Challenges of implementing a reliable and accurate non-intrusive ultrasonic flow measurement on penstocks at large-scale hydroelectric power plants

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Introduction

Flow measurements of penstocks are used to monitor turbine efficiency, ensure velocity thresholds are not exceeded, and to detect leaks at an early stage. Clamp-on ultrasonic flow meters are an established non-intrusive technology and can be employed on nearly all pipes and for all media; from the smallest hydraulic pipes to large gas transportation lines.

There are several factors unique to large penstocks that make clamp-on ultrasonic flow measurements especially challenging. In no other industry does one encounter pipes of several meters in diameter. The large pipe sizes combined with often extremely high flow velocities can lead to an effect known as “beam blow” of the ultrasonic signal. Pipe vibration and large ambient temperature fluctuations at hydropower plants are further aspects that need consideration when employing clamp-on ultrasonic flow meters.

It will be explained, based on several successful international projects, how the unique technical challenges encountered can be solved when monitoring the flow of penstocks at large-scale hydroelectric power plants (HPP). It will furthermore be detailed how the correctness of the clamp-on ultrasonic flow measurements can be verified in the field and how the long-term stability of the measurement ensured.

1. Principle of measurement

Most of the Ultrasonic Clamp on flow meters in industrial applications utilize transit time technology. Experiences and challenges examined in this paper are limited to the transit time technology.

1.1 Meter Formula

The transit time ultrasonic flow meter measures the transit times t_{up} and t_{down} of an ultrasonic signal travelling upstream and downstream respectively. The difference Δt between the transit times is directly proportional to the mean flow velocity v_l on the sound path.

$$v_l = K_\alpha \frac{\Delta t}{2 t_{fl}} \quad (1)$$

K_α is the acoustical calibration factor and t_{fl} is the transit time within the fluid. The volume flow Q is the average flow velocity v_A over the cross section of the pipe multiplied by the area A of the cross section.

$$Q = v_A \cdot A \quad (2)$$

Fig. 1 Ultrasonic Clamp-On Measurement

If the flow profile v is known, the area average v_A of the flow velocity can be calculated from the path velocity v_l measured by the flow meter. The meter calculates the fluid mechanic calibration factor K_{re}.

$$K_{re} = \frac{v_A}{v_l} \quad (3)$$

Thus, the meter formula is

$$Q = K_{\mathrm{Re}} \cdot A \cdot K_\alpha \frac{\Delta t}{2t_{fl}} \quad (4)$$

The meter assumes the flow profile to be fully developed. This requires a sufficiently long distance of the measurement location from disturbances like bends and T-branches. In that case the fluid mechanic calibration factor K_{re} depends on the kinematic viscosity of the fluid and the roughness of the pipe wall only.

If the flow profile cannot be assumed to be fully developed, a deviation of the fluid mechanic calibration factor K_{re} has to be applied.

1.2 Path Configurations

The fact that the flow profile is not always ideal is often addressed by using multiple sound paths. Fig. 2 shows a reflecting configuration in two planes. The advantage of a reflecting path is that non-axial flow components are compensated for. This is because the effect of the non-axial component (cross flow) on the two components of the reflecting path is the same in magnitude but opposite in sign. The use of sound paths in two planes reduces the impact of non-symmetry in the flow profiles caused by disturbances like bends or t-branches.

It is not always possible to use reflecting paths. In such cases the compensation for cross flow can be achieved by using two direct paths as shown in Fig. 3.

