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Real-Time Completion Monitoring Estimates Production Impairment With Acoustic Waves

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Abstract
Deepwater production increasingly relies on a few precious wells that are complex and expensive. Success is critically dependent on our ability to understand and manage these wells particularly at the sandface. These wells are filled with expensive "jewelry" like sand control and production allocation systems that aim at maximizing production and minimizing risk. While this smart equipment can mitigate many anticipated dangers, it can easily fail when something less expected happens. For example, repairing a sand control system failed due to plugging can cost US$30-40 million. Costs of lost production due to long-term well impairment can be much higher. Lower than expected production is often referred to as "well underperformance" and can be caused by various impairments: a plugged sand screen, contaminated gravel sand, clogged perforations, damaged formation around the wellbore or larger-scale compartmentalization. Scarce downhole data from pressure and temperature gauges cannot unambiguously characterize the impairment and 4D seismic has no resolution to address near-well issues. This limits mitigation opportunities and prevents us from finding more effective drawdown strategies for high-rate high-ultimate-recovery deepwater wells. We strongly believe that geophysical surveillance in boreholes has a big role to play in identifying sources of well impairment and optimizing production. Here we describe one possible avenue - Real-Time Completion Monitoring (RTCM) – that utilizes acoustic signals in the fluid column to monitor changes in permeability along the completion. These signals are carried by tube waves that move borehole fluid back and forth radially across the completion layers. Such tube waves are capable of "instant" testing of the presence or absence of fluid communication across the completion and are sensitive to changes occurring in sand screens, gravel sand, perforations, and possibly reservoir. The part of the completion that has different impairment from its neighbors will carry tube waves with modified signatures (velocity, attenuation). We illustrate capabilities of acoustic surveillance through a series of full-scale laboratory tests with a realistic completion and discuss opportunities for deployment in deepwater wells. Thus real-time completion monitoring could be thought of as "miniaturized" 4D seismic and "permanent log" in an individual wellbore.

Motivation
Completions lie at the heart of deepwater production and present a large portion of the overall well cost. Great multidisciplinary effort is invested upfront to design them right. This contrasts with the production stage where little information is available to detect problems, optimize the inflow and prevent expensive workovers. Incomplete gravel packing, development of "hot spots" in screens, destabilization of the annular pack, fines migration, sand screen plugging, near-wellbore damage, crossflow, differential depletion, compartmentalization, compaction represent a typical list of challenges that are extremely difficult to decipher based on just several permanent pressure and temperature gauges [1,2]. Many problems can be identified by production logging, but it is costly and not in real time.

Let us take the problem of underperforming wells in the Gulf of Mexico [1]. "Well performance" absorbs large-scale reservoir issues such as compartmentalization as well as changes in local well skin with time that further comprises of completion, perforations and near-wellbore effects. Therefore multiple explanations can be given to the problem. Apparent compartmentalization and ubiquitous U-shaped boundaries can be one answer on a "reservoir" scale. Yet those boundaries are rarely confirmed by 4D seismic or other data. Shale draping is an alternative reservoir-scale scenario that can lead to well underperformance. Another wellbore-scale explanation suggests that well productivity declines with time due to loss of so called "kh" where k and h are reservoir permeability and thickness respectively. The differential depletion model (Phil Fair and Fritz Rambow, personal communication) argues that this loss occurs mainly due to reduction in producing thickness although the exact mechanisms of flow impairment are still debated. Reduction in permeability is another alternative explanation offered by Pourciau [2] although the amount of this reduction (85-90%) is not consistent with laboratory measurements. Existing sparse data from wells can support any of these scenarios confirming that the problem is underconstrained. In the context of deepwater completions there is an additional emphasis on sand control because it is believed that "Managing produced sand, as we understand it, is generally a costly and mostly unworkable solution for the Gulf of Mexico, but can work well in other places where there is some grain-to-grain cementation present" (Scott Lester of Shell, Sand Control [3]).

To distinguish between different scenarios of underperformance we need more downhole data at various scales that can unambiguously characterize various components of the production system. The aim of this study is to develop new method, Real-Time Completion Monitoring (RTCM) that can characterize permeability impairment of the sand screen, gravel, perforations and the immediate near-wellbore space. RTCM can also listen to flow and sand production as we show below.

Basic concept of evaluating permeability with acoustic waves

At low frequencies acoustic signals in a fluid-filled borehole are mainly carried by tube or Stoneley waves. Inside the fluid column tube wave mainly consists of a piston-like motion. When fluid is compressed, it attempts to expand radially and pushes against the formation or casing. When the borehole wall is permeable, then tube wave can move the fluid through and this leads to a slowdown in velocity and an increase in attenuation (Figure 1a). Currently these principles are employed in

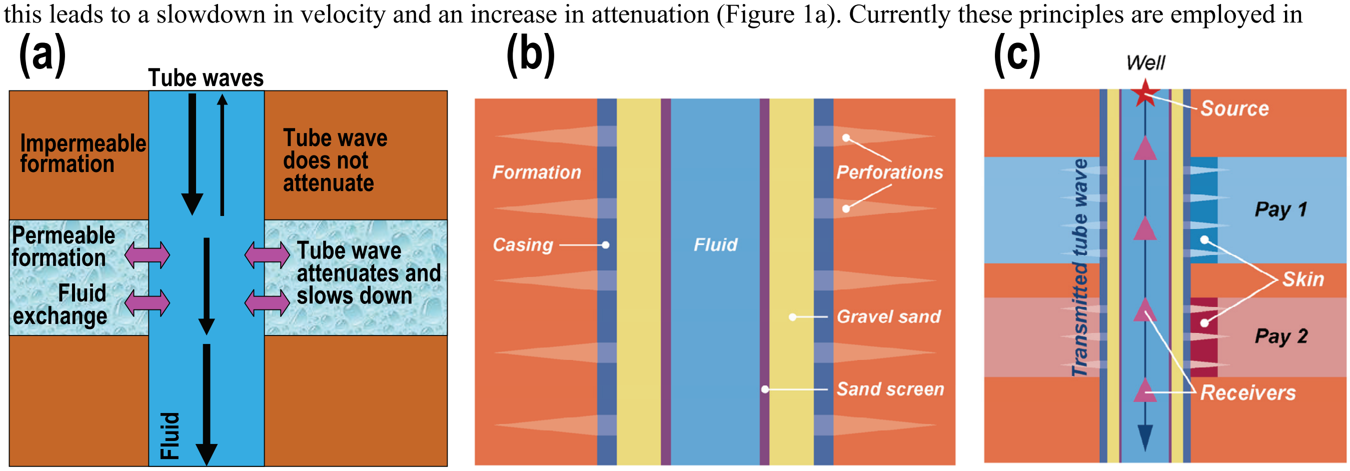

Figure 1: (a) Tube wave attenuates and slows down when it encounters permeable interval that can exchange fluids between borehole and formation. (b) Schematic cross-section of a cased deepwater well with sand-screened completion. (c) Transmission configuration of real-time completion monitoring that can be called "Permanent or repeated log".

