# Density measurement of abrasive slurries

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## The need for slurry density measurement

Abrasive slurries are all around us. These watery mixtures of insoluble matter consisting of hard, abrasive particles are present in applications such as dredging, offshore, well-servicing industry, metal & mineral mining, maritime, cement, power and tunnel construction. For example, in dredging, underwater deposits are excavated and the slurry is transported to another place, whereas in building construction, cement can be transported as a slurry through a pipeline.

To monitor the productivity in these application areas, defined as the amount of material pumped per unit time (in kg/s or ton/s), it is essential to know the slurry density (in kg/$m^3$ or ton/$m^3$) together with the flow rate (in $m^3$/s) or flow velocity (in m/s) of the slurry through the slurry pipeline. Furthermore, density measurement is necessary for quality control purposes, to monitor the process consistency over time. Moreover, such measurements are necessary in preventing the pipe from becoming clogged due to 'too dense' slurries.

In order to be able to adjust the process, from an economical point of view it is desirable to have the slurry density available in real time or near-real time, i.e. within a few seconds after the measurement.

Abrasive slurries deviate in at least two ways from 'average' slurries. Their most striking characteristic is the presence of abrasive particles, which necessitates the use of wear resistant materials for the part of the measurement device that gets in contact with the slurry, or the use of the measurement device outside the process. Furthermore, the density of these slurries is usually high, up to 3 ton/$m^3$. These 'dense materials' will put constraints to measurement types that rely on easily penetration of slurries.

## Ways to conduct abrasive slurry density measurements

Density measurement of flowing (abrasive) slurries is based on physical processes such as absorption of radioactive radiation, reflection of (ultra)sound waves or direct (gravitational) mass/volume measurement with respect to the slurry. Some of the used techniques are discussed here briefly.

### Nuclear measurement

In radioactive slurry density measurements, a gamma radiation source (e.g. from Cs-137 isotope) is present on the outside wall of the slurry pipe, and a gamma radiation sensing scintillation or

Geiger-Müller detector is also present on the outside wall, at the opposite side of the radiation source.

Gamma radiation is sent through the slurry pipe. Part of the radiation is absorbed by the pipe walls and by the slurry flowing through the pipe, before it enters the detector. The higher the slurry density, the lower the remaining gamma radiation measured at the detector will be. The schematic principle is shown in Figure 1.a.

*Principle*: gamma radiation absorption
*Market penetration:* high
*Limitations*: reduced accuracy in large pipe diameters and high slurry densities; these conditions may lead to radiation sensing that is in the order of magnitude of background radiation level
*Pros*: as measurement is conducted at the outside of the pipe, installing of the setup will not interfere with production loss to a large extent, and the measurement will not be subjected to wear
*Cons*: legislation constraints working with radioactive technology, i.e. maximum radiation levels, people have to be skilled/trained in this technology, radiation sources are difficult to transport, high and uncertain costs for removal of the old source over time

### Ultrasonic measurement

Bats and car parking sensors use ultrasound - sound just beyond what can be heard by the human ear - to detect objects or obstacles in their neighborhood. In a similar way, in ultrasonic density measurements a transducer made of a piezo-sensitive material sends ultrasonic pulses into the to-be-measured slurry, and a computer analyses the returned echoes.

At the interface between the transducer and the slurry, the pulse is partly reflected and the remaining part enters the slurry. The reflected ultrasound can be converted to what is called the 'acoustic impedance' of the slurry - some kind of resistance for the sound propagation through the slurry. What's more, a 'mirror' which is positioned somewhere in the slurry at a known distance reflects the ultrasound that has entered the slurry back to the transducer, revealing the speed of (ultra)sound in the slurry. So the first 'echo' leads to the acoustic impedance, and the second echo results in the speed of sound. The ratio of this acoustic impedance and the speed of sound equals the density of the slurry. The schematic principle is shown in Figure 1.b.

*Principle*: reflection and transmittance of (ultra)sound waves
*Market penetration:* runner up, mainly in mining, less in dredging
*Limitations*: difficult measurement at large pipe diameters
*Pros*: small measurement device, low wear
*Cons*: constraints to slurry homogeneity, i.e. difficulties with gases/air inclusions, large particles/rocks in the slurry, high-density sediment at bottom part of pipe.

Measurement using acoustic waves

In this method for density measurement, a transducer is mounted at the outside of the slurry pipe. The actuator part of this transducer impacts the outside wall of the pipe with a certain force for a certain period of time, applying this force perpendicular to the flow in the slurry pipe. This creates vibrations at the pipe wall and in the slurry inside the pipe. The sensor part of the transducer, which is an accelerometer positioned near the actuator, receives these responding vibrations. Making use of Newton's second law of motion, the ratio of the applied force and the resulting acceleration reveals the (slurry) mass, and dividing by the relevant slurry volume gives its density. The schematic principle is shown in Figure 1.c.

