P266 Tube waves in producing wells with tubing and casing

SERGE ZIATDINOV[1], ANDREY BAKULIN[2], BORIS KASHTAN[1], SVETLANA GOLOVNINA[1], VALERI KORNEEV[3]

[1]*St. Petersburg State University, Ulyanovskaya 1, Petrodvorets, St.Petersburg, 198504, Russia*

[2]*Shell International E & P Inc, USA*

[3]*Lawrence Berkeley National Laboratory, USA*

Abstract

Tube waves propagating in producing oil and gas wells are useful for locating fluid interfaces [1], estimating bottomhole pressures [1], 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 results of the numerical modeling are also compared with solutions obtained analytically.

Introduction

At low frequencies dominant part of acoustic/seismic energy in the wellbores is represented by waves formed at the boundary of the borehole. 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 is well studied. Our investigation focuses on low-frequency tube waves propagating in the simplest models of oil and gas producing well. Producing well typically contains two steel pipes - tubing and casing. Space between tubing and casing, called annulus, often contains fluid different from the tubing itself. To generate wave fields 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 matrix method for cylindrically layered system with subsequent integration along real axis of vertical wavenumber.

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 us modeling of two-phase medium: gas bubbles in the fluid or fluid bubbles in the gas. We can model either pure liquid or pure gas. Therefore oil producer can be divided into two parts: lower part with liquid (oil) in the annulus (N 1,2), and upper part where gas is in the annulus (N 3,4). In gas producer tubing is filled with gas while annulus is filled with liquid to counterbalance high gas pressure in the tubing. Six models of oil and gas producers are presented in Table 1.

One receiver array is put in the tubing fluid, while another is placed in the annulus (Figure 1). For models N 1 and 2 tubing radius is 3.1 cm, casing radius 5.4 cm, while thickness of both steel pipes is 5.5 mm. For models N 3,4,5, and 6 tubing radius is 10 cm, casing radius – 20 cm, tubing thickness – 4 mm and casing thickness – 4 cm. 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. Point pressure source has Ricker wavelet with a central frequency of 100 Hz. To excite wavefield in the annulus fluid, ring source is used (collection of point pressure sources located along the circle).

N	Producer	Tubing		Annulus		V_{FAST} (m/s)	V_{SLOW} (m/s)	Source position
		V_{fl}(m/s)	ρ_f (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

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

Oil producers

For model N 1 (lower part of oil producer) wavefield consists of two tube waves: fast (1440 m/s) and slow (1275m/s). We believe that fast wave is mainly associated with the tubing fluid. However due to identical fluid properties it has similar amplitudes in tubing and annulus fluid and it's pressure is in phase (Figures 3 and 4). Amplitude of slow tube wave in the annulus fluid is ~3 times bigger then in the tubing fluid and it is out of phase (has 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. Also this excitation is such that in tubing fluid fast and slow waves have the same polarity (first kick upward), whereas in the annulus they have opposite polarity. Analytical solution of dispersion equation for five-layered model (Figure 2) confirms wave speeds estimated from the seismograms.

The model N 2 is the same but the source is in the annulus fluid. As expected, the wave speeds of two tube-wave modes are the same and 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 as above can be made. However the relative excitation of two modes with respect to each other is changed dramatically due to source location in the annulus: 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 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). Amplitude of fast wave in tubing fluid is 10000 times bigger, in terms of pressure, than in the annulus fluid. Fast wave also propagates 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 scenario typical for echometer measurement [1] that is used to locate liquid level by shooting gas gun in the annulus and measuring traveltime of reflection from gas-liquid interface. 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. In model N 3 we were unable to estimate slow-wave amplitude in the tubing due to weak excitation and numerical noises of the finite-difference code.

Gas producers

Model N 5 represents gas producer with source in the tubing fluid. Likewise, 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 via 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 [3] 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 [1].

Conclusions

We demonstrate both analytically and numerically that typical producing well with tubing and casing supports propagation of two tube waves: fast and slow. 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 [2] 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.

Acknowledgement

This work was supported by the grants CRDF RG0-1318(9) and A04-2.13-460. We thank Shell International Exploration & Production for support and permission to publish this work.

References

1. Rowlan, L., McCoy, J.N., Becker, B., Podio, A.L., 2003, Advanced techniques for acoustic liquid-level determination, SPE 80889.
2. Norris, A.N., 1987, The tube wave as a Biot slow wave, Geophysics, 52, 1694-696.
3. Norris, A.N., 1990, The speed of a tube wave, J. Acoust. Soc. Am., 87, 414-416.

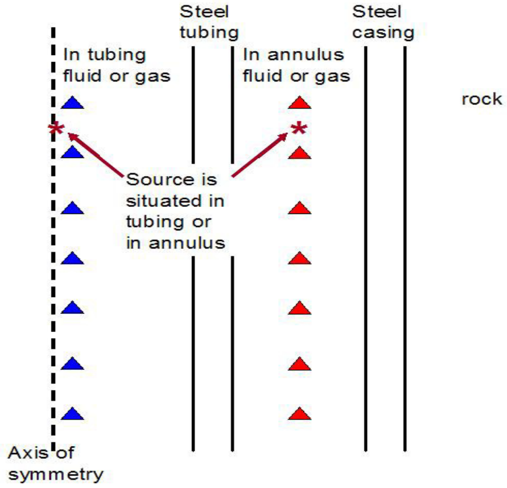

Fig. 1. Model of oil and gas producers.