estimating near-wellbore permeability from an open-hole acoustic logging [4]. Conceptually similar principles may be extended to deepwater production wells with sand-screen completions. These wells contain multiple permeable layers (sand screen, gravel sand, perforated casing, formation) as shown in Figure 1b. In unimpaired wells fluid can freely flow from the reservoir through all of these layers inside the borehole. However, a reduction of permeability in any of these layers (impairment) may greatly reduce the fluid flow. Low-frequency tube waves can conduct instant pressure testing and therefore indicate whether fluid communication is blocked, thus providing valuable information about impairment location and strength. While this sounds conceptually similar to the open-hole case, the quantitative interpretation is quite different because wells with sand screens support two tube waves and their permeability dependence is more complicated [5]. Initial experiments and modeling [5] confirmed our ability to identify sand-screen plugging in completions without gravel packs. Here we present more realistic experiments with gravel-packed completions and examine other completion scenarios beyond screen plugging.

Experimental setup

A sketch and photo of the full-scale laboratory setup of a completed horizontal well are shown in Figure 2a and 2b. On the outside it consists of a 30 ft aluminum outer pipe (casing) with perforations while the inside has a sand screen and gravel pack. Other details of the experimental setup are pictured in Figure 2c-g. Acoustic measurements are performed with 24 fiber-optic sensors (Figure 2c) wrapped around the outer pipe (casing) as described by Bakulin et al [5]. The sensor spacing is 38 cm. On the outside of the pipe, the tube or "breathing" waves have mainly radial motion. Minute expansion or contraction of the pipe volume is reliably picked up by 10 m of the wrapped sensing fiber (2c). The wire-wrapped sand screen is placed inside the casing (Figure 2a) and consists of an aluminum base pipe with perforations and a plastic wire-wrap with 0.008" gaps (Figure 2d). To model plugged sand screens, we used the same but unperforated aluminum base pipe (Figure 2e). The gravel packing process fills the annulus between the sand screen and casing (as well as perforation tunnels in real wells) with high-permeability gravel sand. The sand screen and gravel pack prevent migration of reservoir sand into the wellbore as well as maintain the structure of the reservoir around the wellbore. Figure 2f shows a picture of a gravel-packed model where a small channel at the top remains free of sand to ensure that proper cleanout can be achieved. Acoustic signals are excited with a piezoelectric acoustic source placed inside the screen (Figure 2g).

