Tube waves in producing wells with tubing and casing

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Summary

Tube waves in producing oil and gas wells are useful for locating fluid interfaces, estimating bottom-hole pressures (Rowlan et al., 2003), investigation of properties of fluids inside the boreholes as well as that of surrounding formations. We consider tube-wave propagation in different models of oil and gas producers using numerical finite-difference modeling. Whenever possible, the results of the numerical modeling are also compared with analytical solutions.

Introduction

At low frequencies, a dominant part of acoustic/seismic energy in the well-bores is represented by waves formed at the borehole walls. Such waves are usually called tube waves. They have no geometrical spreading and thus propagate for very long distances. Properties of the tube waves depend on the medium which fills the borehole as well as on the medium around the borehole. Propagation of tube waves in model with fluid-filled borehole surrounded by elastic medium was a subject of many studies (References). Our investigation focuses on low-frequency tube waves propagating in the simplest models of oil and gas producing well, where the producing well typically contains two steel pipes‘— tubing and casing. Space between tubing and casing, called annulus, often contains a fluid such as gas or water. To generate wave fields, a pressure source located in either tubing fluid or annulus fluid is used. Wavefield is computed by finite-difference program jointly developed by Keldysh Institute of Applied Mathematics and Shell. Simulated tube-wave signatures are compared with the analytical solution for layered systems. The analytical solution was constructed by the mode separation method for cylindrically layered system with subsequent integration along the wavenumber of the vertical component.

Model description

While realistic oil and gas wells can be much more complex, we focus our attention on several idealized models depicted on Figure 1. Codes that we use for investigation of tube wave propagation do not allow modeling of two-phase medium: gas bubbles in the fluid or fluid bubbles in the gas. We can model either pure liquid or pure

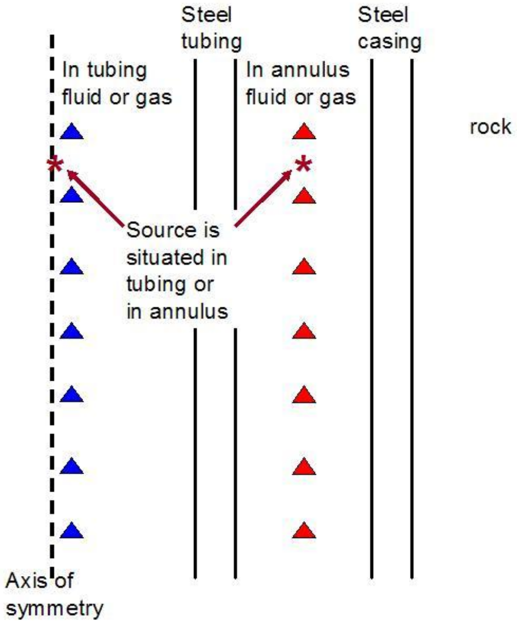

Fig. 1: Model of oil and gas producers.

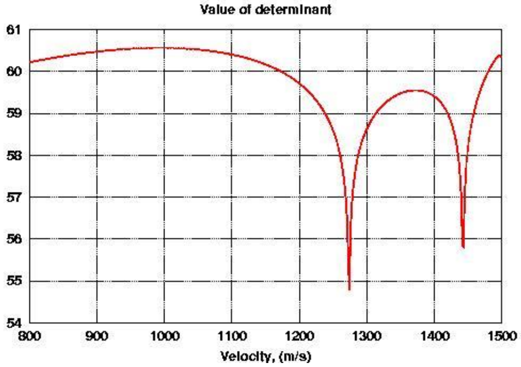

Fig. 2: Logarithm of determinat of dispersion equation. Minimums define tube-wave speeds.

N	Producer	Tubing		Annulus		V_{FAST} (m/s)	V_{SLOW} (m/s)	Source position
		V_s(m/s)	ρ (kg/m^3)	V_f (m/s)	ρ_f (kg/m^3)			
1	Oil	1500	1000	1500	1000	1440	1275	Tubing
2	Oil	1500	1000	1500	1000	1440	1275	Annulus
3	Oil	1500	1000	330	15	1226	329	Tubing
4	Oil	1500	1000	330	15	1226	329	Annulus
5	Gas	330	15	1500	1000	1314	329	Tubing
6	Gas	330	15	1500	1000	1314	329	Annulus

Table 1: Properties of the fluids and source location for each model of producing well.

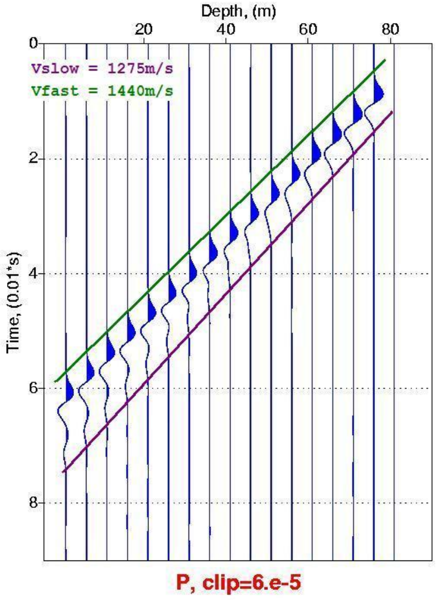

Fig. 3: Pressure seismograms for receivers on the borehole axis (model N 1).

