# Acoustic Waves See Completion Impairment and Flow

a report by

**Andrey Bakulin**,[1] **Alexander Sidorov**,[2] **Boris Kashtan**[2] and **Mikko Jaaskelainen**[1]

1. Shell Bellaire Technology Center; 2. St Petersburg State University

Deepwater production is challenged by well underperformance issues that are hard to diagnose early on and expensive to deal with later. Problems are amplified by reliance on a few complex wells with sophisticated sand control media. New downhole data are required for better understanding and prevention of completion and formation damage. We have introduced realtime completion monitoring (RTCM), a new non-intrusive surveillance method for identifying impairment in sand-screened completions that utilises acoustic signals sent via the fluid column. 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, reservoirs. The part of the completion that has different impairment from its neighbours will carry tube waves with modified signatures (velocity, attenuation). The method relies on permanent acoustic sensors performing acoustic soundings at the start of production and then repeating these measurements during the life of the well. Thus, it could be thought of as 'miniaturised' 4D seismic and 'permanent log' in an individual wellbore.

## 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, the tube wave can move the fluid through; this leads to a slowdown in velocity and an increase in attenuation. Currently, these principles are employed in estimating near-wellbore permeability from open-hole acoustic logging. 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 and formation), as shown in *Figure 1a*. In unimpaired wells, fluid can flow freely from the reservoir through all of these layers inside the borehole. However, 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 indicate whether fluid communication is blocked, thus providing valuable information about impairment location and strength. Here we present some realistic experiments with gravel-packed completions and also examine the problem of detecting flowing perforations.

## Experimental Set-up

A photograph of the full-scale laboratory set-up of a completed horizontal well is shown in *Figure 1b*. On the outside it consists of 30ft aluminum outer pipe (casing) with perforations, while the inside has a sand screen and gravel pack. Acoustic measurement is performed with 24 fibre optic sensors wrapped around the outer pipe (casing), as described by Bakulin et al.[1] 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 10m of the wrapped sensing fibre. Wire-wrapped sand screen is placed inside the casing and consists of an aluminum base pipe with perforations and a plastic wire-wrap with 0.008-inch gaps. To model plugged sand screens, we used an unperforated aluminum base pipe.

## 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 involves 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 decisions. 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 whether and how wells are becoming impaired and decide what kind of workover is required and when. Similar to 4D seismic, one makes a decision about acquisition type and frequency. We expect repeatability of time-lapse logs to be suboptimal and information to be scarce and non-realtime. In addition, well shut-in would be required for borehole monitoring. If permanent sensors are installed downhole, we

Andrey Bakulin is a Geophysicist at Shell Bellaire Technology Center. His industrial career began with three years at Schlumberger Cambridge Research, and continued with six years at Shell Bellaire Technology Center. He has made many contributions to seismic technology, notably with the virtual source method. Dr Bakulin has received several awards from the Society of Exploration Geophysics (SEG), including the Best Paper and J Clarence Karcher awards in 2005 and the Hart's Exploration and Production Special Meritorious Awards for Engineering Innovation for Virtual Source Technology in 2007. After receiving his geophysics PhD in 1996 from St Petersburg State University in Russia, Dr Bakulin had a brief academic career as an Assistant Professor of Geophysics.

Alexander Sidorov is a Researcher at St Petersburg's Shell Cluster in Russia. He works on a Shell-sponsored project devoted to the use of tube waves for downhole reservoir surveillance. His research interest is in advanced studies of wave propagation in anisotropic and multilayered cylindrical shells. Mr Sidorov received his MSc in physics from St Petersburg State University in 2006.

Boris Kashtan is a Professor of Geophysics at St Petersburg State University in Russia, where he is also Head of the Laboratory of Dynamic Elastic Media in the Institute of Physics of the St Petersburg State University. He is also one of the leaders of the St Petersburg Shell Cluster, which performs advanced geophysical studies for Shell. Professor Kashtan is a world expert in advanced problems of seismic wave propagation in anisotropic and complex media. He received his PhD in geophysics in 1981.

Mikko Jaaskelainen is a Senior Research Engineer at Shell Bellaire Technology Center. He has 12 years of experience in developing fibre optic systems for telecommunications and sensing in oil and gas exploration and production. He has spent the past five years with Shell working on fibre optic technology development for downhole sensing applications. He received his MSc in electrical engineering from Lund University in Sweden in 1993.