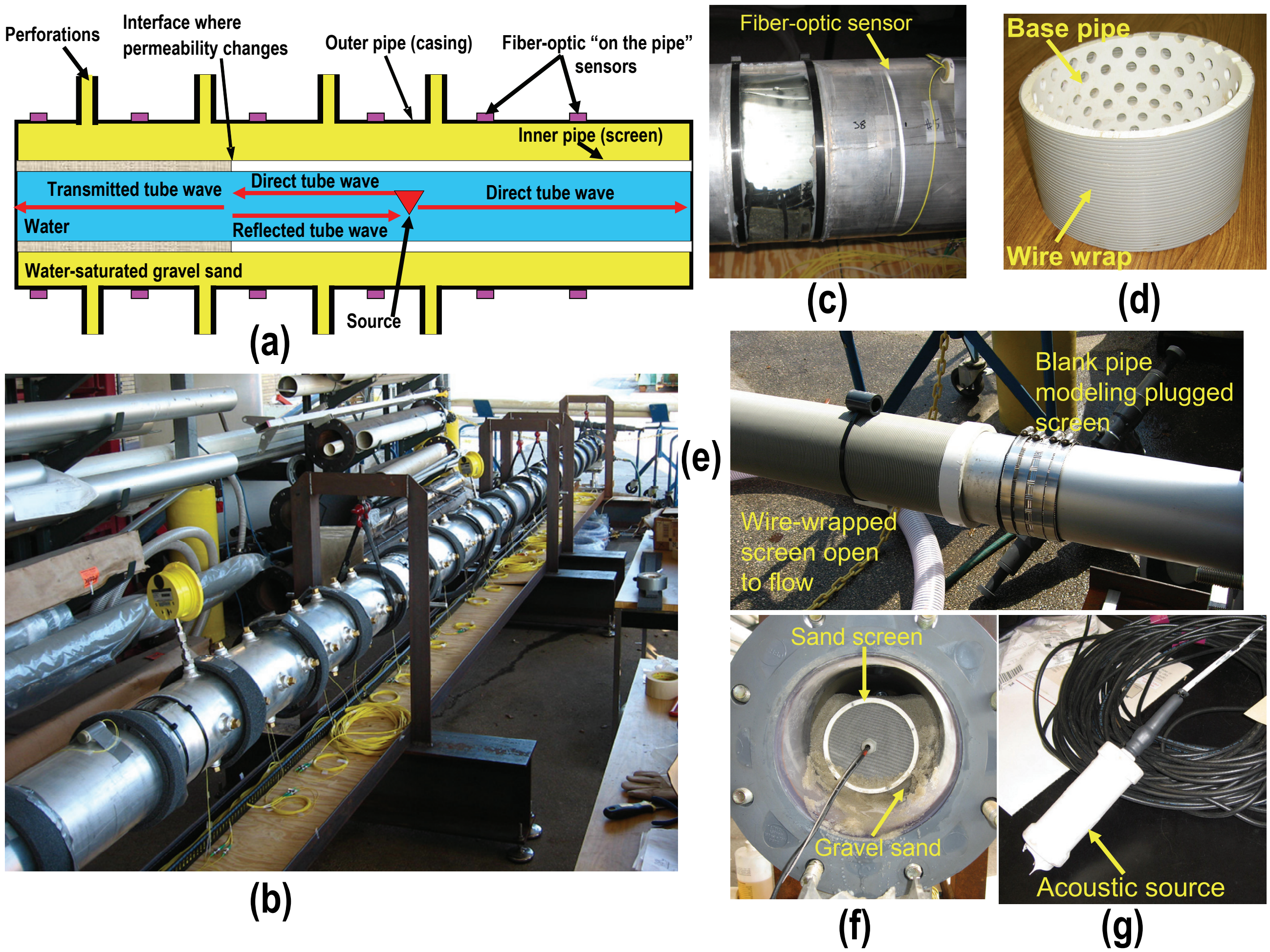

Figure 2: Sketch (a) and photograph (b) of the full-scale laboratory model of completed horizontal well. Components of experimental setup: (c) fiber-optic "on the pipe" acoustic sensor; glass windows were inserted every 5 ft to observe gravel packing process; (d) cross-section of the screen showing wire wrap and base pipe (although plastic base pipe is shown, aluminum one was actually used in the experiment); (e) wire-wrapped sand screen and blank pipe; (f) gravel-packed annulus; (g) piezoelectric acoustic source.

4D monitoring in a well

The concept of completion monitoring with acoustic waves is a natural extension of 4D seismic ideas into the smaller-scale near-wellbore environment. In 4D seismic we build time-lapse images of the subsurface and interpret changes in terms of various fluid flow or production scenarios. In completion monitoring, tube waves repeatedly "illuminate" the completion and near-wellbore space and we interpret changes in terms of important reservoir and completion parameters. In both instances monitoring simply consists of measuring those parameters of the reservoir or producing equipment (say wells) that are needed to make the most critical (read expensive and risky) reservoir management decision. In 4D seismic we can observe how a reservoir is drained and decide where to drill the next well. In completion monitoring, we can observe if and how wells are getting impaired and decide what kind of workover is required and when.

One can distinguish two RTCM configurations: "permanent or repeated log" (transmission) and "mini-4D seismic in a well" (reflection). In both cases we detect changes in acoustic signatures of tube waves over time and infer changes of permeability along the completion. Here we focus on the transmission configuration where we measure velocity and attenuation of the tube wave(s) along the completion and thus have to have sensors along the entire sandface (Figure 1c). Reflection configuration may also be used as described by Bakulin et al. [5,6]. In this case we may have sensors only above the completion and analyze the change in reflected arrivals from permeability interfaces. The depth location of the change can be found by analyzing the arrival times just like in reflection seismic.

Similar to 4D seismic, one makes a decision about acquisition type and frequency. To characterize change in the completion and near-wellbore properties in a non-permanent transmission configuration, one simply needs to acquire time-lapse wireline acoustic logs across the sandface. We expect repeatability of time-lapse logs to be sub-optimal as well as information to be scarce and non in real time. In addition, a well shut-in would be required for borehole monitoring. If permanent sensors are installed downhole, then we expect generally better repeatability and more rich real-time information. As an extra benefit, permanent systems can also be used for passive monitoring. In 4D seismic this would be listening to microseismic events. In real-time completion monitoring, we can listen to flow, cross-flow behind the pipe, sand production, and any malfunctioning downhole equipment.

In the remainder of this paper, we adopt a 4D seismic approach: we experimentally create contrasting completion scenarios like impaired-unimpaired screens and analyze change in the associated acoustic signatures. Thus we concentrate on distinguishing these contrasting scenarios as opposed to inverting for absolute static values of the completion properties. While numerical modeling also reveals similar time-lapse signatures [5] we felt that full-scale experimental study would be more convincing. In addition, the experimental approach brought many "4D surprises" in that we discovered we can monitor things that we did not expect to.

To summarize, we feel that real-time information about inflow ability of the well could be valuable input to well engineers or production technologists that can potentially allow them to:

- detect changes in permeability in and around the well (and thus the inflow ability) in real time
- identify the well structure responsible for any problems (screen, perforation etc)
- help design best practices for drawing the wells without impairing them
- raise red flags early on when problems are not acute and can be fixed with lighter effort, as opposed to major problems when intervention is unavoidable
- help characterize cross-flow and differential depletion in wells with multiple commingled producing intervals.

Detecting sand-screen plugging

One typical impairment mechanism that can restrict deepwater well production is plugging of sand screens. Figure 3 compares responses for open to flow wire-wrapped screen and completely plugged screen modeled as a blank pipe (Figure 2e). The top of the plot contains a visual display picturing exact sand-screen assembly placed inside the casing. Plugged

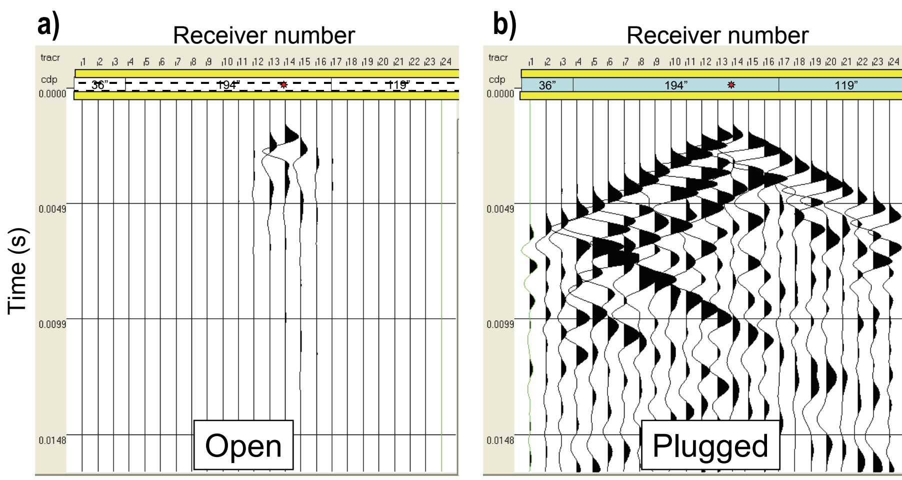

Figure 3. Acoustic response of open to flow sand screen (a) and unperforated base pipe (b) modeling plugged screen. Both displays are shown with equal magnification. Notice greatly increased attenuation of tube-wave signal in open screen. These displays suggest large difference in acoustic signature of open and plugged screens that should be easily detectable.