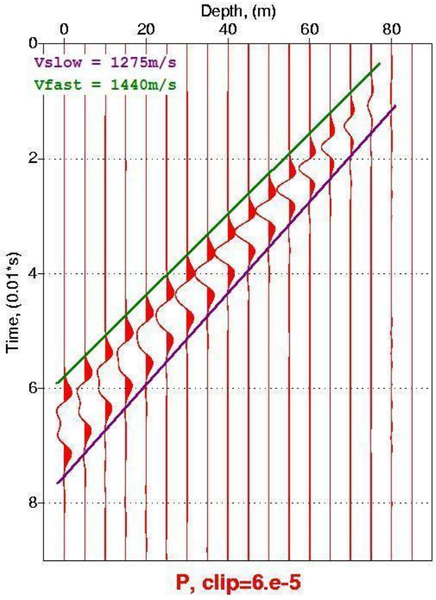

Fig. 4: Pressure seismograms for receivers inside annulus fluid (model N 1).

gas. Therefore oil producer can be divided into two parts: lower part where the annulus (N 1,2) is filled with liquid (oil) , and upper part where the annulus (N 3,4) contains gas. In gas producer well, the tubing is filled with gas while the annulus is filled with liquid in order to counterbalance high gas pressure in the tubing. Six models of oil and gas producers are presented in Table 1.

One vertical receiver array is in the tubing fluid, while another is placed in the annulus (Figure 1). For the models N 1 and 2 the internal tubing radius is 3.1 cm, the internal casing radius is 5.4 cm, while the thickness of both steel pipes is 5.5 mm. Models N 3,4,5, and 6 have 10.6 cm internal tubing radius, 20 cm internal casing radius, 4 mm tubing thickness, and 4 cm casing thickness. Parameters for steel tubing, steel casing and rock are the same for all six models: $V_{p\,steel} = 6000$ m/s, $V_{s\,steel} = 3600$ m/s, $\rho_{steel} = 7800$ kg/m^3, $V_{p\,rock} = 4200$ m/s, $V_{s\,rock} = 2500$ m/s, $\rho_{rock} = 2700$ kg/m^3. For the point-pressure source we use Ricker wavelet with a central frequency of 100 Hz. To excite wavefield in the annulus, a fluid ring-shaped source (a collection of point pressure sources located along the circle) is used.

Oil-producing well

For model N 1 (lower part of oil producer), the wavefield consists of two tube waves: fast (1440 m/s) and slow (1275 m/s). The fast wave is mainly associated with the tubing fluid. However, due to identical fluid properties this wave has similar amplitudes in both tubing and annulus fluid with in-phase pressure (Figures 3 and 4). Amplitude of slow tube wave in the annulus fluid is 3 times bigger then in the tubing fluid. In this case, the two fields propagate being out of phase (have opposite polarity in the tubing and annulus). Pressure source in the tubing excites fast wave with bigger amplitude than slow wave inside the tubing fluid. In contrast, fast and slow wave have almost the same amplitudes in annulus fluid. For this excitation the fast and slow waves in tubing fluid also have the same polarity (positive first kick), while in the annulus they have opposite polarity. Analytical solution of dispersion equation for five-layered model (Figure 2) confirms wave speeds which were estimated from the seismograms.

The model N 2 is the same as N 1 but the source is in the annulus fluid. As expected, the wave speeds of two tube-wave modes are the same as in the previous case because they are independent of the source type and location (Figure 5 and 6). Radial dependence of the pressure for each mode is also source-independent and thus same conclusions about wave velocities and polarizations as for the model N 1 can be made for the model N 2. However the relative excitation of two modes with respect to each other is changed dramatically due to source location in the annulus: the amplitudes of slow and fast waves are almost the same in the tubing; and slow wave amplitude is larger than fast one in the annulus.

The model N 3 is representative to upper part of an oil

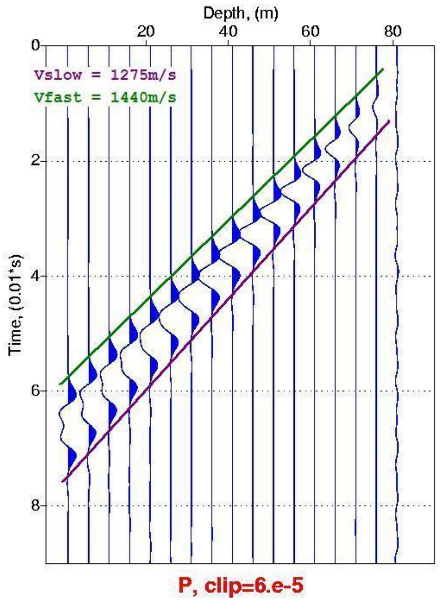

Fig. 5: Pressure seismograms for receivers on the borehole axis (model N 2).