**Figure 1a: Schematic Cross-section of a Cased Deepwater Well with Sand-screened Completion**

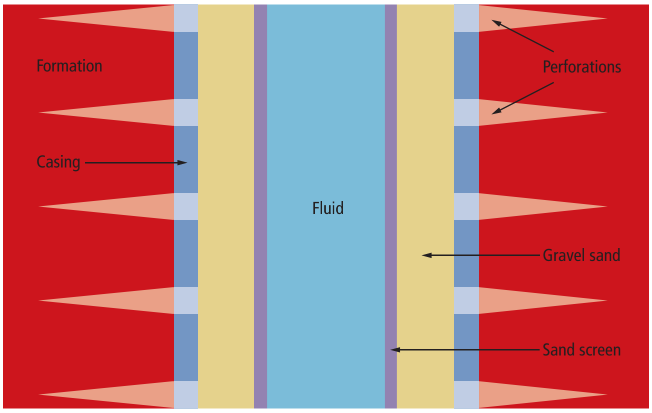



**Figure 1b: Photograph of the Full-scale Laboratory Model of a Completed Horizontal Well at Shell Bellaire Technology Center in Houston**

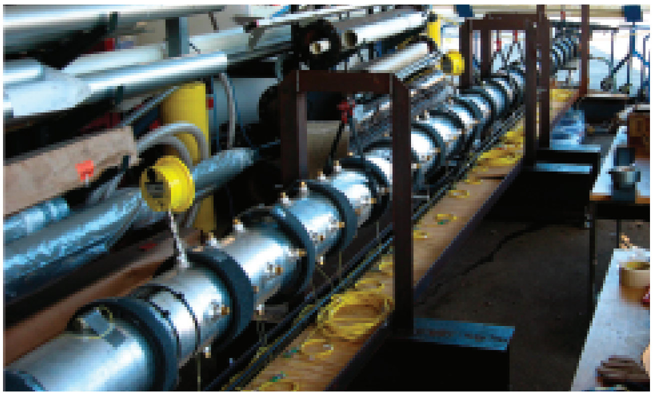
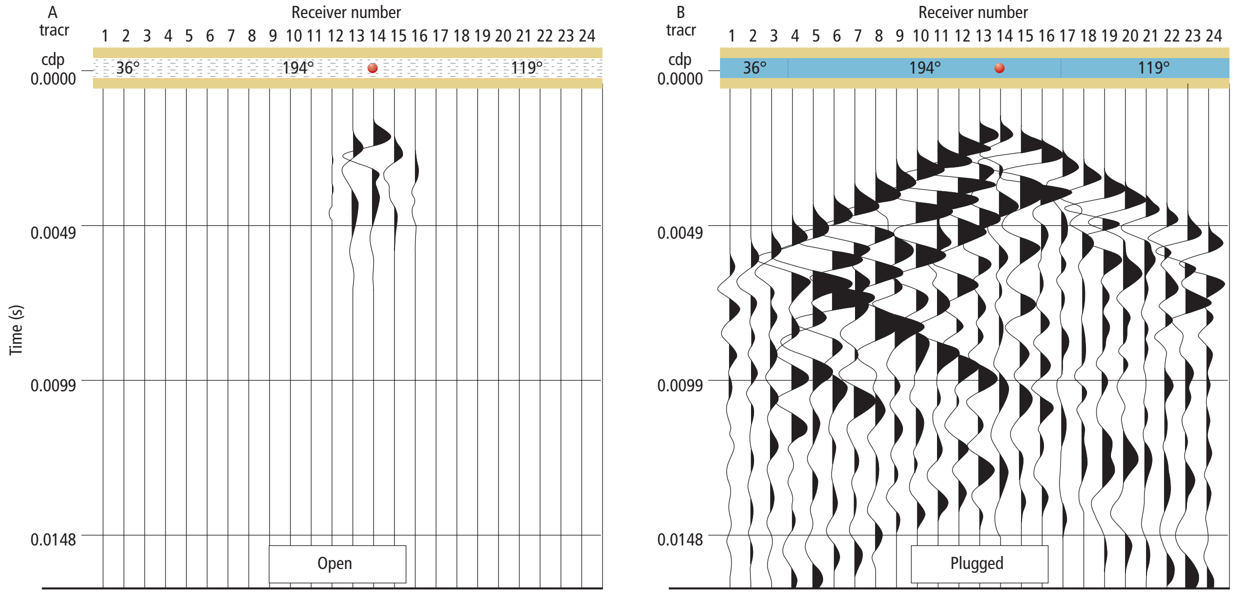


**Figure 2: Acoustic Response of Open-to-flow Sand Screen (A) and Unperforated Base Pipe (B) Modelling Plugged Screen**




*Both displays are shown with equal magnification. Notice greatly increased attenuation of tube-wave signal in open screen.*

expect generally better repeatability and more rich realtime 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 realtime completion monitoring we can listen to flow, sand production and any malfunctioning downhole equipment. To summarise, we feel that realtime information about inflow ability of the well could be valuable to well engineers or production technologists, potentially allowing them to:

- detect changes in permeability in and around the well (and thus the inflow ability) in realtime;
- 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 less effort, as opposed to major problems when intervention is unavoidable; and
- help to characterise cross-flow and differential depletion in wells with multiple commingled producing intervals.