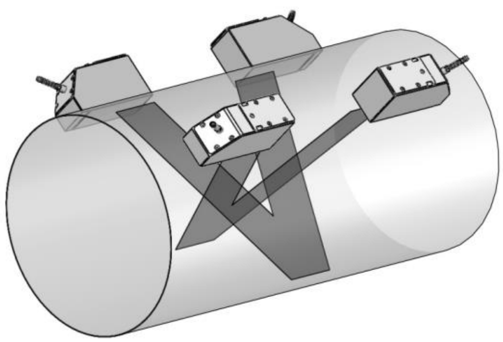

Fig. 2 - Reflecting Paths in Two Planes

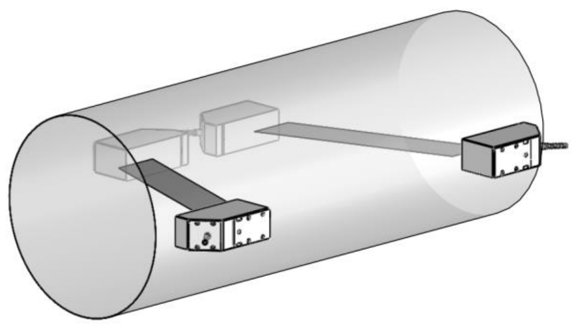

Fig. 3 - Two Direct Paths

1.3 Sound Transmission

The clamp on technology requires that a sufficient amount of the sound energy can be transmitted from the transducer on the outside via the pipe wall into the flowing fluid. The angles under which the sound waves propagate through the pipe wall and the fluid are given by Snell's law as expressed by formula (5).

$$\frac{\sin\alpha}{c_\alpha} = \frac{\sin\beta}{c_\beta} = \frac{\sin\gamma}{c_\gamma} = K_a \quad (5)$$

The acoustic calibration factor K_a is a parameter of the transducers that can be calculated from the angle α and the sound speed c_α in the coupling wedge. The propagation angles β and γ in the pipe wall and the fluid are given by Snells law (5).

Two different modes of propagation are used with clamp-on measurement on steel pipes, the shear or transversal mode and the Lamb mode. The advantage of the shear waves is that the sound absorption within the pipe wall is negligible and nearly independent of the transducer frequency. So, there is practically no upper limit in pipe wall thickness and the choice of the transducer frequency is not restricted by the pipe wall. This makes them suitable for a broad variety of applications. Shear wave transducers are usually used for almost all liquid application and typically high-pressure gas measurements with thick pipe walls as shown in Fig. 5. Lamb waves travel in parallel to the pipe wall boundary thereby producing a broad sound beam within the fluid. The effect can be seen as an impedance transformation reducing the strong mismatch between the high density pipe wall and the low density media thus increasing the efficiency of the sound transmission through the pipe wall as shown in Fig. 4. However, the frequency needs to be matched to the pipe wall thickness.

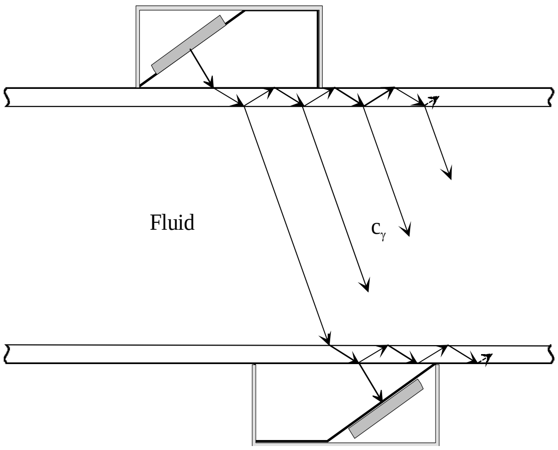

Fig. 5 - Shear Wave Transducers

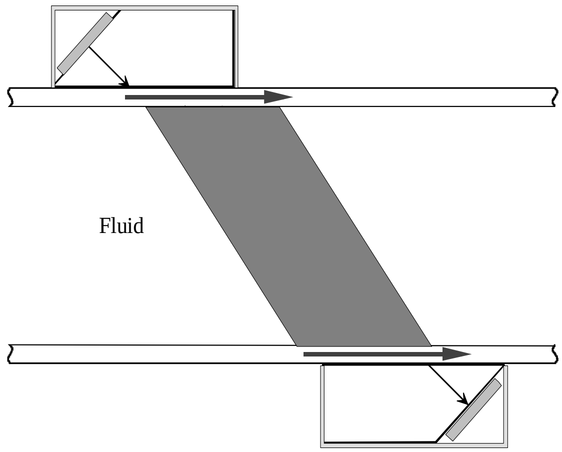

Fig. 4 - Lamb Wave Transducers

2. Challenges of implementing a non-intrusive ultrasonic flow measurement on penstocks at large-scale hydroelectric power plants

Following it will be explained, which challenges occur implementing clamp-on ultrasonic flow measurements based on the transit time technology. In this paper it will be focused on three different main challenges. The selection is based on the experience of the company FLEXIM GmbH and their engineers. It is not an all-embracing listing.