sections are shown in blue solid color while open sections are depicted in a dashed pattern. Yellow strips around sand screen indicate that the completion is gravel-packed. Permeability of the wire wrapped screen is estimated at ~ 250-1000D, whereas permeability of the blank pipe is zero. Plugged screens support tube-wave signals with small attenuation, whereas open screens have huge attenuation. Figure 4 shows that velocity of the fast tube wave signal is greatly reduced in the open screen. Therefore we conclude that decreased velocities and large attenuation of the fast tube wave characterize open screens. We stress that examples of plugged and open screens represent the end members with large (~1000 Darcy) and vanishing (0 Darcy) permeability, whereas partial plugging will manifest itself as an intermediate permeability, thus generating velocity and attenuation intermediate between the two extremes. Relatively large differences between signatures of plugged and open screens suggest that we are likely to be able to distinguish various levels of partial plugging or intermediate permeability of sand screens.

Figure 5 shows a simulated wireline survey conducted with a moving source in a model where the left part of the screen is open and the right one is plugged. Acoustic data can be easily interpreted by visual inspection and the location of the open-plugged interface is identified between sensor locations 11 and 12. When the source is in the plugged section, we observe a fast tube wave velocity of ~ 1000 m/s and little attenuation, whereas highly permeably open screen reduces this velocity to ~ 600 m/s and leads to extremely high attenuation. Since simple visual interpretation by inspection is straightforward, one expects that tube-wave velocity and attenuation can be plotted as logging curves along the well depth. However, presence of both fast and slow tube waves makes this task more challenging and requires delicate wave separation before reliable attributes can be extracted.

We conclude that sand-screen plugging can be reliably identified using tube-wave signatures.

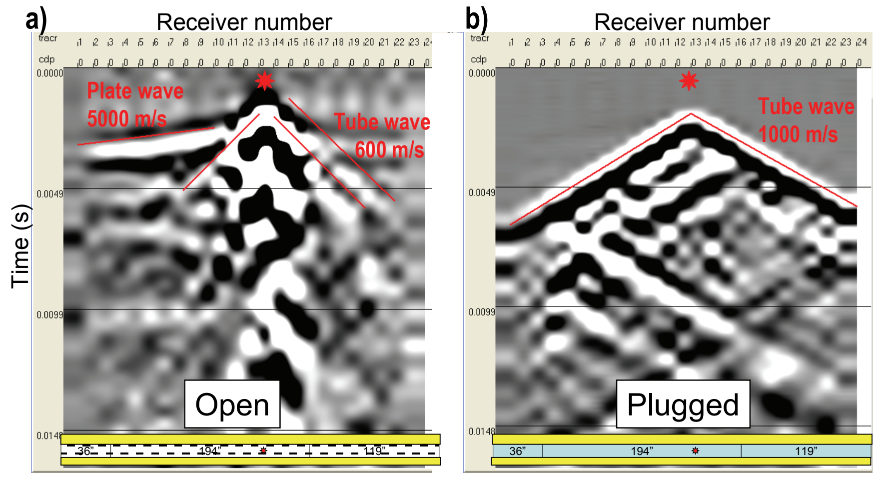

Figure 4. Same as Figure 3 but with variable density display and larger magnification. Notice slower velocity of tube-wave signals in open screen compared to the plugged one. Again large difference in velocity (~40%) suggests that not only we can distinguish open and plugged but also we should be able to detect any partial plugging. Plate wave, supported by a free casing, is seen in the lab data, but this wave would disappear in all downhole scenarios when casing is in contact with the cement and formation.

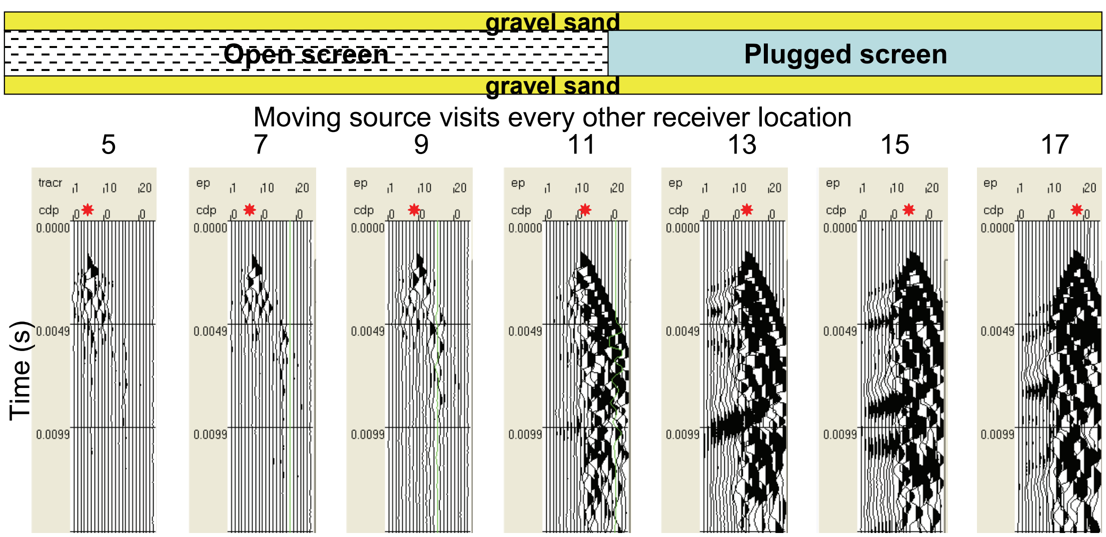

Figure 5. Simulated wireline survey with a source moving from sensor location 5 to 17 with the increment of 76 cm in the gravel packed completion with an open-plugged interface. Note that location of the open-plugged interface (between receivers 11 and 12) is easily found by tracking attenuation and velocity attributes.