We adopt a 4D seismic approach. We experimentally create contrasting completion scenarios such as impaired–unimpaired screens and analyse changes 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.

## Detecting Sand Screen Plugging

One typical impairment mechanism that can restrict deepwater well production is plugging of sand screens. *Figure 2* compares responses for open-to-flow wire-wrapped screen and completely plugged screen modelled as a blank pipe. The top of the plot contains a visual display picturing exact sand screen assembly placed inside the casing. Plugged sections are shown by the blue solid colour, while open sections are depicted in a dashed pattern. The yellow strips around the sand screen indicate that the completion is gravel-packed. The permeability of the wire-wrapped screen is estimated to be ~250–1,000D, whereas the permeability of the blank pipe is zero. The plugged screen supports tube-wave signals with small attenuation, whereas the open screen has huge attenuation. Despite high attenuation, signal processing shows that the 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 characterise open screens. We stress that examples of plugged and open screens represent the end members with large

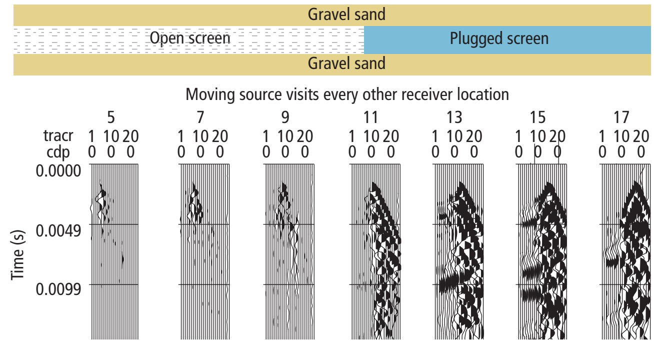
(~1,000D) and vanishing (0D) permeability, whereas partial plugging will manifest itself as an intermediate permeability, thus generating velocity and attenuation intermediately between the two extremes. Relatively large differences between the signatures of plugged and open screens suggest that we are likely to be able to distinguish various levels of partial plugging or intermediate permeability of sand screens. *Figure 3* 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 ~1,000m/s and little attenuation, whereas the highly permeably open screen reduces this velocity to ~600m/s and leads to extremely high attenuation. We conclude that sand screen plugging can be reliably identified using tube-wave signatures.

### Detecting Flowing Perforations with Passive Permanent System

While active surveillance represents the main task, a permanent non-intrusive system provides opportunities for passive measurements detecting various flow conditions. We present a first attempt to detect flowing perforations based on passive acoustic data. *Figure 4* 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 5* reveals that a flowing perforation acts as a constant source of very low-frequency 'noise' of about 0–50Hz. This noise has a structure of ridges with peaks at the perforation location. Gysling et al.[2] describe similar "convective ridges" that are due to acoustic noise from vortices induced by turbulent fluid flow in pipes. They suggest that these 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 (approximately two-fifths 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 (about two pipe diameters), we can still claim that a signal can be picked up at several neighbouring sensors near flowing perforation.

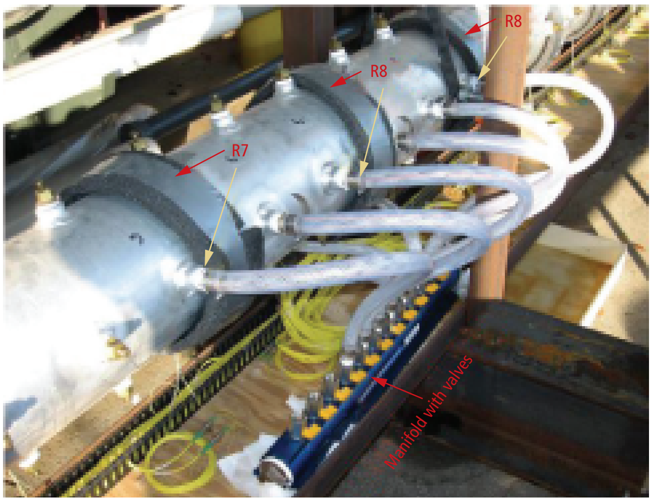
The apparent slope of ridges in *Figure 5* is around 20–50m/s, whereas estimated flow velocity through the perforation is less than 1m/s (for a flow rate approximately four to six gallons per minute). It is likely that our large sensor spacing leads to severe aliasing, and precludes us from estimating such small flow velocity. Nevertheless, we believe that the nature of observed ridges is certainly similar to that described by Gysling and co-authors for flow in the pipes.[2] The presence of gravel sand is likely to modify flow conditions and the behaviour of vortices considerably. These effects should be the subject of future studies where sensor spacing should be substantially smaller. If only the location of the flow is of interest, the same data can be analysed in a simpler fashion following principles of 'noise logging'. Again, the location of single flowing perforations is easily found from the strength of the acoustic noise level. Thus, we conclude that both 'noise logging' and 'acoustic flow-metering' approaches can likely be applied to identify flowing perforations, fluid velocities and flow rates. Further work is needed to quantify more precisely what type of information can be extracted from these signals in realistic multiphase flows from reservoir into gravel-packed completions.