2.1 Selection of the transducers

Penstocks of large-scale hydroelectric power plants usually present pipes with outer diameters from 1000mm up to several meters. The flow velocities varying from plant to plant. Anyway, it can be recognized, that the water running through a penstock is flowing usually with several meters per second.
The combination of pipes with large outer diameter and high flow velocities are unique compared to other water applications in other industries, e.g. water and waste water, thermal power generation and processing plants.

Transit time flow measurement relies on contra-propagating transmission of sound bursts between pairs of transducers situated diagonally across the pipe (section 1). The upstream signal is delayed, and the downstream signal is speeded up by the moving fluid. The ultrasonic beam is shifted accordingly. Every transducer frequency and type is restricted to a specific outer pipe diameter range and related maximum flow velocity. In case the actual flow velocity is exceeding the maximum flow velocity of a transducer pair, the ultrasonic beam shift is bigger than it is acceptable for proper operation. This effect can be called “beam blow”. Considering the combination of large outer diameter and relatively high flow velocities this can get a challenge on penstocks of HPP.

The two methods of sound propagations (section 1.3) are having different restrictions regarding the maximum flow velocity at the same pipe geometry. The experience of FLEXIM showed, that on penstocks with outer diameters of several meters lamb wave transducer might be less affected by “beam blow” due to their higher maximum flow velocity limit. The pipe wall thickness influences the choice of the transducer frequency and type of sound propagation strongly. Lamb wave transducers are just applicable on metal pipes.
Considering both methods of sound propagation seems to lead to good results for this application. Evaluation of a fitting transducer can be done by testing or calculation. Commonly clamp-on ultrasonic manufacturer provide software for transducer selection and their restrictions based on applications information.

2.2 Mounting and coupling of the transducers

Mounting the transducers on the penstocks can be done in different ways (fig. 6), e.g. with magnetic mounting assembly, straps, glued or welded. In any case the correct alignment of the transducers must be ensured for reliable measurement. Especially for permanent measurements the installations should be tamper-proof.

The acoustic coupling between the transducers and the pipe wall is typically realized by semi liquid couplants (grease, paste) or durable elastic coupling foils. The coupling material fills the always existing gap between the transducer and the pipe wall and compensates the roughness of the outer surface of the pipe. The coupling of the transducers to the pipe is influencing the measurement quality immense. Poor coupling can lead to unreliable and instable measurement. Considering most of the permanent installations are outside, the equipment including mounting as well as the coupling must withstand ambient conditions like weather.
From experience of FLEXIM dry coupling leads to reliable and long-term stable coupling on penstocks influenced by ambient. ASME is also recommending dry coupling in their standard MFC-5.1-2011 and in addition describing, that negative effects by pipe vibration can be reduced with dry coupling [1].

Next to the long-term stability, dry coupling is also maintenance friendly in comparison to coupling with gel or grease, which must be renewed after a specific period due to drying or washing out.

Fig. 6 – Example of a non-intrusive ultrasonic flow measurement installation by FLEXIM on a penstock of a pumped storage plant, 2-channel with 1 sound path each

2.3 Temperature fluctuations

Usually the penstocks of large-scale hydroelectric power plants are directly influenced by the local ambient conditions. With changing ambient conditions, temperature fluctuations might occur, effecting the penstock structure as well as the ultrasonic clamp-on flow measurement. Typically, those temperature fluctuations are occurring along the day and night.
A change of the fluid, transducer or pipe temperature causes different changes in the acoustic measuring setup. These include changes of the fluid properties and of the acoustic properties of the transducers.