Towards permanent system - recording while flow

Results shown so far have been obtained when the well was not flowing. A real-time system would require conducting similar measurements, while the well is flowing. To investigate effects of flow on the signals of interest, we performed the measurement while pumping fluid through thre test setup. To increase the signal-to-noise ratio, ten firings of the source were stacked together. Resulting wavefields for three consecutive 10-second periods are shown on Figure 6a-c. One can see that tube-wave signals of interest are easily recognized in all three records. Notice that low-frequency oscillations (~ 30Hz) due to pump noise are also visible despite applying a DC blocking filter and removing frequencies below 100 Hz. To validate that signals of interest are indeed unaffected by flow, Figure 6d compares records with and without the flow. It can be seen that agreement between the two sets of measurements is excellent. Some low-frequency noise due to flow occurs largely below 100 Hz and is successfully removed by bandpass filtering. We conclude that measurements of interest can be conducted while the well is flowing.

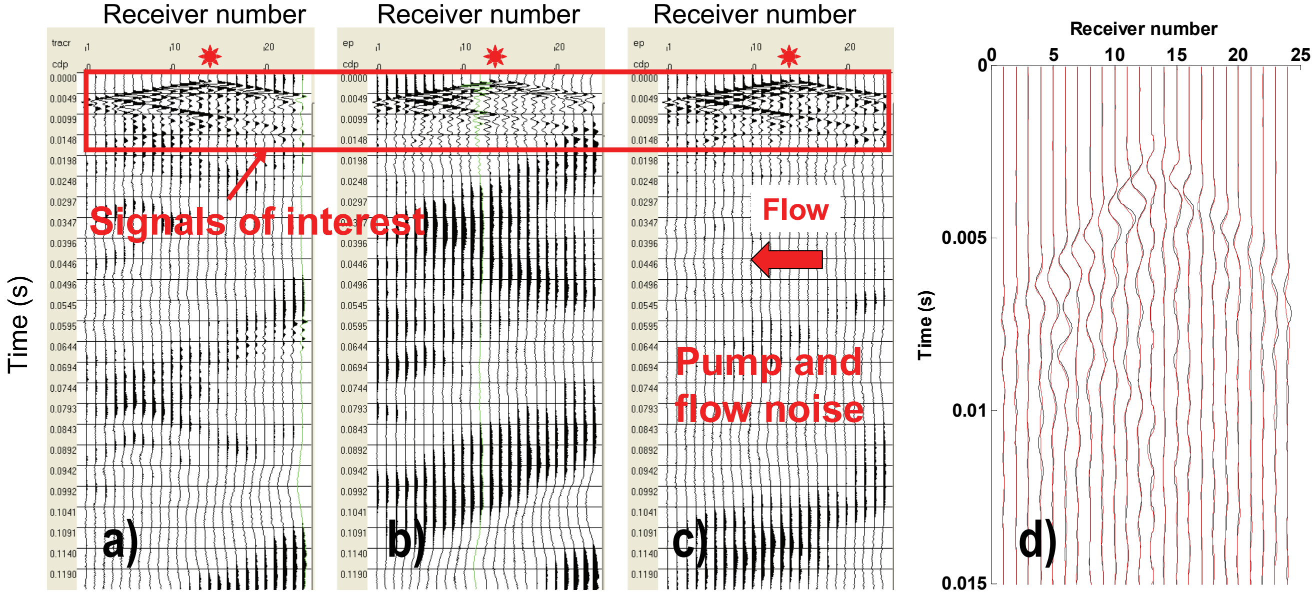

Figure 6. Recording while flowing at 150 gallons per minute (5,100 bbl/day) in a gravel-packed completion with plugged screen. Each of the records (a)-(c) is a stack of ten consecutive traces with firings of the source occurring every second. Additionally DC blocking filter is applied removing frequencies below 100 Hz. Note that higher-frequency tube-wave signals are easily detectable in the early part of the record and exhibit good repeatability despite presence of pump and flow noise at lower frequencies. (d) Comparison of (early-time) records obtained with (red) and without flow (black) in a gravel-packed completion with plugged screen. Both datasets were subject to identical filtering removing low frequencies contaminated with pump and flow noise. Note good agreement between two sets proving that higher-frequency signals of interest can be detected while flowing.

Detecting placement of the sand with active permanent system

Once recording during flow is proved possible, real-time acoustic systems can be used to monitor technological processes such as gravel packing. Let us examine three practical scenarios of interest and find out whether parts of the completion with and without sand can be distinguished.

Plugged screen without washpipe

Let us first examine the gravel packing process of a completion with a plugged screen without washpipe. Washpipe is an additional pipe inserted inside the screen for gravel packing completions with open sand screens. The washpipe serves to prevent the the flow from going into the screen. Without the washpipe the flow prefers to travel inside the screen. As a consequence the main flow would occur inside the screen, whereas fluid velocity in the annulus becomes small and unable to transport sand along the well. In this experiment with a plugged screen, the washpipe was not required. Figure 7 shows four responses obtained during various stages of the gravel packing process while the well was flowing. The estimated front of the gravel pack is shown with yellow boxes. One can clearly observe that a dim amplitude anomaly is moving across the model closely tracking the back front of the gravel pack. Similar conclusions can be reached by analyzing the acoustic movie of the entire gravel packing operation. Once the pack is in place, this anomaly is gone. Judging by the repeatability and consistency of the response and the anomaly, we believe that this amplitude anomaly is a reliable diagnostic of the pack front.

Sand screen with washpipe

To gravel pack an open screen, having a washpipe is a must and thus it is of interest to be able to detect presence or absence of gravel pack along the completion in such a configuration. In the laboratory experiment a plastic washpipe was used while the acoustic source was placed inside the washpipe. Figure 8 shows that in the presence of a gravel pack, we observe tube waves with slower velocity and larger attenuation compared to the same case but without gravel pack. Therefore tube waves can differentiate between the presence or absence of gravel-packed annulus even if an additional washpipe is introduced into the system. Numerical modeling confirms that one of the tube waves is slowed down by the presence of a higher-density gravel pack.

