Borehole vibration response to hydraulic fracture pressure

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Summary

Passive-seismic recordings in cased wellbores, including data acquired to monitor hydraulic fracture treatments, can be used to detect resonant vibrations of the casing. The resonant vibrations are linked to the geometry of geophone arrays, which are clamped to the borehole casing with sufficient force to affect the fundamental casing vibration frequency. Using field examples from western Canada, we document temporal variations of vibration frequency that occur over the course of a multistage hydraulic fracture treatment. Finite-element simulations suggest that vibrational frequency is sensitive to local stress conditions. We propose that this effect can be used for *in situ* monitoring of stress variations.

Introduction

Microseismic methods have emerged as an important tool for hydraulic fracture monitoring (HFM). Microseismic data can be recorded using three component geophones clamped to the side of an observation well. Industry practice is to install the geophones with an equidistant spacing and to secure them in place with an electromechanical or magnetic device that has a clamping force to weight ratio of at least ten. Observations from three HFM datasets in western Canada reveal distinct frequency peaks that change over the duration of the frac treatment.

Research into harmonic vibration of pipelines and piping systems can be applied to the vibration of borehole casing. Frid (1989) presented a structural mechanics approach to predict the harmonic vibration in industrial plant piping systems. Singh and Mallik (1979) examined the harmonic response of a pipe filled with flowing fluid. The pipe was supported at periodic intervals. Wave theory was used to predict the harmonic oscillations that occur. Liu and Li (2011) presented a frequency domain approach for calculating the harmonic oscillation of constrained liquid filled pipes. Barnes and Kirkwood (1972), Drumheller (1989) and Lous, et al. (1998) presented analytical models for trying to analytically describe with an acoustic transfer matrix the sound transmission through a drill pipe with equidistant drill collars at the pipe connections.

Observations

The work presented here is a heuristic analysis of data from a central Alberta hydraulic fracture monitoring survey. The data were sampled at time intervals as low as 0.25 msec (equivalent to a Nyquist frequency of 2000 Hz.). Frac-related microseismic signals contain frequencies approaching 800 Hz. The data were recorded in steel cased boreholes cemented to the strata, ranging in depths from 1200m to 3100m with geophone spacing ranging from 11m to 20m in strings of 7 to 12 geophones; one dataset is presented here.

Figure 1 shows five 0.5 second traces recorded during a 2010 microseismic survey in central Alberta. The data were recorded using 11 three-component geophones in a wellbore 140 meters offset from a horizontal well that was being stimulated. A representative frequency-amplitude spectrum for trace 1 is shown in Figure 2. Distinct peaks in the spectra are present throughout the 4.5 hours of monitoring. A particular set of peaks has a fundamental mode at ~ 467 Hz. Overtones (indicated by arrows) are observed at integer multiples of this fundamental frequency, in addition to various other modes. To investigate these line spectra further, the data for each of the 33 geophones were divided into 1 second segments. Each of the 1 second segments were transformed to the frequency domain and the frequency of the fundamental mode was identified. The results of this analysis are shown in Figure 3, and reveal the time-dependent variation of the fundamental mode. During approximately 4.5 hours of monitoring, the fundamental-mode frequency gradually changed from about 468 Hz. to 476 Hz. It then fell to almost 460 Hz by the end of the frac program, as is shown in Figure 3.

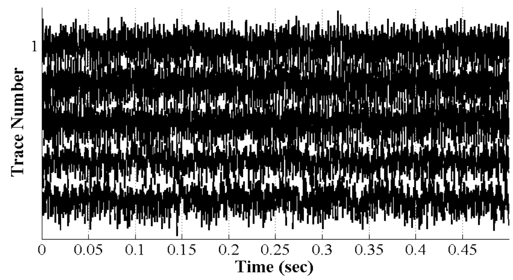

Fig. 1 - A 0.5 second window of five traces of vertical-component data from a 2010 microseismic survey in central Alberta. The borehole geophones are clamped 12.37 m apart.

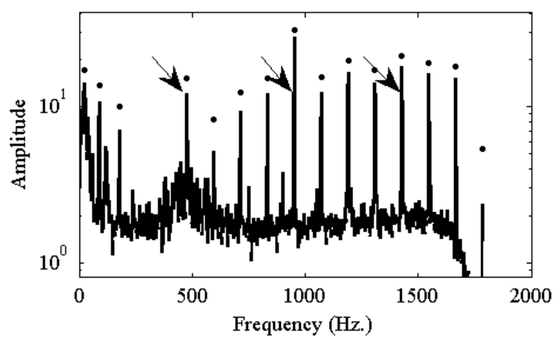

Fig. 2 – The frequency spectrum from trace number 1 in Figure 1. The fundamental mode occurs at ~ 467 Hz. (indicated by the left arrow). Overtones (arrows) and other spectral peaks are evident.