Sound speed and viscosity of the fluid change with temperature and can thus cause measurement errors. The transit times of the acoustic signals change with the sound speed. A changed viscosity results in a change of the Reynolds number (Re) and thus possibly of the flow profile.

FLUXUS flowmeters determine the sound speed in every single measurement. Thus, any influences of a changed sound speed on the measurement error are automatically compensated.
Like all other fluid data, the function of viscosity depending on related to a specific temperature can be is stored in the transmitter and is used for calculating the Reynolds number according to the viscosity based on fluid temperature measurement.

The bigger temperature-related influence on the measurement error is caused by changed acoustic properties of the transducer materials (section 1.3). It depends on the transducer type and material and corresponds to approx. 1 % per 10 K, thus being more than 50 times greater than other influence factors.
FLUXUS flowmeters therefore use a model-related compensation method based on the measured transducer temperatures according to ASME [1]. Each transducer is equipped with a temperature probe measuring continuously the transducer temperature.

Field experience from a pumped storage hydroelectric power plant showed high stability of zero flow, even though the two transducers of the transducer pair had different temperatures. One transducer was exposed to direct sunlight the other not (fig. 6).

3. Diagnosis and Signal Evaluation

3.1 Meter operation

A block diagram of a digital ultrasonic clamp on flow meter is shown in Figure 7.

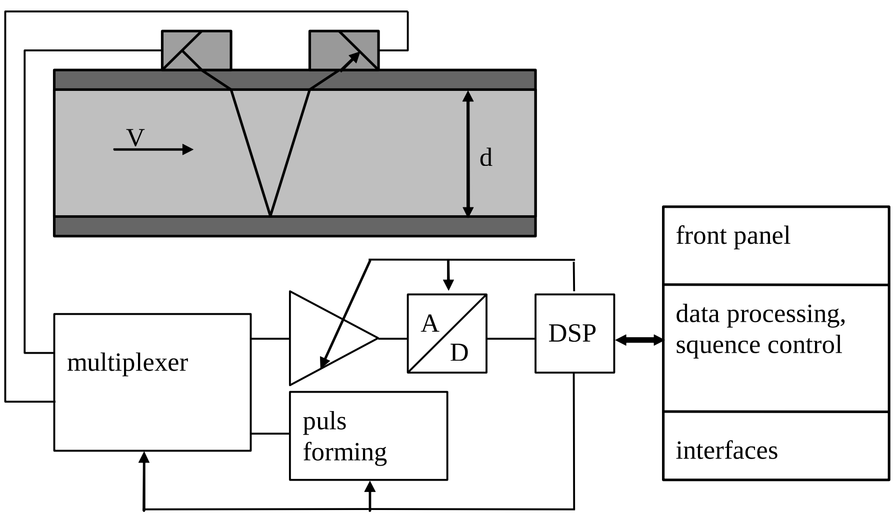

Figure 7 Typical hardware of an ultrasonic clamp on flow meter

The signal amplifier and the pulse forming are connected to the transducers via the multiplexer. The signal processing required to measure the transit time and transit time differences is performed by a fast Digital Signal Processor (DSP). The time difference is often measured by calculating the cross-correlation function of the upstream and downstream signal. Another processor performs the data processing and controls the interfaces. The whole meter operation is based on fully digitized ultrasonic signals. Therefore, the sample signals can be processed further to obtain additional diagnostic information about the measurement process and its reliability. This makes it possible to assess the quality of the installation and to monitor the efficiency of measures taken to improve the signal quality, such as the generally required installation of pipe noise suppressors or the selection of the optimal transducer. As the processing of diagnostic parameters is fully integrated in the signal processing an ultrasonic clamp on meter inherently offers self-diagnosis possibilities which are available online.