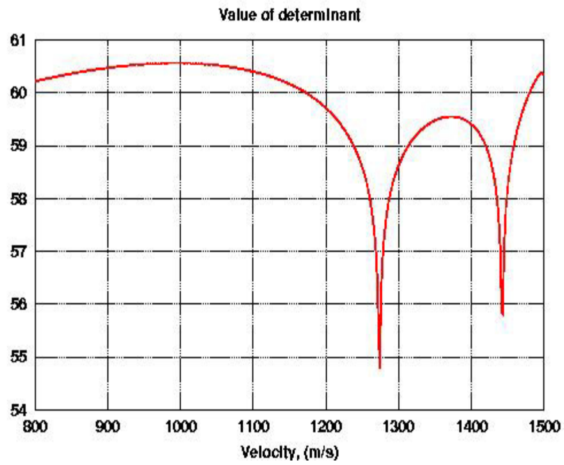

Fig. 2. Logarithm of determinant of dispersion equation. Minimums define tube-wave speeds.

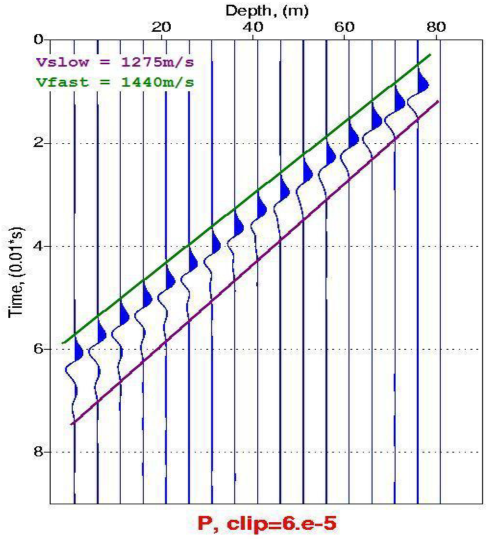

Fig. 3. Pressure seismograms for receivers on the borehole axis (model N 1).

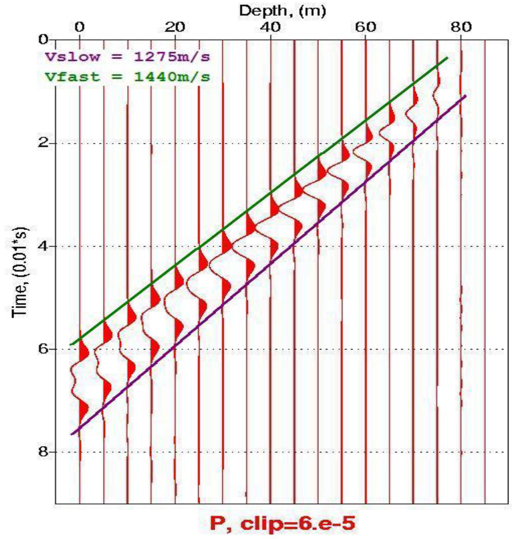

Fig. 4. Pressure seismograms for receivers inside annulus fluid (model N 1).

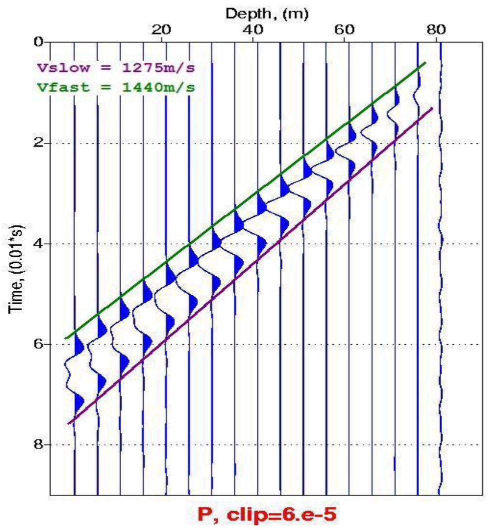

Fig.5. Pressure seismograms for receivers on the borehole axis (model N 2).

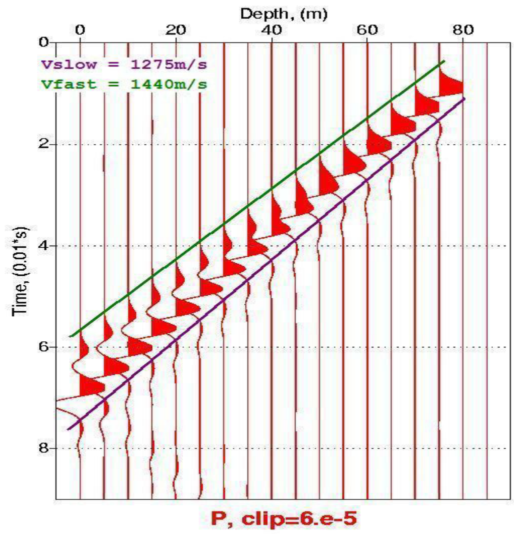

Fig.6. Pressure seismograms for receivers inside annulus fluid (model N 2).