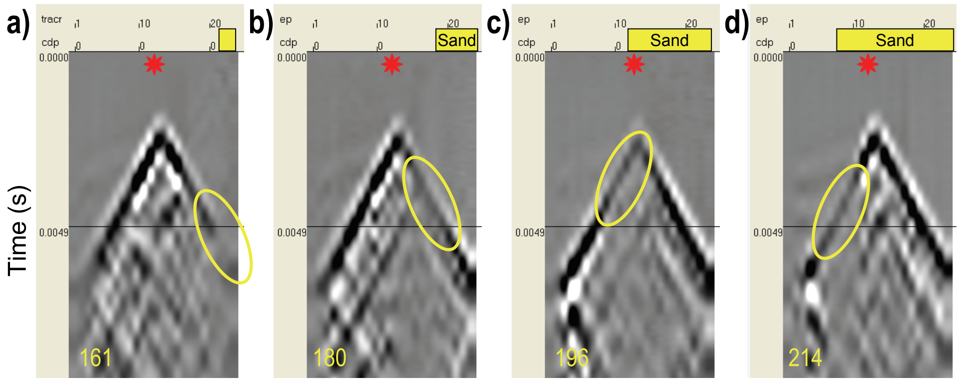

Figure 7. Real-time monitoring of a gravel-packing process in a completion with plugged screen without washpipe. (a)-(d) denotes consecutive time periods. Note the dim spot anomaly (yellow ellipse), which moves along with the estimated sand front location and is denoted with a yellow box above the display. This suggests the ability to monitor the gravel packing process in real time.

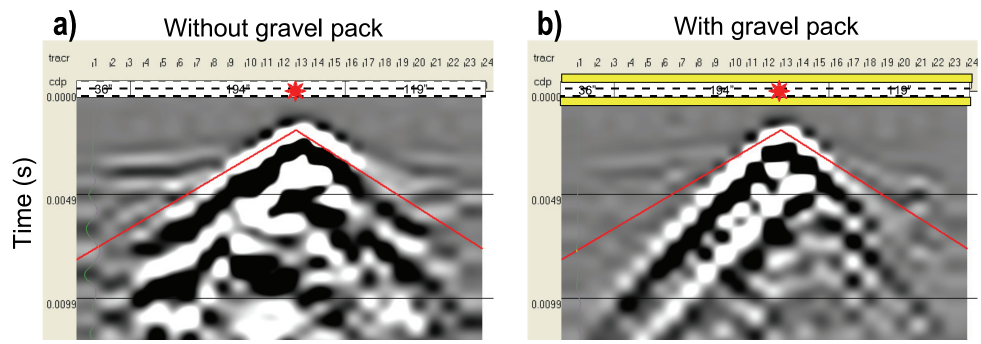

Figure 8. Acoustic responses of sand-screened completion containing washpipe: (a) without gravel pack; (b) with gravel pack. The sand screen is open to flow. The red line shows velocity of 740 m/s and is the same on both plots. Clearly the presence of the gravel pack leads to slowdown in velocity and an increase in attenuation. Difference in these attributes allows us to detect the presence of sand.

Sand screen without washpipe

For completeness, we also modeled the case when the washpipe is removed and a sand screen open to flow is maintained. Figure 9 proves that presence of the gravel pack is manifested by strong attenuation of the tube-wave signals. In particular, the slow tube wave becomes greatly attenuated compared to the case of no gravel sand.

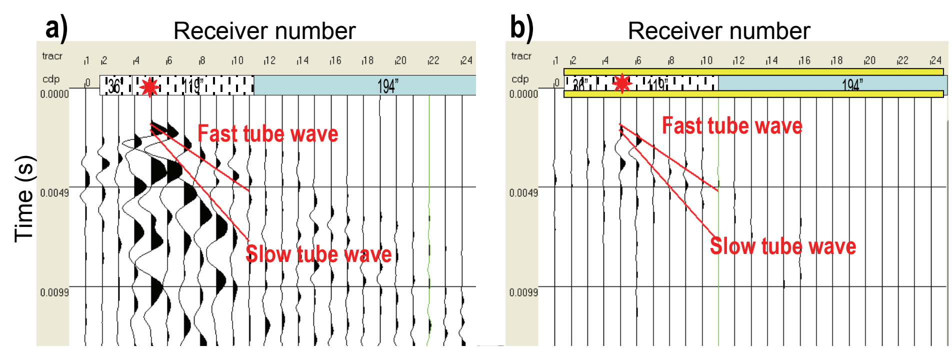

Figure 9. Acoustic responses of a sand-screened completion without the washpipe: (a) without gravel pack; (b) with gravel pack. The figures are shown with equal magnification. Note that the presence of sand decreases the overall amplitude level of all waves, and increases attenuation in particular for the slow tube-wave arrival. The presence and absence of sand is again easily detectable.

We conclude from all three cases, that acoustic data can clearly differentiate between the presence and absence of gravel pack in the annulus and possibly monitor gravel packing in real time. This is an additional benefit of the permanent system that was not envisioned before experiments.

Detecting flowing perforations with a passive permanent system

While active surveillance represents the main task, a permanent non-intrusive system gives opportunities for passive measurements detecting various flow conditions. We present a first attempt to detect flowing perforations based on passive acoustic data. Figure 10a shows several perforations connected to the water line via a manifold. The water line was chosen to simulate a static flow through the perforations. Water is injected through a single perforation at a time inside the completed well to simulate reservoir production.

