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# Conceptual design of an apparatus for measuring frequency-dependent streaming potential of porous media

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## Introduction

Electro-kinetic phenomena link fluid flow and electrical flow in porous and fractured media such that a hydraulic flow will generate an electrical current and vice versa. Such a link is likely to be extremely useful, especially in the development of the theory of the electro-seismic method. However, surprisingly little experimental determination, numerical modeling and theoretical development have taken place, and what exists is for steady state flow. There have been only a few attempts at making experimental determinations of the frequency-dependent streaming potential coupling coefficient because of their difficulty, and only one rare measurement made on rocks.

Our goal was to design and construct an apparatus capable of measuring the streaming potential of porous media as a function of frequency that would provide valid data for the greatest range of frequency, sample porosity and permeability, and sample size possible. Hence some balance has to be struck in order to obtain a design that is financially and technically optimal.

Since we require to measure the streaming potential, we seek to impose a time-varying fluid flow, which is measured and logged together with the electrical potential that it creates. The streaming potential is then simply the ratio of the two measurements.

$$C_s(\omega) = \frac{\Delta V(\omega)}{\Delta P(\omega)}$$

We present here four approaches to making laboratory determinations of the frequency-dependent streaming potential coupling coefficient. In each case, we have quantified the practical difficulties involved in each method to pulse the flow at high frequency.

We have also constructed a simplified trial apparatus using the electro-magnetic drive to test the conceptual design with samples in the form of sands and beads. We have used our experience with the trial apparatus to design a new apparatus for a 1 cm diameter sample, and with the help of an engineering approach we have determined the range of possible sample permeabilities for samples between 0.5 and 2 cm in length.

## Approaches

### Scotch yoke drive and spring system

The driving force is provided by an electric motor and a system of connecting rods and springs. The motor drives a wheel upon which an excentred rod has been attached. The rotation of the motor is transformed into a linear motion by the action of the excentred rod [1] within a slot in the connecting rod (Figure 1 (2)). The linear movement compresses a spring (3) which is calibrated to require 160 N for each 1 cm compression. The spring acts upon the compression piston (4) in such a manner that a maximum pressure can be applied to the pore fluid. The spring is necessary to allow the motor to turn while using low porosity samples with an incompressible pore fluid, which would otherwise lock-up the mechanism.

**Problems:**
- The maximum frequency [2] is too low (Maximum 33Hz)
- A 60 000 RPM electric motor is needed for a 1000 Hz frequency.
- High friction on the excentred pin implies a high torque on the motor.

**Summary.** In conclusion, neither a motor with a combination of sufficient couple and speed, nor a spring with sufficient stiffness per mass is currently available for this design to be feasible up to 1 kHz. Such a system would be currently possible, but could attain frequencies only up to about 33 Hz.