3.2 Plausibility check

After installation of an ultrasonic clamp-on flow meter the measurement is supposed to be checked for plausibility prior to further evaluation. Therefore, the fact can be used, that every fluid is having a specific speed of sound at a certain temperature. Considering the application, we can define, that the media is water.
The FLUXUS flowmeter measures the actual speed of sound of the water. The measured speed of sound can be compared to the specific speed of sound of water at the according temperature. In case of a significant deviation the measurement cannot be plausible. The fluid and its temperature must be known for this check.

3.3 Evaluation of ultrasonic signals

Figure 8 shows the typical signals received by an ultrasonic clamp on meter for both upstream and downstream propagation direction. The signal shape of both signals is practically the same. Easy to identify is the characteristic transit time difference.

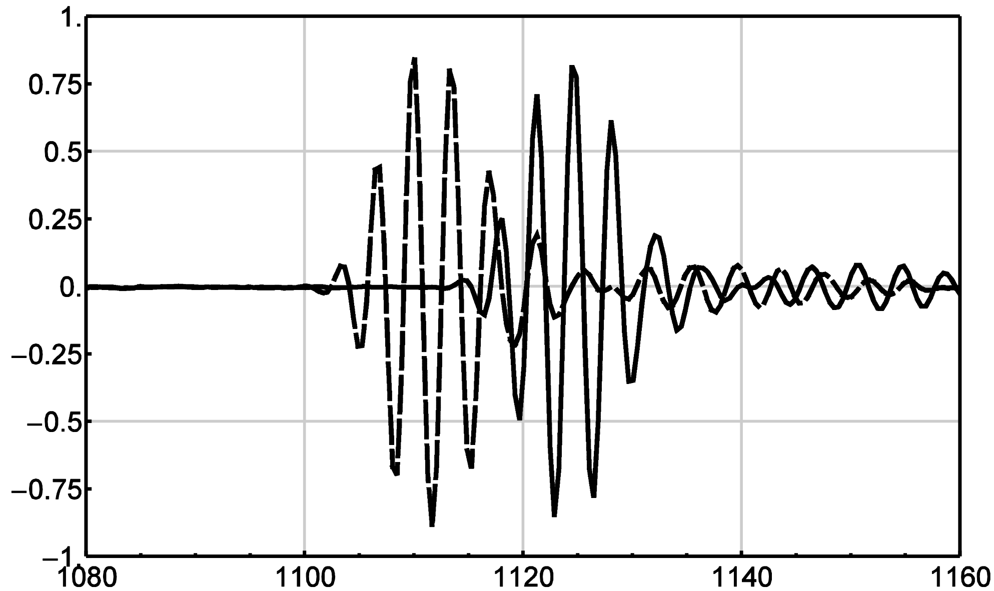

Figure 8 Typical pair of ultrasonic signals

3.3.1 Signal amplitude

One basic requirement of a reliable signal processing and stable transit time difference measurement is a save signal detection. This requires a sufficient signal to noise ratio and accordingly a sufficient signal amplitude.
Ultrasonic clamp on systems make use of variable gain amplifiers to achieve an optimal signal level for the subsequent signal processing by amplifying the received signals. Practically the maximum gain is limited by the inherent noise of the amplifier. As a result, the attenuation of the ultrasonic signal cannot be fully compensated. The most important primary measured values of an ultrasonic flow meter are the transit time and the transit time difference which are not influenced by the actual gain. The transit time is not changed by a pure amplification. Only the amplitude is changed. If the maximum gain is insufficient the measurement will fail because the ultrasonic signal cannot be detected anymore.
The difference between the actual gain and the maximum gain can be considered as a reserve for more attenuation of the signal which is available for the application until the measurement falls off in quality or in extreme cases its failure has to be taken into account. If a sufficient reserve is available, the meters works save and reliable. The operational reserve increases with signal amplitude.

3.3.2 Noise

One of the most important questions in reliable operation of meters is their sensitivity to disturbances especially noise. The inherent diagnostic possibilities of ultrasonic clamp on meters allow a very detailed evaluation of the influence of several kinds of noise to the measurement result.
Noise that superposes the ultrasonic signal can influence the ultrasonic flow measurement. The influence on the measurement result differs with the nature of noise. Therefore, a difference is made between noise which has a strong well-defined relation to measurement process, the so-called correlated noise and noise that has no relation to measurement process, the so-called uncorrelated or random noise.