Figure 10b-d reveals that a flowing perforation acts as a constant source of very low-frequency "noise" of about 0-50 Hz. This noise has a structure of ridges with peaks at the perforation location. Gysling et al [7] describe similar "convective ridges" that are due to acoustic noise from vortices induced by turbulent fluid flow in pipes. They suggest that those vortices create coherent acoustic disturbances that can be tracked at a distance of about two pipe diameters. Therefore they use acoustic sensors with a fine spacing (~2/5 of the pipe diameter) to track these signals and thus estimate fluid flow velocity inside the pipe. Although in our case the sensor spacing is too coarse (38 cm or about two pipe diameters), we can still claim that the signal can be picked up at several neighboring sensors near the flowing perforation. Gysling et al [7] provide examples of monitoring single and multi-phase flow in pipes suggesting that acoustic signals are of similar low frequencies (0-40 Hz). The apparent slope of ridges on Figure 10b-d is around 20-50 m/s whereas estimated flow velocity through the perforation is less than 1 m/s (for a flow rate ~ 4-6 gallons per minute). It is likely that our large sensor spacing leads to severe aliasing and precludes us from estimating such a small flow velocity. Nevertheless, we believe that the nature of the observed ridges is certainly similar to those described by Gysling and co-authors for flow in pipes. Presence of gravel sand is likely to modify flow conditions and behavior of the vortices considerably. These effects should be subject of future studies where sensor spacing should be substantially smaller.

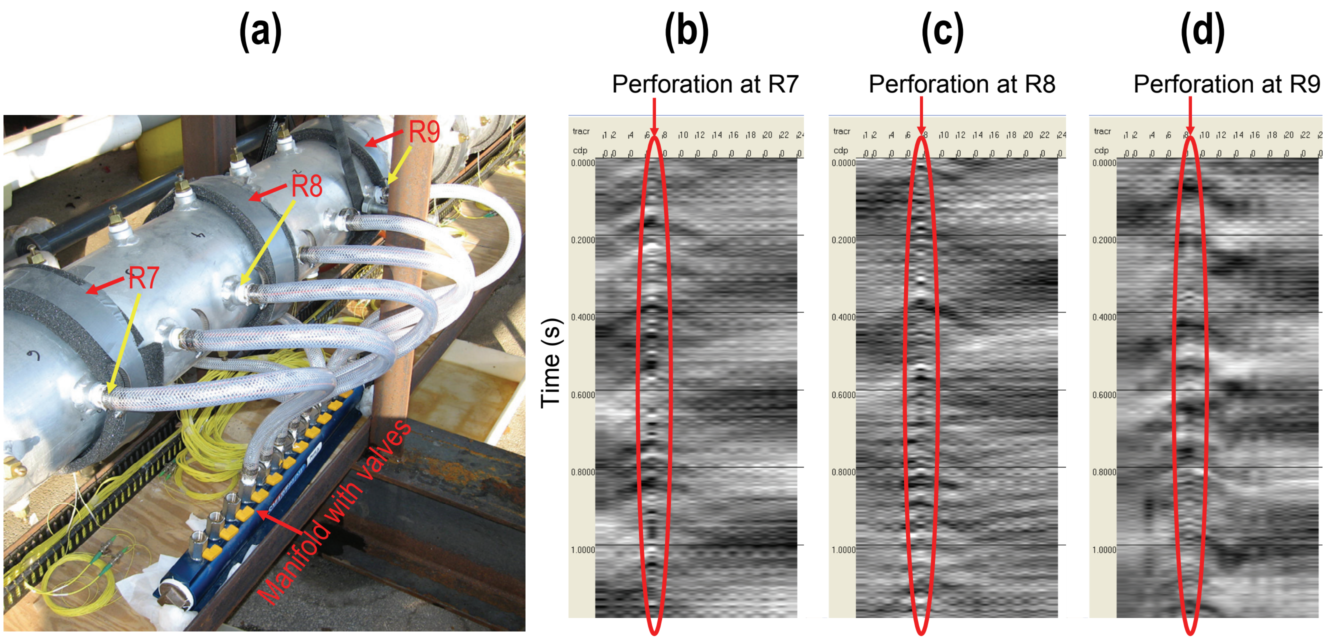

Figure 10. (a) Picture of the setup with connected flowing perforations. Three fiber-optic receivers of interest (R7-R9) are shown with red arrows. Yellow arrows point to the nearby perforation that was used for flow. Water, injected through one per perforation at a time, flows inside the completed well thus simulating reservoir production. (b)-(d) Acoustic responses of flowing perforations after simple pre-processing. Observe low-frequency ridge-like signals with the peaks located near perforations flowing at: b) next to receiver 7; c) next to receiver 8; d) next to receiver 9.

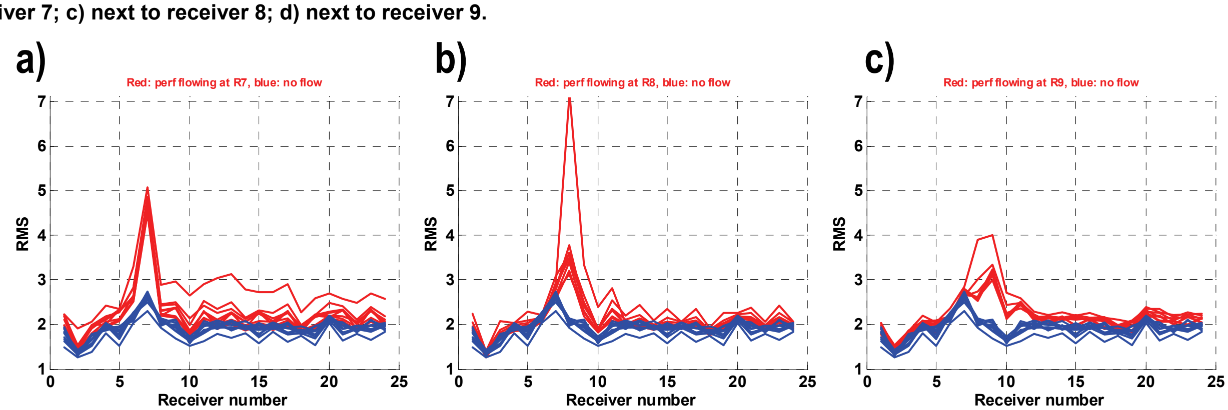

Figure 11. Same data as on Figure 10b-d but recast as RMS values of the entire trace (16 s) versus receiver location. Red curves correspond to perforations flowing at: a) next to receiver 7; b) next to receiver 8; c) next to receiver 9. Blue curves show similar measurements of acoustic noise but without flow. Note that in case of flow, maximum value of acoustic signal occurs next to the perforation and quickly drops out away from it.