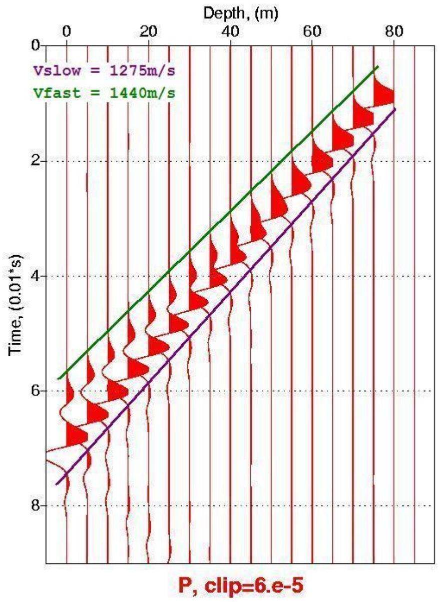

Fig. 6: Pressure seismograms for receivers inside annulus fluid (model N 2).

producer with the source in the tubing fluid. At low frequencies main part of energy propagates in the tubing fluid. Again two tube waves are present: slow (329 m/s) and fast (1226 m/s). The pressure amplitude of the fast wave in tubing fluid is about 10000 times bigger, than in the annulus fluid. Fast wave is also propagate in-phase (same polarity in tubing and in annulus). Slow wave propagates almost entirely in the annulus fluid and with the polarity opposite to that of the fast wave. Velocity values are confirmed by the analytical solution of the dispersion equation for such model.

Model N 4 describes typical echometer measurement (Rowlan et al., 2003) scheme, which is used to evaluate a liquid level in the well. In this technology, a gas gun shot is made in the annulus and the traveltime of reflection from gas-liquid interface is measured. Velocities and radial behavior of fast and slow modes are the same as for model N 3. However, due to annulus excitation most of the energy propagates via annulus fluid with the velocity of the slow wave. Here we can observe that slow-wave pressure inside the tubing is about 30 times less than in the annulus. For the model N 3 we were unable estimate slow-wave amplitude in the tubing because of weak excitation and numerical noises of the finite-difference code.

Gas-producing well

Model N 5 represents a gas producing well with source in the tubing fluid. Similarly to the oil-producing well case, the two tube waves are present: slow (329 m/s) and fast (1314 m/s). Due to the source in tubing fluid, most part of the energy propagates in tubing fluid with slow-wave velocity. Pressure of slow wave in tubing fluid is 100 times bigger than in the annulus. Slow wave is also out of phase in liquid and gas (opposite polarity in tubing and in annulus). Pressure of fast wave in the annulus fluid is ∼4000 times bigger than in the tubing. Fast wave propagates in phase (same polarity in tubing and in annulus). Amplitude of slow wave in tubing fluid is ∼12 times bigger than amplitude of the fast wave in the annulus fluid.

Model N 6 is the same as N 5 but with the source in the annulus fluid. Velocities and radial pressure dependence of fast and slow modes remain the same as in model N 5. However, due to annulus excitation, most of the energy propagates through the annulus fluid with the fast-wave velocity.

Velocity of slow tube wave in the annulus in models (N 3,4) and in the tubing in models (N 5,6) is almost equal to the P-wave velocity of pure gas. Low-frequency equation (2) by (Norris, 1990) proves that this is always the case provided that gas bulk modulus is substantially less than shear modulus of the formation and casing. This conclusion justifies use of pure gas velocity in interpretation of the echometer measurements (Rowlan et al., 2003).

Conclusions

We demonstrate both analytically and numerically that typical producing well with tubing and casing supports propagation of two tube waves: fast and slow. The distribution of radial functions for these tube waves computed by the program for modeling seismo-acoustic wave propagation in vertically stratified waveguides with cylindrical symmetry using wavenumber integration combined with the Direct Global matrix solution technique shows coincidence with amplitudes picked up from the seismograms. While excitation of these two fundamental axisymmetric modes is dependent on the source location, there are several common conclusions applicable to all models:

- In the fluid waveguide containing the source, fast and slow waves always have the same polarity, while in the other (sourceless) fluid waveguide, they have opposite polarity;
- Fast wave always propagates in-phase in tubing and in annulus fluid (has the same polarity);
- Slow wave always propagates out-of-phase in tubing and in annulus fluids.

These observations lead us to generalization of (Norris, 1987) result. He concluded that conventional tube wave in a borehole with a single fluid is a limiting case of slow P-wave in two-phase poroelastic Biot media. We conclude that fast and slow tube waves in producing well (with two fluids) are limiting cases of two additional slow P-waves that appear in three-phase poroelastic medium with two different fluids.

Acknowledgements

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