used is described in Chichinina and Obo lentseva (2003). Comparison between HTI anisotropy and VTI gyrotropy is given in Chichinina and Obo lentseva (1998a). Possible physical causes of gyrotropy are discussed in Obo lentseva and Chichinina (1997), Chichinina and Obo lentseva (1997; 1998b), and in Chichinina (1998; 2000).

Now we report results from the physical modelling performed for verifying our ideas on physical reasons of sedimentary rocks gyrotropy. The objects of investigations are artificial models of sedimentary rocks constructed on the principle "azimuthal turn plus translation". From Curie's symmetry principle, it creates the preconditions of gyrotropy, namely an ability to rotate the polarization plane of shear waves. Our goal is in checking this ability referred to in optics and acoustics as natural activity.

MODELS

Scheme of experiments

Several models of sedimentary rocks answering a principle "an azimuthal turn plus translation" were made. Of them, three models have appeared to be rather adequate. In two models, cement was selected as a matrix; elements responsible for gyrotropy were inclusions oriented in a special manner, i.e., according to above-mentioned principle. Sand strips were taken as inclusions in one model, and aluminum-foil strips in the other. The third model imitated a thin-layered medium with linear slip interfaces. It was collected from fiber-glass plastic plates positioned according to the same principle and glued together. In all three models, structural elements intended for creating gyrotropy are situated in xy planes and oriented at angles $\phi = 0^\circ, 10^\circ, \ldots, 90^\circ$ relative to the x-axis towards the y-axis (Fig. 1). A general view of models is shown in Fig. 2a.
Fig. 1. Structural elements of models: Model 1 (a), Model 2 (b), Model 3 (c). The elements are located in horizontal parallel planes $xy$ and oriented at angles $\varphi = 0^\circ, 10^\circ, \ldots, 90^\circ$ from the $x$-axis towards the $y$-axis: sand strips in cement (a); rows of aluminum-foil strips in cement (b); fiber glass plastic plates (c).
Models look like rectangular parallelepipeds with 100 by 100 mm xy-sections and a height of 54 mm in the first two models and 20 mm in the third. The element with \( \varphi = 0^\circ \) is in the lower part of each model, whereas the element with \( \varphi = 90^\circ \) is at the top (Fig. 2a).

The scheme of experiments is as follows. The 11 pairs source (X-force) - receiver (x,y) are positioned with a step of 5 mm on the upper and lower sides of the model along profiles passing through centres of these sides in parallel to the lower structural element \( \varphi = 0^\circ \) of the model, i.e., along the x-direction (Fig. 2b). Thus, sources are at the bottom side, and receivers at the top side of the model. Piezoceramic transducers with frequency 100 kHz were used for the source and receivers.

The S-wave generated by the X-source propagates along the symmetry-axis direction of the model which coincides with the z-direction. If the model will exhibit gyrotropy, then both x-,y-receivers will record S-wave oscillations; otherwise, the S-wave will be only at the x-receiver. Orientation of the coordinate axes is shown in Fig. 2c and should be looked at in combination with Figs. 2a, 2b.

**EXPERIMENTAL DATA**

We present the experimental data giving the two-component \((x,y)\) seismograms and amplitude spectra of \(x-,y\)-components of S-waves as first arrivals. For the three models, the seismograms and the spectra are shown in Figs. 3 - 10.
Looking at the seismograms shown in Figs. 3, 5, 7 and 9, we can see that S-waves have not only x-components, but y-components as well. The intensity of oscillations at y-components therewith is several times less than the intensity at x-components. The other characteristic feature of records at y-components which stands out is that there are higher frequency contents in y-components than in x-components. To facilitate the comparison of S-wave displacements $u_i(t), u_i(t)$, x- and y-seismograms are given not only separately, but superimposed as well.