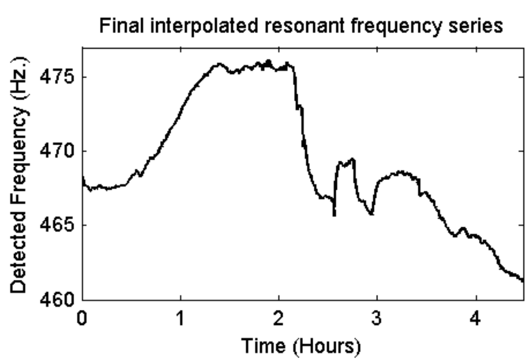

Fig. 3 – The detected frequency vs. time for the fundamental mode in Figure 2. This plot is the median filter for the detected fundamental frequency from the 33 geophones that recorded the central Alberta dataset. The observations are robust; about 100 samples out of 645000 values before the median filter fell outside of a 0.2 Hz corridor around this curve.

Model

A cased borehole is a closed cylinder that will resonate at frequencies proportional to the cylinder length divided by the appropriate wave velocity. The P-wave velocity for steel is about V_P = 5,780 m/s. The cylinder resonant frequency will change if there are internal stiffeners placed a distance *L* apart. Neglecting the effects of pressure, the resonant frequency and its integer harmonics are:

$$f_{res} = n^*V_P/L,\ n = 1, 2, 3, \qquad \textbf{Eqn. 1}$$

Equation 1 predicts a fundamental vibration frequency of approximately 468 Hz. for the 12.37 m geophone spacing for the data shown here. Other local maxima observed in Figure 2 are given by:

$$f_{modal} = f_{res} + m * f_{res}/4, \quad \text{where } m = 1, 2, 3 \quad \textbf{Eqn. 2}$$

These modal frequencies are the result of the geophone array creating an acoustic transfer matrix that filters out most of the frequencies travelling through the casing.

Most recent studies of vibration frequencies of ring-reinforced cylinders under load have been done with the help of finite analysis programs (see, for example Liu and Li, 2011, or Palacz and Krawczuk, 2002). Work by Szechenyi (1971) estimating the natural frequencies of cylinders shows that

$$\omega^2_f \approx F(D, M, k_m, k_n, \sigma_l, \sigma_h, h, R) \qquad , \qquad \textbf{Eqn. 3}$$

where, ω_f denotes the vibrational frequency, *D* is the casing flexural rigidity given by $Eh^3/12(1 - v^2)$, *v* is Poisson's ratio, *M* is mass per unit area, $K_{m,\,n}$ denote bending wave numbers, $\sigma_{l,h}$ are longitudinal and hoop stresses, *h* is casing thickness, and *R* is casing radius. Equation 3 implies that a functional relationship exists between vibrational frequency squared and stresses, as most of the other parameters are material or geometrical parameters. Initial finite element modeling has supported this relationship.

The COMSOL acoustics module was used to model a 2 m steel pipe clamped at both ends. The pipe has an inner diameter of 0.1 m and an outer diameter of 0.112 m (similar to the wellbore considered here) and is encased in concrete (V_P = *4200 m/s*). A point source was used to excite an acoustic vibration within the system. At low initial pressures, the resonant vibration was predicted by Equation 1. The same computation was done with an external pressure of 30 MPa. The peak vibration for the pipe reduced to 2840 Hz, a 2.5% reduction. This reduction is consistent with the magnitude of the frequency variation shown in Figure 3. Work is underway model a fluid-filled porous rock around the steel casing and to use the vibration variation as a stress meter.

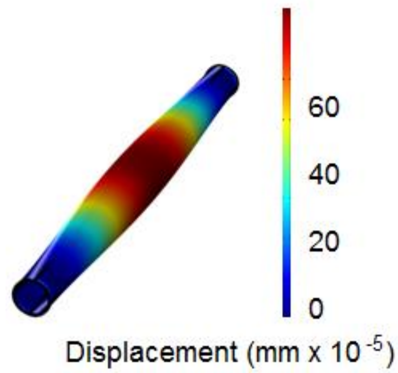

Fig. 4 –A COMSOL model showing an exaggerated view of fundamental-mode displacement of a 2 m long steel pipe fixed at the ends after excitation by an internal acoustic source.

Discussion

An example microseismic dataset considered here illustrates a resonant phenomenon in which resonant frequencies are determined by the geophone array spacing and surrounding pressure. The resonant frequencies are accentuated because the clamping of the geophones creates a new boundary condition in the casing. The frequencies observed are the fundamental frequency, integer harmonics of that frequency and frequencies in between these that are equally spaced modal vibrations around the pipe. The line spectra are independent of any other signal or noise being recorded.

Observed variation of the harmonic frequency appears to be temporaly related to frac-induced variation in the reservoir pressure. If this association can be validated, it implies that this technique may be used for in-situ monitoring of stress changes.

Conclusions

Resonant phenomena associated with equidistant geophones clamped to a wellbore have been examined using theory, numerical simulation and field examples. Robust temporal variations of vibration frequency over a fracture stage appear to be temporally related to changes in stress conditions. We are currently investigating the applicability of this technique for in situ stress monitoring.

Patent

Most of the work presented here is covered under U.S. patent pending 13/3353,376.

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