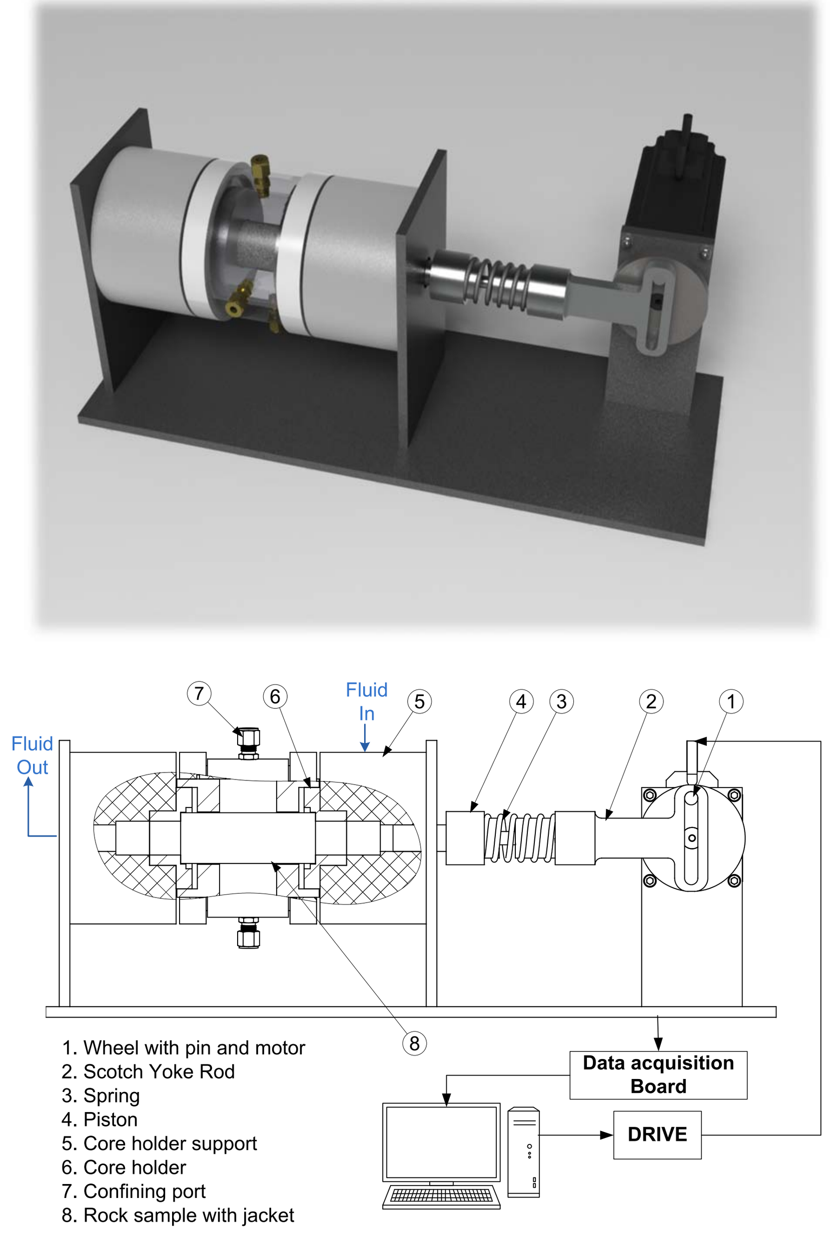



Figure 1: A conceptual connecting rod-drive AC electro-kinetic cell

### Pneumatic drive system

The pneumatic system consists of two small jacks (Figure 2 (1)) that are situated on each side of the sample cell (4). In order to decrease the response time and fluid friction in the pipes, the jacks are controlled in extension and allowed to retract in neutral mode. Hence a jack is required on each side of the sample in order to complete the full cycle. The two jack approach also allows an external reservoir to be eliminated, while using the space that is occupied by the piston in the other designs to act as an internal fluid reservoir. In order to impose a sinusoidal fluid pressure, a rectified half-wave is first sent to the servo-valve controlling the first jack, while the other jack is subject to atmospheric pressure. At its end a rectified half-wave is sent to the servo-valve controlling the second jack, while the first jack is subject to atmospheric pressure.

The advantage of the pneumatic system is that the air is compressible. The compressible air allows the imposition of the force without the need for a spring, which eliminates the frequency limit that was caused by the springs in the mechanical design. A variation on this design might replace both jacks with membranes that are activated by pneumatic pressure. Such a design has the potential to reach higher frequencies still.