*Principle*: applying force and measuring acceleration
*Market penetration:* runner up, mainly in mining, less in dredging
*Limitations*: to be used for slurries and loose solids
*Pros*: simple setup at outside of slurry pipe, installing will not interfere with production loss to a large extent
*Cons*: vibration need to be set in advance; constraints with respect to gaseous compounds

Coriolis principle

An actuator exerts a force to a flexible slurry pipe, perpendicular to the direction of flow, causing it to vibrate at its natural frequency. This frequency is a direct measure of the density of the slurry. A water-filled pipe vibrates at a higher frequency than a pipe filled with slurry and with a higher density.

This method is also suitable for measuring mass flow. Two sensors, each at one end of the pipe, measure the deflection of the pipe. If the pipe is empty, or if the slurry doesn't flow, then both sensors measure the same signal. However, if there is a flow through the pipe, then the inertia of the slurry causes the flexible pipe to twist, so that the entry and exit of the pipe are no longer synchronous and therefore out of phase. The phase difference is a direct measure of the mass flow through the pipe.
The schematic principle is shown in Figure 1.d.

*Principle*: density proportional to natural frequency of liquid/slurry pipe
*Market penetration:* mainly for liquids and gases
*Limitations*: abrasive fluids will erode thin flexible pipe walls easily
*Pros*: direct density measurement; simultaneous measurement of mass flow rate and density
*Cons*: the larger the pipe diameter, the more expensive the equipment will be

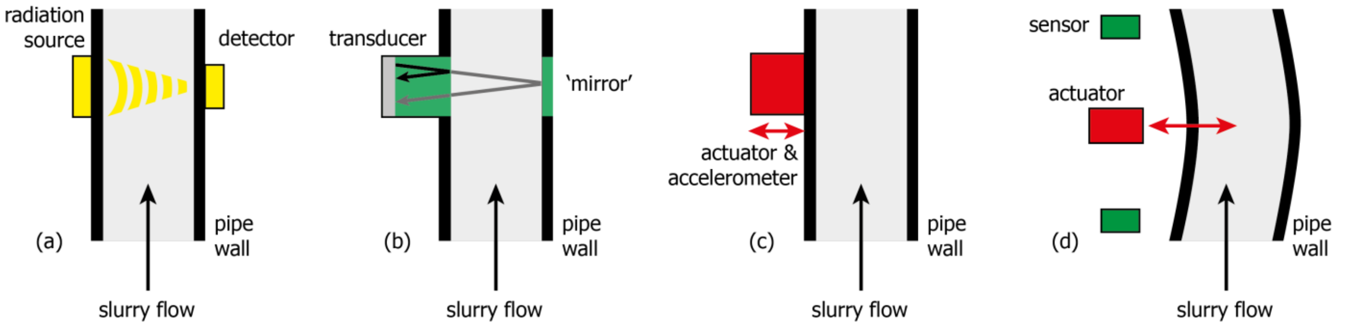

Figure 1: Schematic principles of some slurry density measurements: (a) nuclear; (b) ultrasonic; (c) acoustic wave; (d) coriolis.

## Alia Density Meter

### General working principle

The Alia Density Meter is positioned in-line in the slurry pipeline. The density, defined as the slurry mass per volume unit, is measured under dynamic conditions, i.e. when the slurry is flowing, but can also be measured for non-flowing, stationary fluids.

Figure 2: Alia Density Meter mounted in slurry pipe

Inside the density meter, an actuator exerts a force with a known value and frequency onto the slurry, while an accelerometer measures its resulting acceleration. Newton's second law of motion F = m x a, which relates the force F to the acceleration a via the mass m, is utilized to determine the mass of the slurry. The slurry volume is a known factor in the measuring tube of the meter. This means that the slurry density, i.e. the mass per volume unit, is nearly immediate and accurate, regardless of pipe diameter or slurry composition.