The peculiarities of S-wave records at x-, y-components are very much more pronounced with spectra $u_i(t) \rightarrow S_i(f)$, $u_i(t) \rightarrow S_i(f)$. Amplitude spectra $|S_x|(f)$, $|S_y|(f)$ are shown in Figs. 4, 6, 8, 10. It is seen that maxima of spectra $|S_x|(f)$ and $|S_y|(f)$ do not coincide: the maxima of $|S_x|(f)$ are shifted to the higher frequencies, so that only their left slopes fall on the maxima of $|S_y|(f)$. Amplitude spectra $|S_x|(f)$, $|S_y|(f)$ for pairs source - receiver 6 (these are central pairs in the models, see Fig. 2b) are plotted separately. For all pairs, except the
left-most two and the right-most two, i.e., for pairs 3-9, the curves \(|S_x(f)|\) are given all together, and so are the curves \(|S_y(f)|\). Such positioning of graphics clearly shows that the polarizations of S-wave are different for different parts of the models. It is quite explicable if we look once again at the structure of the models (Figs. 1, 2a). The models are nonuniform in their different parts. The uniformity which we are interested in refers to identical symmetry properties at all points (or parts) of the models. Symmetry properties are the main properties which determine the phenomenon under investigation (natural activity). Only for the central parts of the models all structural elements are arranged in such a manner that the model may be called "right" or "left".

Phase spectra \(\text{arg} S_x(f)\) and \(\text{arg} S_y(f)\) which are not shown here, differ from each other for the most part by \(\pi\). A behaviour of functions \(\text{arg} S_x(f)\) is substantially different for different points of the models.

Fig. 4. Amplitude spectra for Model 1. Plotted are \(|S_x(f)|\), \(|S_y(f)|\) of the S-wave in first arrivals at x-, y-seismograms. The upper plot is for x-, y-components at traces 6; the middle plot is for x-components at traces 3-9, the lower plot is for y-components at traces 3-9. The spectra \(|S_x(f)|\) are marked by circles, the spectra \(|S_y(f)|\) by squares.
Fig. 5. Seismograms (x, y) for Model 2, "right". The arrangement of components is as in Fig. 3.

Let us now compare the seismograms and amplitude spectra for models 1-3 given in: Figs. 3, 4 - for model 1 (turning sand strips embedded into the cement block); Figs. 5-8 - for model 2 (turning aluminum-foil rows embedded into the cement block), of them Figs. 5, 6 for "right" modification of the model and Figs. 7, 8 for its "left" modification; Figs. 9, 10 - for model 3 (turning fiber-glass plastic plates glued together).

Models 1 and 2 are made of the same material, cement, and cement blocks are identical in size, but differ by inclusions, and this distinguishing feature determines distinctions between experimental data for these two models. In the case of model 1, the seismograms and amplitude spectra of x-, y-components of S-waves look more uniformly for different points (3 - 9) than in the case of model 2. It is clearly seen that a scatter in amplitude values for both spectra, $|S_x|(t)$ and $|S_y|(t)$, is well below in the case of model 1 than in the case of model 2. These distinctions are apparently due to much more compact arrangement of inclusions in model 1 than in model 2 (see Fig. 1). There is only one strip of sand in each layer in model 1, whereas each layer in
model 2 contains ten aluminum-foil strips which spread all over the area of a given structural element.

It is interesting to compare the seismograms and amplitude spectra for the "right" and "left" modifications of model 2, i.e., Fig. 5 with Fig. 7, and Fig. 6 with Fig. 8. Here it should be defined what models we name "right" and "left". We name a model "right", if its structural elements deviate from positive direction of x-axis to positive direction of y-axis, we name a model "left", if deviations of structural elements are going from the positive direction of the x-axis to the negative direction of the y-axis (see Figs. 1, 2). It is meant that one looks from the tip of the positive direction of the z-axis and the coordinate system is right-handed. Then in "right" models turn angles $\varphi$ can be considered as positive and as negative in "left" models.

![Graph](image)

Fig. 6. Amplitude spectra for Model 2, "right". The arrangement of plots and notations are as in Fig. 4.
The models 1 and 3 are "right". Looking at the obtained x-, y-seismograms for the "right" model 2 (Fig. 5), we see that they are akin to x-, y-seismograms for models 1, 3 (Figs. 3, 9). However, when we look at the x-, y-seismograms for the "left" model 2 (Fig. 7), we encounter something confusing. At first glance, it would be reasonably to expect that x-seismograms will be practically the same for the "right" and "left" models, while y-seismograms will differ by polarity of events. What actually happens is that the sign of events changes at x-components and remains the same at y-components.