**Problems:**
- The maximum servo-valve frequency is 100 Hz.

**Summary.** The lack of a high speed servo-valve makes a pneumatic system impossible above about 100 Hz.

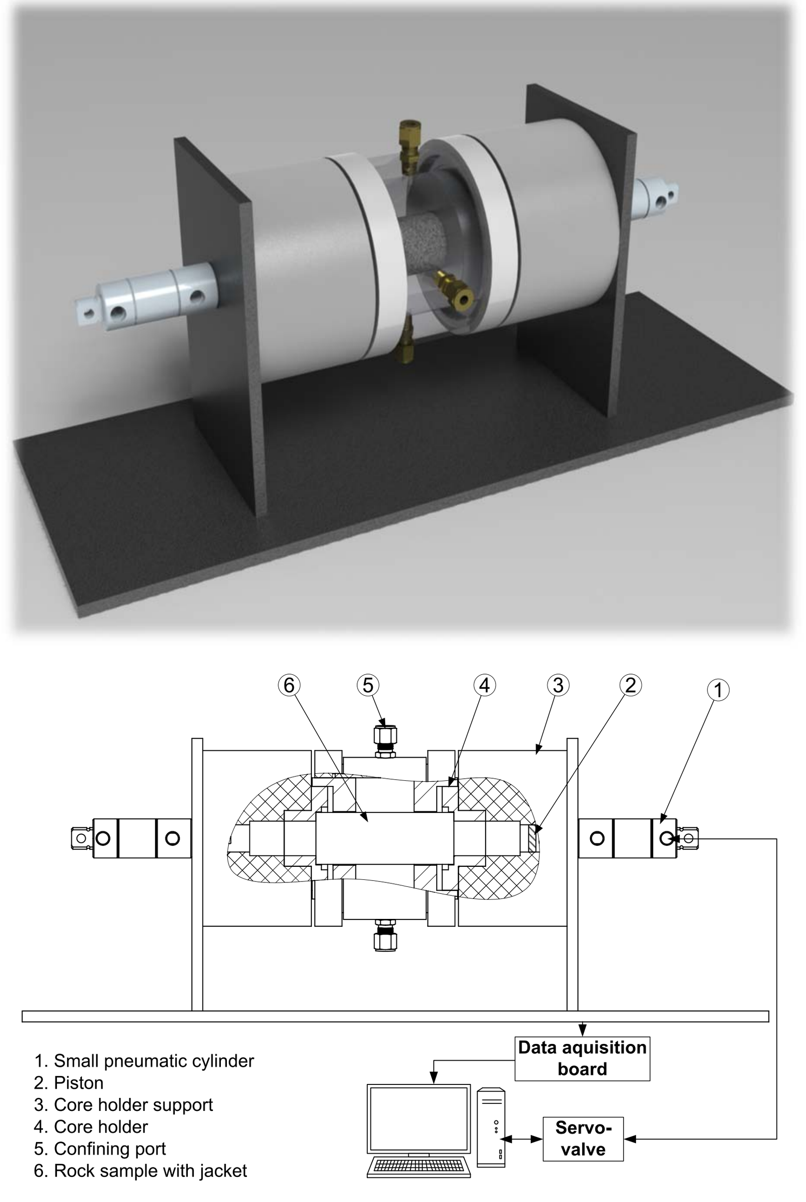



Figure 2: A conceptual pneumatic AC electro-kinetic cell.

### Electro-magnetic drive

The electro-magnetic drive system relies on the use of an electro-magnetic shaker [3]. Such shakers (Figure 3 (1)) provide high quality sinusoidal displacements at low or high frequencies. Their main use is in the testing of mechanical structures and aircraft. A sine wave generator is used to drive a DC amplifier which provides an amplified current sufficient to drive the electro-magnetic shaker. This current passes through the coils of the shaker (3) producing an electro-magnetic field which in turn displaces a magnetic rod. The force on the rod is proportional to the current. The rod (4) is attached to a piston that drives the fluid through the sample (8) with a sinusoidally varying force. Two one-way valves are arranged at each end of the sample to allow new fluid to be drawn into cell on the return stroke which is then pushed through the sample on the compression stroke. The result is a sinusoidally varying fluid pressure during the compression stroke and a quasi-sinusoidally varying fluid pressure during the return stroke. There are a range of different shakers available. There is a balance between force and frequency; shakers with high maximum frequencies have lower maximum forces and vice versa. It is possible to increase the maximum frequency by replacing the electro-magnetic shaker by a piezoelectric stack.

**Summary.** The electro-magnetic drive has the power to drive the AC electro-kinetic system up to 1000 Hz. At low frequencies the piston displacement must be limited to ensure that it, and the piston velocity, do not reach the maximum values specified for the shaker.