3.3.2.1 Correlated Noise

Correlated noise of ultrasonic clamp on flow meters is usually directly connected to the transmission pulse of the emitting transducer. It is independent of the flow velocity of the fluid.

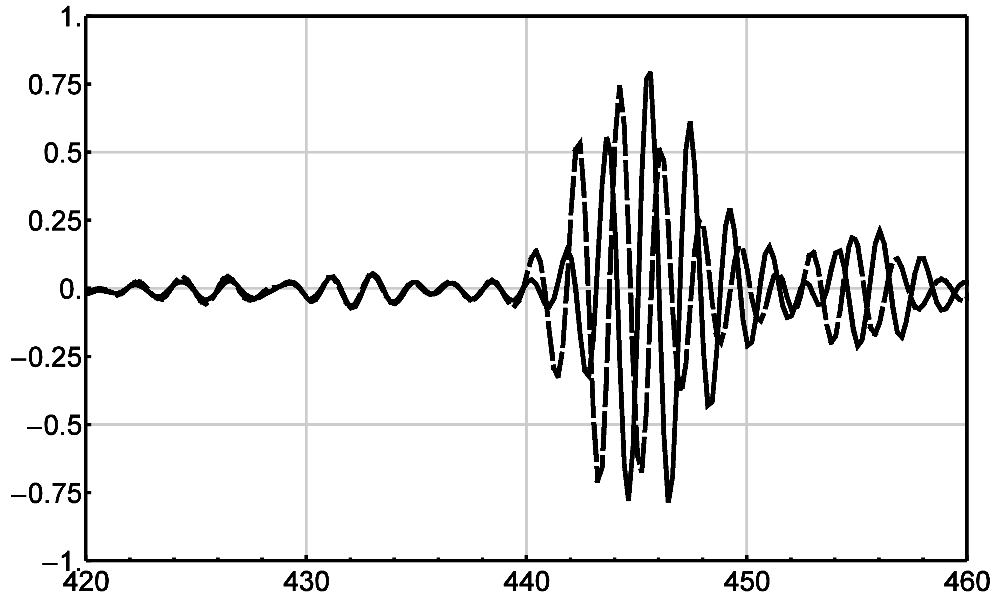

Figure 9 Typical received signal with correlated noise

Figure 9 shows an example of a pair of ultrasonic signals that are superposed by a correlated noise signal. Clearly visibly are the upstream and downstream signals similar to Figure 8. In addition a part of the signal can be seen that is the same for both propagation directions and which does not show any time difference. This part has not passed the fluid. The received signal consists of two parts, the fluid signals that pass the fluid and show a time difference and a disturbing noise signal that has not passed the fluid. As both fluid signals have slightly different transit times different parts of the noise signal superposes on the equivalent parts of the fluid signals. As a result, the fluid signals are distorted in a slightly different way which yields a slight change in the time difference of the detected signals in comparison to the undisturbed signals. For this reason a slight deviation in the measurement result occurs.
The measurement deviation depends on the amplitude of the correlated noise signal and the time delay between noise signal and fluid signal. As the transit time of the fluid signal depends on the speed of sound of the fluid which changes randomly between different measurement cycles the time delay between noise and fluid signal cannot be predicted. This yields a random uncertainty of the flow measurement result due to correlated noise signals.
The maximum measurement error can be estimated considering the application dependent relation between the fluid signals and the noise signal. Thereto the power of the fluid signals relative to the power of the noise signals is measured. For that purpose, the meters signal processing is expanded by an additional diagnostic algorithm. The resulting characteristic value is called ScNR -signal to correlated noise ratio- equivalent to the well know definition of the signal to noise ratio.