After attentive consideration of the situation with the observed polarities of events at x- and y-seismograms, we have understood that it arises because the aluminum-foil strips in themselves are not "right" or "left". (They would be "right" and "left", if they were marked, for example, their width was growing from one end of the strip to the other, so we could differentiate these ends). Therefore, the arrangement of strips in the "right" and "left" models looks identically in the sense that they are turned for both types of models quite

![Fig. 7. Seismograms (x, y) for Model 2, "left". The arrangement of components is as in Fig. 3.](image-url)
identically: from "+x" to "+y" by angles $\varphi + \pi$, where $\varphi > 0$, if the model is "right", and $\varphi < 0$, if the model is "left". For more clarity, we illustrate this geometry in Fig. 11. The ends of strips are marked by letters A an B. If we remove these marks, the cases with turns by angles $\varphi$ and $\varphi + \pi$ ($\varphi > 0$, $\varphi + \pi > 0$ or $\varphi < 0$, $\varphi + \pi < 0$) will not be recognizable. From Fig. 11, it also follows that visible angles between strips and x-axis are positive, by definition, for "right" models and are negative for "left" models. Hence, in "right" models the strips have positive projections on x- and y-axes, whereas in "left" models, projections on x-axis are negative, and projections on y-axis are positive (we assume that the strips are directed from end A to end B). In real seismograms, corrections should be made, if necessary, for polarity of recording at x- and y-channels, if they differ from those which are meant in the plots of Fig. 11. This is our case, as it is seen from seismograms presented in Figs. 3, 5, 7, 9.

![|S|](image.png)

Fig. 8. Amplitude spectra for Model 2, "left". The arrangement of plots and notations are as in Fig. 4.
We considered the right- or left-handedness of models and silently spread it to events on x-, y-seismograms. It should be noted that in doing so we implicitly used the Curie’s symmetry principle according to which the symmetry elements of causes (i.e., of models) must be contained in the generated effects (i.e., in polarization of shear waves).

Model 3 is substantially different in its material and construction from models 1, 2. It is made from glued together identical thin fiber-glass plastic plates, and it would be transversely isotropic (VTI) due to linear slip at contacts between plates, if the material of plates was isotropic. However, it is finely fibred, and therefore the arrangement of plates in such a manner as it is shown in Fig. 1 must lead to gyrotropy. The x-, y-seismograms and amplitude spectra confirm that such is the case. A general picture for model 3 is very much similar to those of models 1, 2. Perhaps that the data in the case of model 3 are noisier than for models 1 and 2. It seems likely that a minor deterioration is due to the presence of glued surfaces which are not smooth enough.

Fig. 9. Seismograms (x, y) for Model 3. The arrangement of components is as in Fig. 3.
Fig. 10. Amplitude spectra for Model 3. The arrangement of plots and notations are as in Fig. 4.

Fig. 11. Illustration to a structural element positioning in "right" (A) and "left" (B) modifications of Model 2. The structural elements are aluminum-foil strips turned by angles $\varphi, \varphi + \pi$ in Model 2, "right" (the first column) and by angles $-\varphi, -(\varphi + \pi)$ in Model 2, "left" (the second column).
Polarization Analysis

Records \( u_x(t), u_y(t), i = 1, \ldots, 11 \), i.e., for eleven observations for each model, were processed in a spectral area for comparison with theoretical notions for harmonic oscillations. Spectra \( S_{x_i}(f), S_{y_i}(f), i = 1, \ldots, 11 \), were found for one period of S-wave first arrivals. Then ratios of amplitudes \( r(f) \) and phase differences \( \delta(f) \),

\[
r(f) = \frac{|S_{y_i}(f)|}{|S_{x_i}(f)|}, \quad \delta(f) = \arg S_{y_i}(f) - \arg S_{x_i}(f),
\]

were calculated and then recalculated into ellipse parameters, since a harmonic oscillation \( r(f)\exp[i\delta(f)] \) represents an ellipse. Ellipse parameters \( E(f), \alpha(f) \), where \( E(f) \) is the ratio of the semi-axes, and \( \alpha(f) \) is the angle between the major axis of the ellipse and the x-axis, are related to parameters \( r(f), \delta(f) \):