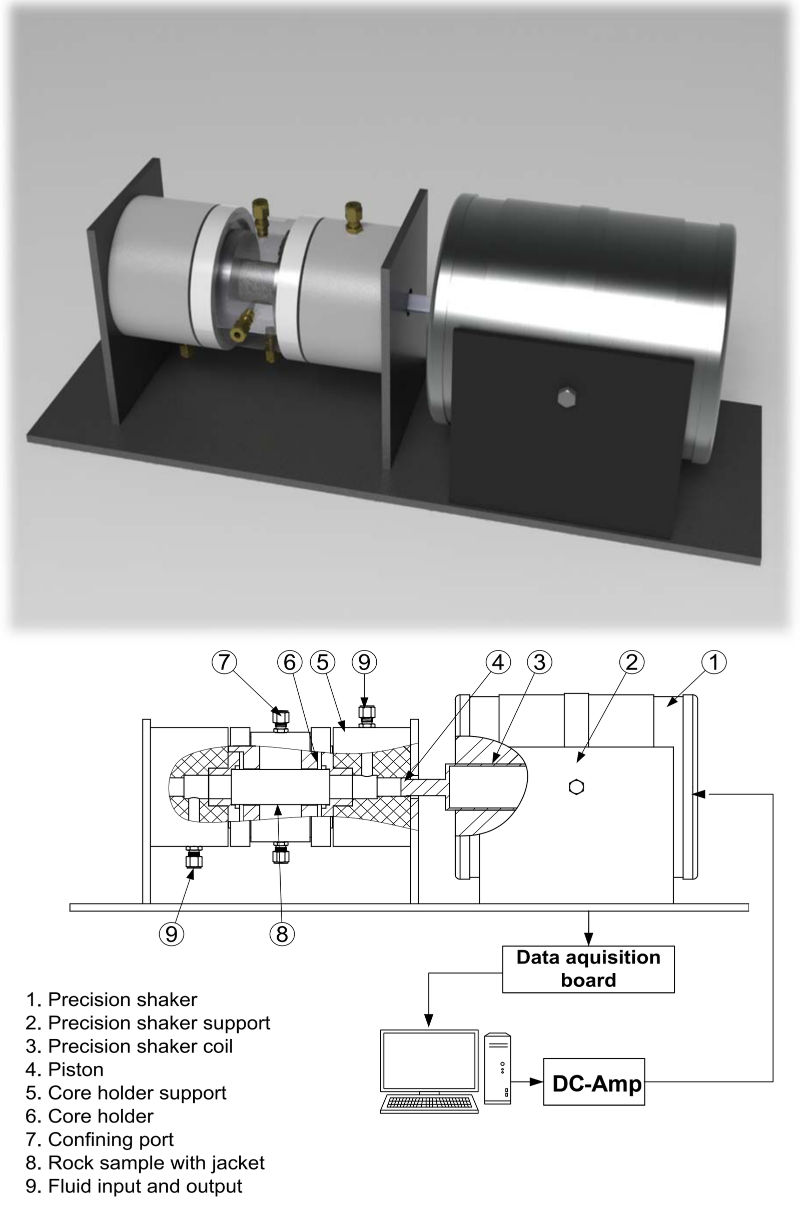



Figure 3: A conceptual electromagnetic drive AC electro-kinetic cell.

### Experimental apparatus for sand

An experimental apparatus was designed and constructed to allow AC electro-kinetic measurements to be made upon granular material using a shaker (Figure 4a). The sample is held in a thick horizontal perspex tube by perforated perspex discs and a spring (3). At each end of the sample, arranged radially with an offset of 90 degrees, there are ports (6) for up to two non-polarizing electrodes, for a pressure transducer (1) and for a check valve. Axially, the tube end is either left open to accept a piston (4) with a rubber seal or can be coverted with a rubber membrane. The output end is connected directly to the output fluid reservoir. While it is possible to raise the output fluid pressure with the aid of a back-pressure regulator, it was kept at atmospheric pressure for the following tests. The sample cell is held extremely rigidly in a frame to which the shaker (5) is also attached. The shaker drives the piston directly along the axis of the sample cell. Hence the system is conceptually and in reality extremely simple.

Non-polarising Ag/AgCl electrodes from Cypress Systems were used. Their signals were conditioned and amplified using noise-rejection circuitry that was specially developed in-house (Figure 4b) before being passed for logging to a National Instruments USB-6211 DAC board/LabView combination. The bandwith of the potentiel electronic and the pressure transducer is respectively 30 kHz and 800 kHz. The phase lag between the input signal and the output signal is 0,5 μs for the potentiel measurement and 0 s for the pressure measurement.