**Figure 3: Simulated Wireline Survey with a Source Moving from Sensor Location 5 to 17 with the Increment of 76cm in the Gravel-packed Completion with a Open–Plugged Interface**



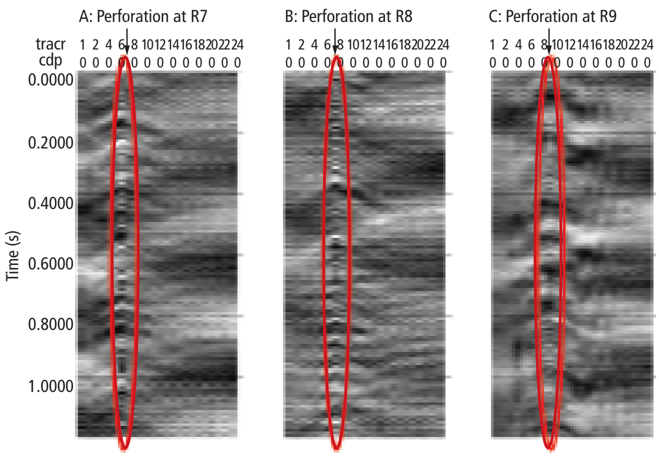

*Note that location of the open-plugged interface (between receivers 11 and 12) is easily found by tracking attenuation and velocity attributes.*

**Figure 4: Picture of the Set-up with Connected Flowing Perforations**




*Three fibre optic receivers of interest (R7–R9) are shown with red arrows. Yellow arrows point to the nearby perforation that was used for flow. Water is injected through a single perforation inside the completed well, thus simulating reservoir production.*

**Figure 5: Acoustic Responses of Flowing Perforations After Simple Pre-processing**




*Observe low-frequency ridge-like signals with the peaks located near perforations flowing at: A) next to receiver 7; B) next to receiver 8; C) next to receiver 9.*

## 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 opportunity to apply this technology is to utilise 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 realtime 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 fibre optic sensors and passive noise source, as suggested by Bakulin et al.[1] 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 the following important advantages over wireline option: it provides realtime information; there is no well shut-in required and thus no lost production incurred; it allows for monitoring of gravel-packing and other technological processes; and it enables passive measurements characterising flow, open and closed perforations, cross-flow and sand production.

While the development of a permanent system may seem impossible at first, it should be stressed that downhole tools with fibre wrapped around downhole tubulars are already under development. For example, the realtime casing imager (RTCI) is expected to monitor deformation of the sand screens in complex deepwater wells as a means by which to assess compaction. The RTCI requires fibre helically wrapped around the entire screen, and is already addressing various challenges related to downhole placement and connection of the fibre. If RTCI is deployed, the acoustic system has an even easier ride, especially as it needs only point sensors that can be deployed at a pre-determined locations in the most protected place, i.e. on the outside of the base pipe.

## Summary and Outlook

Just as 4D seismic revolutionised our ability to manage reservoir production, realtime completion monitoring has the potential to revolutionise our ability to manage deepwater wells by understanding the evolution of flow, drawdown and impairment in realtime. We have presented results of full-scale laboratory tests proving this potential. Further progress might be achieved by performing field trials with available acoustic logging tools run inside sand screens. In 4D seismic, various fluid flow scenarios are used to predict seismic response and are then benchmarked against real measurements. Similarly, RTCM would require the ability to take possible production technology scenarios, predict their acoustic signatures and benchmark them against actual downhole measurements. While quantitative inversions may or may not be achievable, such closing-the-loop methodology of 4D seismic has proved to be of superior value to reservoir management. We have no doubt that acoustic in-well monitoring following the same methodology will lead to substantial progress in managing deepwater wells. ■

1. Bakulin A, Sidorov A, Kashtan B, Jasskelainen M, Realtime completion monitoring with acoustic waves, *Geophysics*, 2008;73:E15–33.
2. Gysling D, Loose D, van der Spek A, Clamp-on, SONAR-based volumetric flow rate and gas volume fraction measurement for industrial applications, Proceedings of the 13th International Conference on Flow Measurement, 2005.
3. Childers BA, Rambow FHK, Dria DE, et al., Downhole Fiber Optic Realtime Casing Monitor, SPIE's 14th Annual International Symposium on Smart Structures and Materials and Non-destructive Evaluation and Health Monitoring, 2007;6527–35.