\[
E(f) = \frac{1 + r^2(f) - \sqrt{(1 + r^2(f))^2 - 4r^2(f)\sin^2\delta(f)}}{1 + r^2(f) + \sqrt{(1 + r^2(f))^2 - 4r^2(f)\sin^2\delta(f)}}^\frac{1}{2},
\]

\[
\sin\alpha(f) = 2rcos\delta(f)\sqrt{(1 - r^2(f))^2 + 4r^2(f)\cos^2\delta(f)} ,
\]

\[
\cos\alpha(f) = \frac{(1 - r^2(f))\sqrt{(1 - r^2(f))^2 + 4r^2(f)\cos^2\delta(f)}}{\sqrt{(1 + r^2(f))^2 - 4r^2(f)\sin^2\delta(f)}}.
\]

Consider two special cases: absence of ellipticity and absence of rotation. In the first special case, \( \delta(f) = \pi I, I = 0,1,2, \ldots \), then \( E(f) = 0 \), i.e., polarization is linear. Such polarization would be observed in a non-attenuative medium, when the displacement vector did not turn by an angle \( \alpha \), for which \( \sin\alpha = 2r/(1 + r^2), \cos\alpha = (1 - r^2)/(1 + r^2) \). In the second special case, \( \delta(f) = \pi/2 + \pi I, I = 0,1,2, \ldots \), then \( E(f) = r(f), \alpha(f) = 0 \), i.e., at a frequency \( f \), the ratio of semi-axes of ellipse is equal to the ratio of amplitudes at \( x, y \)-components: \( E = |S_y|/|S_x| \), and the major axis of the ellipse is directed along the x-axis.

Knowing of ellipse parameters \( E(f), \alpha(f) \) enables us to determine the parameters for a gyrotropic medium. In such a medium, the velocities of the two shear waves \( S_x \) and \( S_y \), having circular polarizations with opposite directions of circulation and forming a compound S-wave, are

\[
V_{1,2}(f) = V_g \pm a(f),
\]

where \( V_g \) is the velocity \( V_g \) in the medium without gyrotropy and \( a(f) \) is a gyrotropic addition to \( V_g \), which is an arithmetic average of additions \( a_1(f), a_2(f) \) to \( V_1, V_2 \), correspondingly.
In attenuative media, i.e., in those which exist in reality,

\[ V_{1,2}(f) = V_0 \pm a(f) - ib(f) , \]

where \( b(f) \) is attenuation constant. For such media, we determine gyration constant \( a(f) \) and attenuation constant \( b(f) \) at given ellipse parameters \( E(f), \alpha(f) \).

To do this, the following system of equations should be solved:

\[
\omega h b \left[ \frac{1}{(V_0 - a)^2 + b^2} - \frac{1}{(V_0 + a)^2 + b^2} \right] = \ln \left[ \frac{1+E}{1-E} \right],
\]

\[
\omega h \left[ \frac{(V_0 - a)^2}{(V_0 - a)^2 + b^2} - \frac{(V_0 + a)^2}{(V_0 + a)^2 + b^2} \right] = 2\alpha,
\]

where \( \omega = 2\pi f \), \( h \) is the distance, \( E = E(f) \), \( \alpha = \alpha(f) \), \( a = a(f) \), \( b = b(f) \). The solution is

\[
b = \frac{[(M^2 + 4V_0^2)P - M]/(2P) }{},
\]

\[
a = \frac{(V_0^2 - b^2 - Mb)^{1/2} }{},
\]

where

\[
M = (4|\alpha|V_0)/L ,
\]

\[
L = \ln \left[ \frac{1+E}{1-E} \right] ,
\]

\[
P = 1 + [(M^2 + 4V_0^2)L/(4\omega h V_0)]^2 .
\]

A derivation of above formulae for determining \( E(f), \alpha(f) \) from \( r(f), \delta(f) \) and then the gyration constant \( a(f) \) and attenuation constant \( b(f) \), at given \( E(f), \alpha(f) \) parameters, is given in Obolentseva (1992; 1996), see also Chichinina and Obolentseva (2003).