The AC pressures were measured using DPX101 dynamic pressure transducers which have a rise time of approximately 1.0 μsec, a resonant frequency of 500 kHz and a high frequency range of 170 kHz (approximately 1/3 of the resonant frequency). These transducers are driven by a separate instrument which also conditions the signal and passes it on to the National Instruments USB-6211 DAC

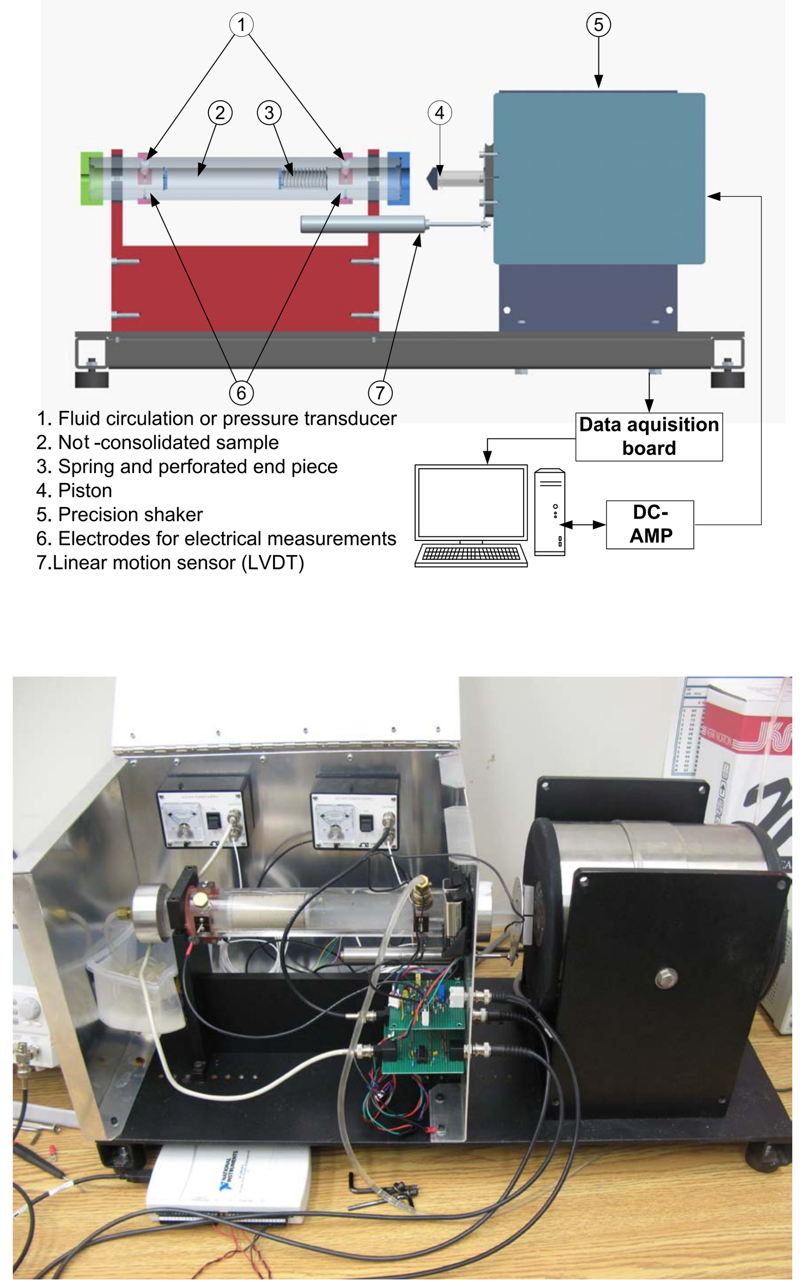
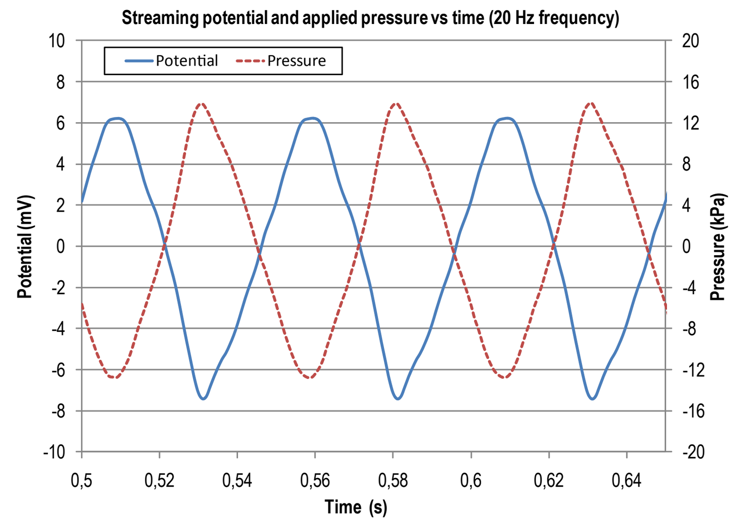
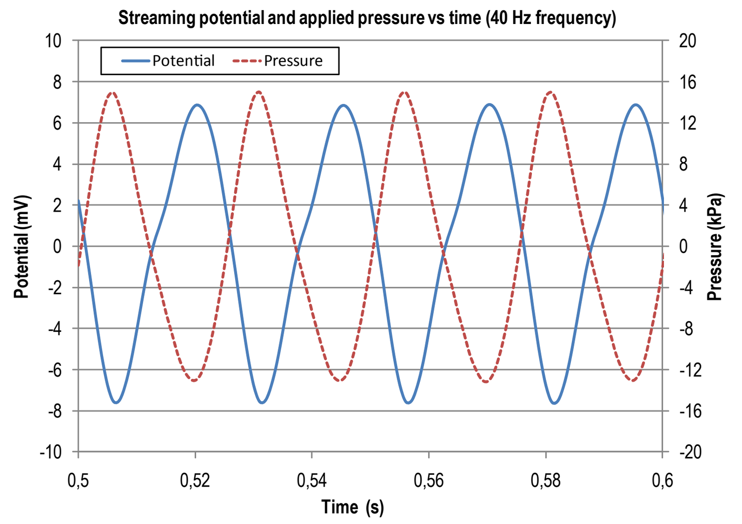