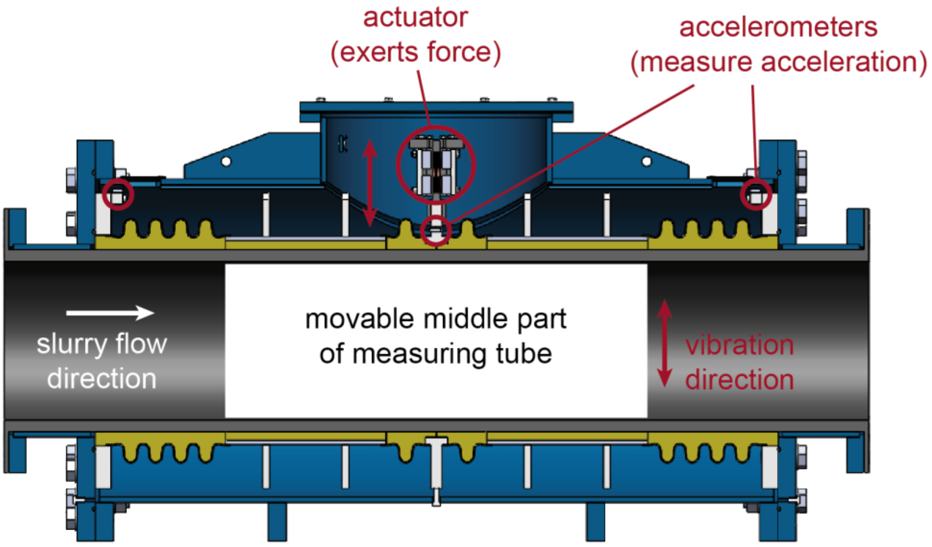

Figure 3: Cross-section of the Alia Density Meter

## Description of the Alia Density Meter

The central part of the density meter is the measuring tube through which the slurry flows. This tube consists of an outer part made of metal, giving stiffness to the tube, an intermediate part of polyurethane, and a straight inner part made of (natural or EPDM) rubber, giving flexibility to the tube. This rubber part gets in contact with the flowing slurry. To minimize the influence of the measurement on the slurry flow, the inner diameter of the density meter equals the inner diameter of the application's slurry pipe. The housing of the density meter is made of stainless steel.

At the outer ends, near the position where the density meter is connected to the slurry pipe, the metal outer part of the measuring tube consists of bellows, allowing the middle part of the measuring tube to move in one lateral direction. Movement in perpendicular direction is prevented by the construction of the measurement device.

The actuator, consisting of a copper electrical coil surrounded by a permanent magnet package, exerts a force onto the measuring tube. This force has a typical value of several tens to several hundreds of Newtons, and a frequency between 30 and 180 Hz, usually at a frequency of 50 to 60 Hz. This force allows the middle part of the measuring tube to vibrate in the direction perpendicular to the slurry flow, with a hardly noticeable amplitude in the sub-millimeter range. The central accelerometer, which is positioned at the radial outer part in the middle of the measuring tube, measures the resulting acceleration of the measuring tube with the slurry flowing through.

In addition to the central accelerometer, two accelerometers are positioned near the outer ends ('left' and 'right') of the measuring tube. Besides measuring the position, velocity and acceleration at positions just adjacent to the movable middle part of the measuring tube, they also generate input to compensate for external influences to the measurement.

## Mechanical model

As a first approach, Newton's universal second law of motion F = m x a applies to each mass, including the measuring tube with the slurry inside. The actuator exerts the force F onto the measuring tube, the (central) accelerometer measures its resulting acceleration a, and the mass m is calculated as the ratio of both.

When corrected for the mass of the measuring tube itself, the mass of the relevant slurry inside this tube is known. Dividing this mass by the inner volume of the movable part of the measuring tube yields the density of the flowing slurry inside the measuring tube. (Pre-)calibration of the density meter is necessary in order to fit process parameters to the slurry density.

However, we need to do some adaptation to this simple model. The measuring tube is not an isolated 'stand alone' system, and indeed is connected to the rest of the world: via the bellows, the measuring tube is suspended inside the density meter.

Figure 4 shows the mechanical model of the suspended measuring tube including slurry flowing through, with mass $m_1$ and (center of mass) position $x_1$. L(eft) and R(ight) suspension consists of two springs with stiffness $k_L$ or $k_R$, and damping $d_L$ or $d_R$.

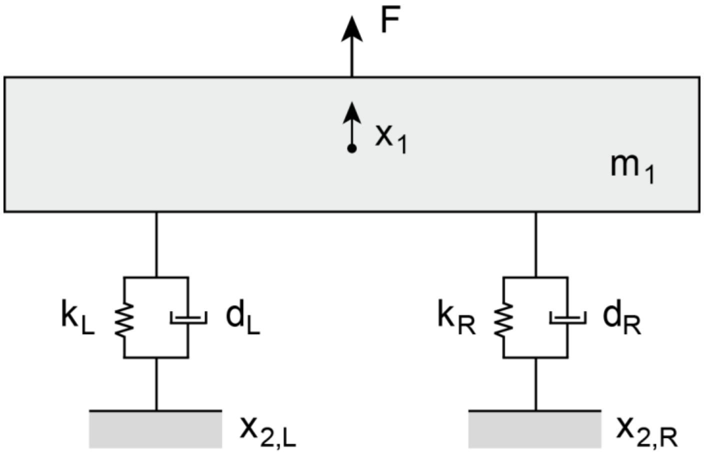

Figure 4: Alia Density Meter mechanical model

Based on the exerted force F and the measured acceleration a, now re-written as $x''_1$ (the second derivative of the position with respect to time), the mass $m_1$ of the movable part of the measuring tube including the slurry can be calculated. The equation of motion for this configuration is now:

$$m_1 x''_1 = F - k_L(x_1 - x_{2,L}) - k_R(x_1 - x_{2,R}) - d_L(x'_1 - x'_{2,L}) - d_R(x'_1 - x'_{2,R}) \qquad \text{[eq. 1]}$$

Where the terms at the right side of F comprise the adaptation of the 'simple model' due to the suspension of the tube.