RESULTS OF POLARIZATION ANALYSIS

Amplitude and phase spectra for the three models were processed by means of the formulae presented in the previous section. Results of the polarization analysis are given in Table 1. Here are listed ellipticity \( E \), turn angle \( \alpha \) (the main characteristic of gyrotropy), gyrotropy constant \( a \) and attenuation constant \( b \), the last two are presented in the form of their ratios to velocity \( V_0 \) in the material without gyration. All data refer to the observational point 6 in each model, since only for central points of the models and the nearest to them, these models can be considered as effective models which present a homogeneous gyrotropic medium.
Table 1. Results of the polarizational analysis for the three models: the values of ellipticity $E$, turn angle $\alpha$, ratios $a/V_0$, $b/V_0$ of gyration and attenuation constants to the velocity $V_0$ for central parts of the models.

<table>
<thead>
<tr>
<th>Model 1</th>
<th>Model 2, &quot;right&quot;</th>
<th>Model 2, &quot;left&quot;</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(sand strips in cement block)</td>
<td>(rows of aluminum-foil strips in cement block)</td>
<td>(rows of aluminum-foil strips in cement block)</td>
<td>(fiber-glass plastic plates glued together)</td>
</tr>
<tr>
<td>$E$</td>
<td>$a/V_0$</td>
<td>$b/V_0$</td>
<td>$E$</td>
</tr>
<tr>
<td>0.002</td>
<td>0.003</td>
<td>0.02</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The values of all parameters presented in Table 1 are given for the frequencies of $\max |S_1(f)|$, which differ slightly from each other for different observational points and which differ somewhat more for models 1 - 3.

Comparison of data in Table 1 for models 1 - 3 shows the following. The parameter $E$, the ratio of ellipse semi-axes, is negligibly small, i.e., polarization is nearly linear. The turn angle $\alpha$ is negative for all "right" models and is equal to $-5^\circ$ in Model 1 and Model 3, and $-17^\circ$ in Model 2, "right". In Model 2, "left", the angle $\alpha$ is positive and is equal to $5^\circ$. The gyration constant $a$ makes up about 1% of the velocity $V_0$ for all models. The attenuation constant $b$ is small for Model 1 (2% of the velocity $V_0$), intermediate for Model 2 (5-10% of the velocity $V_0$), and rather high for Model 3 (17% of the velocity $V_0$). The increase in attenuation for Model 3 is evidently caused by being collected (glued) from individual plates, whereas the other two models were solids with inclusions.

Model 2 was made in two variants: "right" and "left". The experiments disclosed this fact and demonstrated opposite signs of the turn angle $\alpha$ for these models, with "-" sign for Model 2, "right", and with "+" sign for Model 2, "left". This fact is worth noticing.

Thus, the data presented in Table 1 testify that the principle "an azimuthal turn plus translation", which was put into the basis for construction gyrotrropic models, appears to be correct. Hence, our previous speculative constructions (Obozentseva and Chichinina, 1997; Chichinina and Obozentseva, 1997, 1998b; Chichinina, 1998, 2000) are valid and can be applied to real geological media. It also follows, from Curie’s principle, that the S-wave may be rotating the shear-wave polarization plane, when it propagates along the symmetry axis of sedimentary rocks possessing the symmetry of a transversely isotropic medium.
Evidence of presence gyrotropic properties in experimental data is as follows: the theory of gyrotropy holds (Obolentseva, 1992, 1996) that a dependence of turn angle $\alpha$ on the parameters is of the form

$$\alpha = \omega h / V_0 \beta ,$$

where $h$ is equal to the height of a model, see Fig. 2b.

Direct proportionality of the turn angle $\alpha$ to frequency $f$, $f = \omega / (2\pi)$, is easily checked. In our experiments, it looks like it is illustrated by an example for Model 1, see Fig. 12. Here the dependencies of parameters $r$, $\delta$, $E$ and $\alpha$ on frequency $f$ are given for the observational point 6. These functions are drawn for frequency interval from the maximum of $|S_1|$($f$) to the maximum of $|S_2|$($f$), with a slight shift of the interval to frequencies less than the frequency of max $|S_1|$($f$) (see spectra $|S_1|$($f$), $|S_2|$($f$) in Fig. 4). Since the most valuable data are at the frequency of max $|S_1|$($f$), the main attention in Fig. 12 should be focused at the first points of curves. All plots show that the increase in frequency leads to the increase in all parameters characterizing gyrotropy. The turn angle $\alpha$, equal in modulus to 5 degrees at the frequency of max $|S_1|$($f$), increases linearly in the neighbourhood of this frequency, then the increase becomes more rapid, and we see that $|\alpha| = 18^\circ$ near the frequency of max $|S_2|$($f$).