Figure 4: (a) A conceptual electromagnetic drive AC electro-kinetic cell and (b) experimental apparatus

## Results

The cell was loaded with Ottawa sand (length = 7.7 cm, diameter 2.54 cm, grain diameter 400 μm). We imposed a sinusoidal pressure waveform at different frequencies to investigate the frequency response.



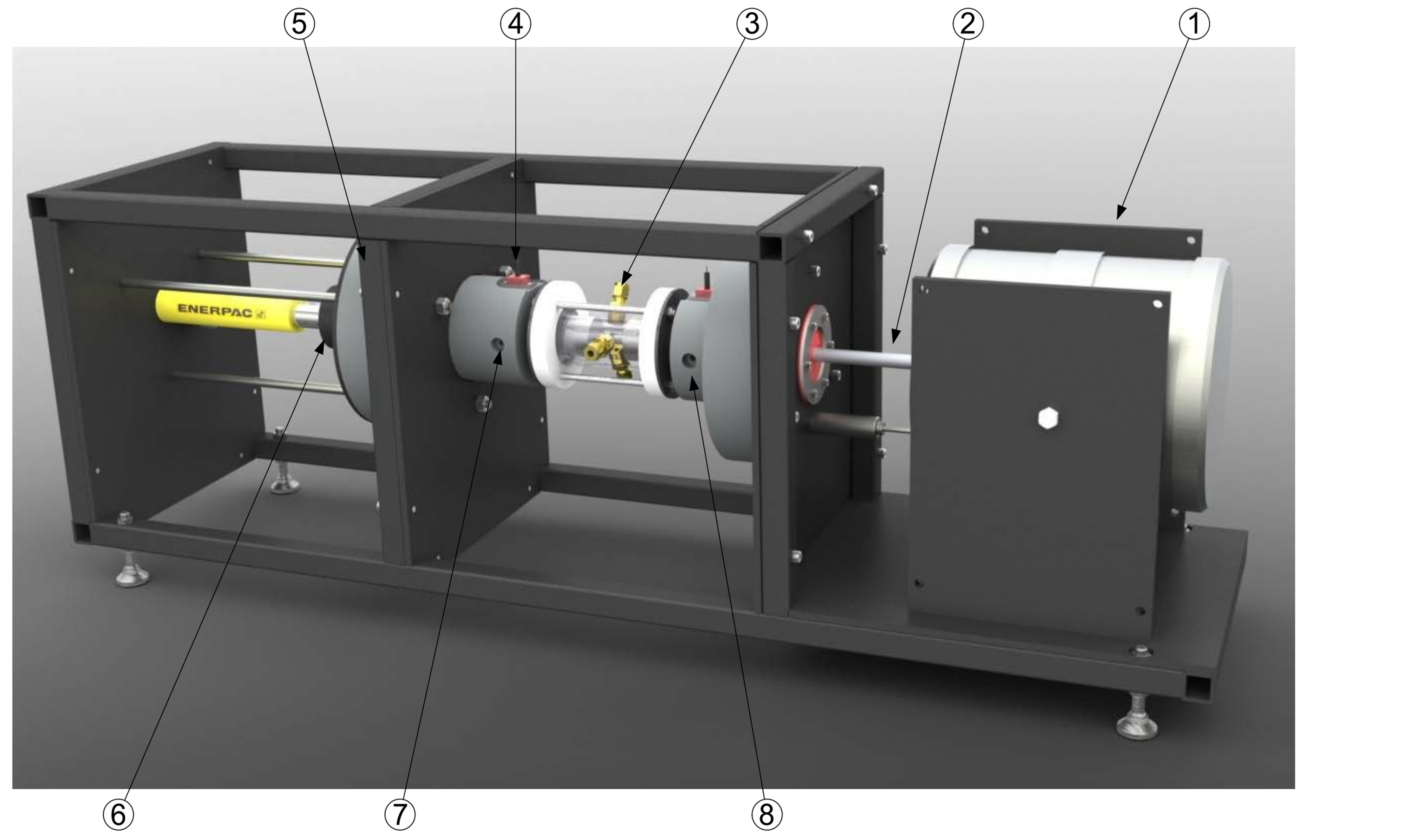




The graphics above show the measured waveforms for two different frequencies. It is clear that the electro-magnetic-drive concept works fairly well at these low frequencies. Both the streaming potential and the dynamic pressure can be measured with acceptable noise levels. The compressive part of each cycle is sinusoidal as expected, whereas the backstroke is slightly distorted due to the inflow for new fluid through the check valve. This slight asymmetry might be corrected by imposing a background DC fluid flow and a back-pressure instead of using check valves. This approach would also remove any risk of fluid cavitation.

It became clear at an early stage that the potential waveform was very sensitive to (a) ambient electrical noise, (b) 60 Hz power-line noise, (c) electrical noise from the shaker, and (d) an antenna effect from the fluid reservoirs. A number of solutions was implemented including earthing one of the fluid reservoirs, adding electrical shielding (Faraday cages) and the development of improved signal conditioning and amplification circuitry as close to the electrodes as possible. The apparatus is being tested with all these modifications.