In order to calculate the mass, the stiffness and damping values need to be known. As these values vary with temperature and pressure, these parameters are continuously updated, i.e. based on the exerted force and the measured acceleration. The mass, stiffness and damping values are jointly calculated.
When vibrating the measurement tube in the way as described here using the actuator, the tube will resonate around its natural frequency which has a typical value of approx. 60 Hz. However, to identify the entire system including the stiffness and damping parameters, a wide frequency range around the natural frequency needs to be taken into account. More specifically, as can be seen in Figure 5:

- at frequencies below the natural frequency, the frequency response as measured by the central accelerometer is mainly determined by the stiffness of the system;

- around the natural frequency, the measured frequency response is mainly determined by the damping;

- at frequencies above the natural frequency, the frequency response is mainly determined by the mass.

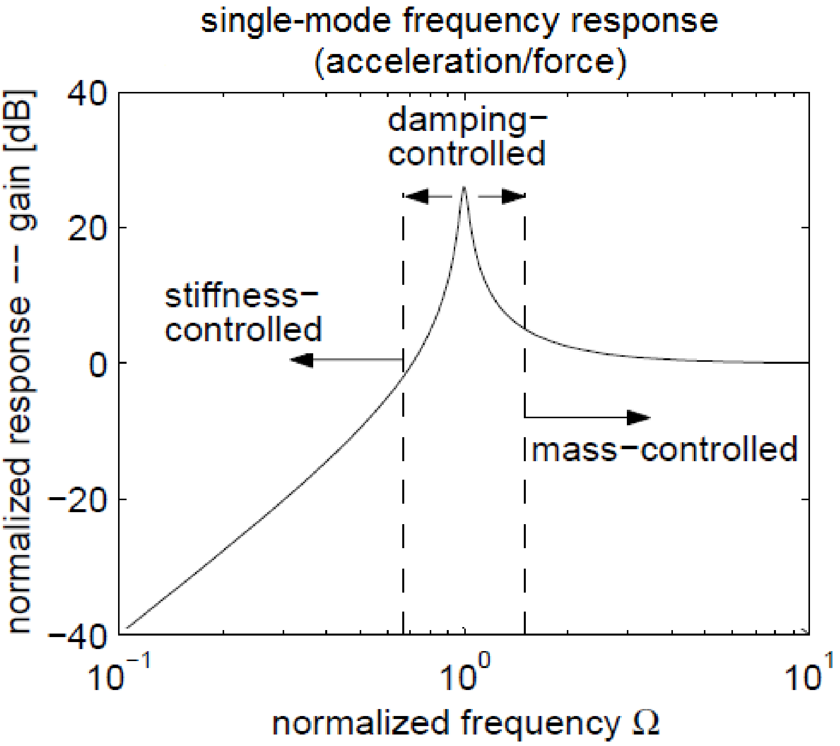

Figure 5: Frequency response over a wide frequency range

Note that the model on which the calculations are based does not involve any knowledge of the environment of the Alia Density Meter, other than the acceleration measured at the suspension points. This implies that the density calculation is in principle not affected by any constraints with respect to the surroundings in which the Alia Density Meter is installed, including temperature variations and the installation angle. This means:

- External vibrations and disturbances, for example due to other machines or components in a plant or ship, will not interfere with the measurement. These vibrations - if any - will be measured by the left and right accelerometers as long as the acceleration levels remain within the accelerometers' range, and will be compensated for in the mass calculation algorithms. Moreover, active damping will suppress the influence of external vibrations even more.

- In principle, the measurement is independent of the support or suspension of the entire density meter.

In conclusion, limitations of other slurry density measurement techniques can be overcome by using the Alia Density Meter with Newton’s universal second law of motion principle. This device measures the slurry density in near real-time, independent of external process conditions, also independent of the slurry composition, and for any size of slurry pipe. With the exception of the rubber inner part of the measuring tube, which is a wear part, the Alia Density Meter is virtually maintenance-free due to its simple setup and the robust materials it is made of. This makes this density meter ideal for challenging conditions, including slurries that contain rocks & stones and gasses that are present in various applications.