![Fig. 12. Amplitude ratios $r = |S_2|/|S_1|$; phase differences $\delta = \arg S_2 - \arg S_1$ of spectra $S_1$, $S_2$; ratios of ellipse semi-axes $E$; turn angles $\alpha$ of a great ellipse axis relative to the $x$-axis of the coordinate system shown in Fig. 2 versus frequency $f$. The data refer to the point number 6 in Model 1.](image-url)
Considering the dependence $\alpha = \omega h / V_0^2$, we used the formula $\alpha(f) = 2\pi f h a(f) / V_0^2$, and the function $a(f)$ therewith has increased in the considered frequency interval by a factor 2.5. If we consider this fact, then the increase of the angle $\alpha$ by the factor 3.6 is to be corrected, and after correction it appears that the angle $\alpha$ increased due to the increase of the frequency $f$ by a factor 1.44. We should bear in mind that for some materials and rocks, the gyration constant can be a decreasing function of frequency, and then it should be expected that $\alpha(f)$ will be a decreasing function of frequency. We have really observed the decreasing of the gyration constant a via frequency for the upper part of the subsurface (Obolentseva, 1992, 1996; Chichinina and Obolentseva, 2003).

The other evidences of gyrotropy based on the dependence $\alpha = \omega h / V_0^2$ are the direct proportionality of the angle $\alpha$ to the path $h$ and the inverse proportionality to the squared velocity $V_0$. However, to check these dependencies using available experimental data has some difficulties, because we cannot change the values of $h$ and $V_0$ within the limits of the same model, as was with the frequency. Nevertheless, we can check qualitatively if it is valid.

From the formula $\alpha = \omega h / V_0^2$, we see that $\omega h / V_0 \approx \alpha / (a / V_0)$. The quantities in the left-hand side of the second equality are directly measured ($h$, $V_0$) or known ($\omega$); the quantities in the right-hand side of this equality have been determined in the experiments (Table 1). Let us calculate, for Model 1 and Model 3, the expressions $\omega h / V_0$, $\alpha / (a / V_0)$ and then compare the ratios $[\omega h / V_0]_1 : [\omega h / V_0]_2$ and $[\alpha / (a / V_0)]_1 : [\alpha / (a / V_0)]_2$, in which the index 1 refers to Model 1, and the index 2 refers to Model 3. In such a way, we shall know, to what extent the constructed models are in agreement with our ideas on gyrotropy. We have $h = 54$ mm, $V_0 = 1.5$ km/s (Model 1); $h = 20$ mm, $V_0 = 2$ km/s (Model 3); $f \approx 100$ kHz. The values of $\alpha$, $a / V_0$ for Model 1 and Model 3 are given in Table 1. After calculations, we obtain that $[\alpha / (a / V_0)]_1 : [\alpha / (a / V_0)]_2 = 4.3$; $[h / V_0]_1 : [h / V_0]_2 = 3.6$. Thus, the agreement is satisfactory.

CONCLUSIONS

The fulfilled laboratory experiments have substantiated the validity of the principle "azimuthal turn plus translation", which was initially advanced by us speculatively. All three models have shown a turn of polarization plane of shear wave. The turn angles appear to be proportional to frequencies of oscillations. The turn angles were of one sign for all right-handed models and of the opposite sign for a left-handed model.

The experiments have revealed what attributes are inherent to two-component (x, y) records of S-waves in gyrotropic transversely isotropic
media with a vertical symmetry axis at propagation along the symmetry axis. The main attributes are, first, the appearance of y-components of rather small amplitudes in comparison with the amplitudes of x-components (X-excitation) and, secondly, more high frequencies at y-components.

Though physical modelling has supported our idea on the principle of construction of gyrotropic models, the models turned out to be not sufficiently adequate in the ratio of a structural-element length to a wave length (0.1 - 0.4 instead of 0.01 or at least less than 0.1). This is connected with difficulties in making models without special equipment. Therefore, the models occurred to be totally valid only for the central parts of the models.

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