If only location of the flow is of interest, then the same data can be analyzed in a simpler fashion following ideas of “noise logging” [8]. Figure 11 shows strength of the acoustic noise estimated as RMS of the entire 16-second trace for each receiver location. Clearly large noise magnitudes occur at receivers near the flowing perforations. When the flow is absent – these peaks disappear. Locations of the peaks identify the position of the flowing perforations as illustrated in Figure 11a-c where flow is simulated through three different perforations. These pictures are independent of the pre-processing applied and have similar structure even if raw unfiltered traces are used. Other noise logging ideas can be used to estimate the flow type and rate based on the magnitude and frequency of the signals [8]. It is expected that multiphase flow will be much “noisier” as compared to the single-phase liquid flow studies here. It may be beneficial to increase the sensitivity of the fiber-optic sensors for passive monitoring. For example, higher sensitivity can be achieved by wrapping longer lengths of fiber on the pipe.

Thus we conclude that both “noise logging” and “acoustic flow-metering” approaches can likely be applied to identify flowing perforations, fluid velocities, and ultimately flow rates. Further work is needed to quantify more precisely what type of information can be extracted from these signals in realistic multi-phase flows from reservoir into gravel-packed completions.

Path to deployment

Conducted experiments suggest with good confidence that completion impairment, as well as other processes, can be monitored using acoustic data. In the short term, the best chance to apply this technology is to utilize wireline acoustic logging. Slim acoustic tools with low-frequency monopole sources and receivers that go inside the screen can be easily manufactured. The disadvantage of the production logging approach is that it is not a real-time 4D measurement. It requires downhole access and possible shut in of the well. The latter two concerns may preclude applications to subsea and other wells with high intervention costs. In addition, repeatability between time-lapse logging runs may be an issue.

The longer-term solution is represented by a permanent downhole system that can be achieved for instance with fiber-optic sensors and passive noise source as suggested by Bakulin et al [5,6]. A permanent system is desirable for many reasons. First and foremost, downhole access is diminishing especially to complex deepwater or subsea wells whereas intervention costs are increasing. In addition, the permanent system has these important advantages over the wireline option:

- it provides real-time information
- there is no well shut in required and thus no lost production incurred
- it allows monitoring gravel packing and other technological processes
- it enables passive measurements characterizing flow, open and closed perforations, cross-flow and sand production.

To illustrate the last point we refer to work by Bakulin and Korneev [9] who showed that direction of cross-flow between two commingled reservoirs can be estimated from repeated acoustic measurements. In essence, the acoustic monitoring method is like a permanently installed “stethoscope & sonograph” at the chest of the patient (sandface of the reservoir). The sonograph constantly conducts an active “health check” of the well, whereas the stethoscope passively listens to “sneezing and coughing” of the reservoir. We expect to detect many other conditions that we can not dream of right now. Early detection and proper diagnostics follow as a natural outcome of permanent monitoring, so that proper treatment (workover) can be delivered before issues get out of hand. Permanent monitoring can also serve as an additional insurance to safeguard expensive completions and sand control “jewelries” as well as the borehole itself.

While development of a permanent system may seem insurmountable at first, it should be stressed that downhole tools with fiber wrapped around downhole tubulars are already under development. For example, Real-Time Casing Imager or RTCI [10] is expected to monitor deformation of the sand screens in complex deepwater wells as a means to assess compaction. RTCI requires fiber helically wrapped around the entire screen and is already addressing various challenges related to downhole placement and connection of the fiber. If RTCI is deployed, then the acoustic system has an even easier ride, especially since it only needs point sensors that can be deployed at a predetermined locations in the most protected places, for instance on the outside of the base pipe. Finally, as speculated by Bakulin et al [5,6], there are new fiber-optic technologies such as Blue ROSE [11] that may allow implementing static deformation (RTCI) and acoustic (RTCM) measurements on a single fiber (Figure 11). As for the sources, the most attractive option is to recover signals by cross-correlating recordings from passive noise sources using the Virtual Source method as described by Bakulin et al. [12]. Field trials should investigate whether frequency content and distribution of natural noises in realistic completions are sufficient for the task. If not sufficient, then several permanent acoustic sources may need to be deployed along the sandface. Such sources could be mounted on the outside of the tubing or screen. Alternatively, passive flow-driven whistles may be designed to act as a “noise” sources with controlled locations.

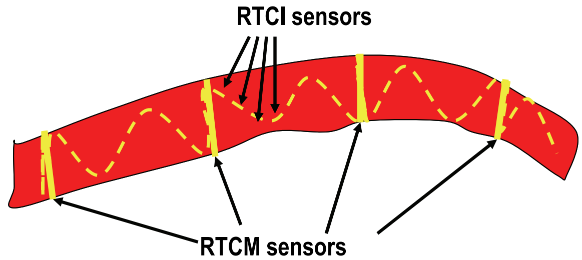

Figure 11. Potential implementation of RTCM (acoustic) and RTCI (static deformation) tools on the same fiber using Blue ROSE interferometric technology.

Conclusions

Just like 4D seismic revolutionized our ability to manage reservoir production, real-time completion monitoring has the potential to revolutionize our ability to manage deepwater wells by understanding evolution of flow, drawdown and impairment in real time. We have presented results of full-scale laboratory tests proving this potential. We showed that with an active source, sand-screen plugging and presence of sand in the completion can be detected. Additional experiments revealed ability to detect state of the perforations and sanded out regions. In a passive listening mode, we can locate flowing perforations and possibly characterize flow velocity. Further progress could be achieved by performing field trials with available acoustic logging tools run inside sand screens. In 4D seismic, various reservoir fluid flow scenarios are used to model and predict seismic responses, which are then benchmarked against actual measurements. Similarly, RTCM could model possible completion scenarios and predict their acoustic signatures. These predictions could be then benchmarked against actual downhole measurement. While quantitative inversions may or may not be achievable, such closing-the-loop methodology of 4D seismic proved of superior value to reservoir management. We have no doubt that acoustic in-well monitoring following same methodology would lead to substantial progress in managing deepwater wells.

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