### Experimental apparatus for rock

Another experimental apparatus has been designed and constructed to allow AC electro-kinetic measurements to be made upon rock. The sample is placed in a deformable rubber sleeve and subjected to a radial confining pressure of compressed nitrogen up to 4.5 MPa. The sample is held between two stainless steel supports (Figure 5 (6)). Axially, an hydraulic cylinder (8) imposes a pressure on the sample and a piston (2) applies a pressure on the fluid with a rubber seal or a rubber membrane . The output end (9) is connected directly to the output fluid reservoir. The shaker drives the piston directly along the axis of the sample cell. Non-polarising Ag/AgCl electrodes are used. Their signals were conditioned and amplified using noise-rejection circuitry (Figure 4b). The AC pressure is measured using dynamic pressure transducers. An LVDT has also been incorporated in the experimental apparatus in order that the precise position of the piston may be monitored with the potential and pressure signals.




1. Precision shaker
2. Piston
3. Sample Support with confining port
4. Streaming potential electrodes
5. Hydraulic cylinder
6. Fluid output port
7. Output pressure transducer
8. Input pressure transducer and fluid port

Figure 5: A conceptual electromagnetic drive AC electro-kinetic cell for a rock

## Conclusion

In summary, this research proposed four different approaches to the design of an experimental apparatus for measuring the time-dependent streaming potential coupling coefficient of porous and granular media. There are fundamental or practical limitations to two of them. The most promising approach was that of using an electro-magnetic drive. The electro-magnetic drive approach has been tested by creating test apparatuses. Results from these apparatuses have shown that it is possible to measure the time-dependent streaming potential coupling coefficient of porous and granular media.

## Acknowledgments

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