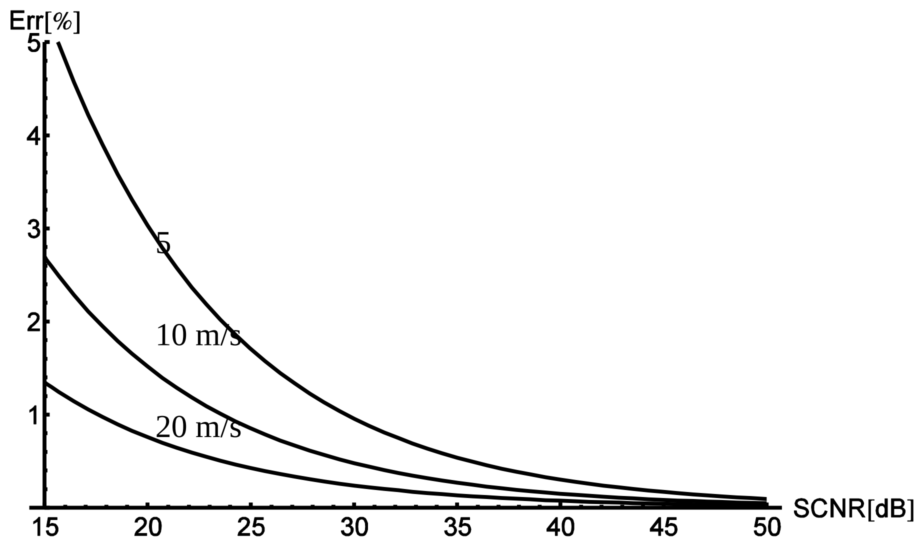

Figure 10 Estimation of the expected maximum measurement error depending on the ScNR

As the ScNR depends on the actual installation, the expected maxim measurement error can be calculated only for certain measurement condition where the ScNR is known. Figure 10 shows an example of the dependency of the expected maximum measurement error on the signal to correlated noise ratio (ScNR) for different flow velocities. The reduction of the maximum measurement error with increasing ScNR is clearly visible. For a reliable and safe measurement, the ScNR should be maximized. The only possible way is usually to reduce the power of the correlated noise signals.

The main source of correlated noise signals of ultrasonic clamp on meters are ultrasonic pulses that propagates on several different ways other than through the liquid from the emitting transducer to the receiving one. These ultrasonic noise signals cannot be reduced by signal processing means and need to be damped. The capability of an ultrasonic meter to calculate the ScNR for each measurement makes it possible to optimize the installation and to observe the measurement quality during the whole operation. Further diagnosis values are existing and used to evaluate measurements.

Most manufacturers providing software for signal evaluation.

Conclusion

Non-intrusive ultrasonic flow measurements on penstocks at large-scale HPP are facing challenges, which differ to other fluid measurement applications. Especially the combination of the large penstock pipes and the high flow velocities of water demand specific consideration to implement a reliable and stable flow measurement.

Transit-time based technology can utilise two modes of sound propagation: shear wave and lamb wave. Each method is having its own advantages and limits. Considering both types of sound propagation can be recommended for successful implementation of clamp-on ultrasonic flow measurement.

The coupling of the transducers to the pipe wall is influencing the measurement quality. Using dry coupling, for permanent and temporary installations should be considered. Dry coupling ensures long-term good coupling results due to resistance against ambient conditions.

Ambient temperature fluctuations, which are affecting the measurement equipment and measurement as well, are challenging too. ASME standard as well as FLEXIM's experience show, that temperature compensation should be applied to increase stability of the measurement.

Ultrasonic flow measurement equipment provides several parameters, which can be used to evaluate the quality of the implemented measurement. Comparing the measured to the theoretical sound speed of water can be used as first plausibility check. Further the signal amplitude can be evaluated for assessment of the measurement quality. The signal to correlated noise ratio is indicating the robustness of the measurement.

References

[1] **ASME standard MFC-5.1-2011,** Measurement of Liquid Flow in Closed Conduits Using Transit-Time Ultrasonic Flowmeters**,** THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, New York, New York., 2011