TECH BYTES 2023

Hydro Solutions*

A sampling of technical content of interest to our customers in the hydropower sector.

vibro-meter

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TECH BYTES 2023

Tech Bytes is designed to give you just a taste of the high-quality content we publish monthly in the form of case histories, application notes, articles, whitepapers, and more – all designed to deliver the expertise we've accumulated over the last seven decades, allowing you to understand more about machinery monitoring technology, the machines it addresses, and the industries it serves.

You'll find this content – and much more – at
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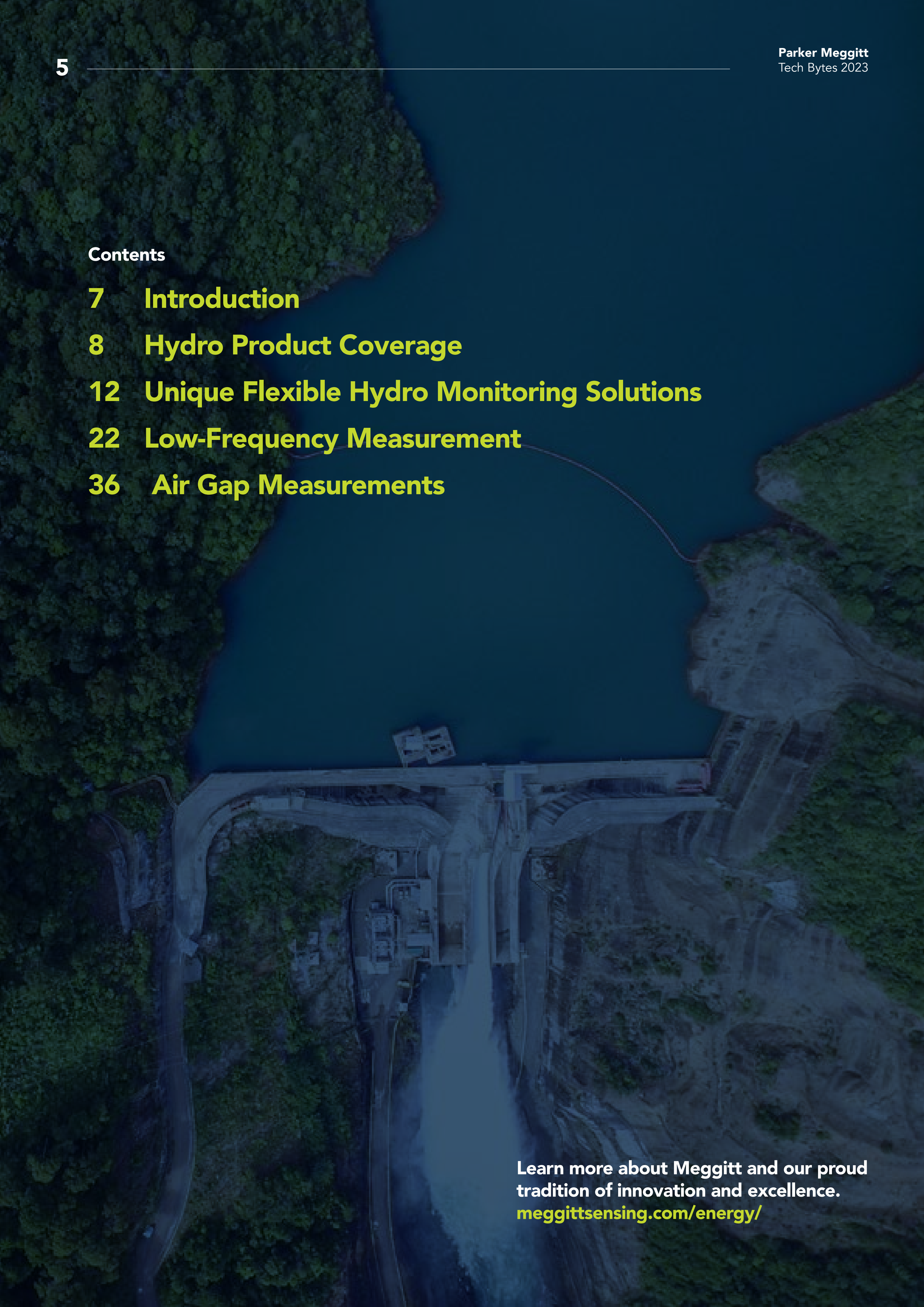

Contents

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Enabling the extraordinary

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Your preferred partner for innovative and high quality monitoring solutions

The Meggitt facility in Fribourg, Switzerland, designs and manufactures complete condition monitoring, vibration monitoring, and measurement solutions for the energy and aerospace industries.

Since its foundation in 1952 as vibro-meter, our products and expertise have enabled superior solutions for the sensing and monitoring of vibration, pressure, air gap and other essential parameters in critical plants and equipment. Today, our solutions are trusted by major OEMs globally and have become standard-fit components on machinery used in Power Generation, Oil & Gas and other industrial applications.

Hydro product coverage

Corresponding Measurements \ Malfunctions	Mechanical, Electrical or Hydraulic Unbalance	Rough Load Zone	Shear Pin Failure	Misalignment	Cavitation	Rotor Rim Movement	Stator Winding Vibration	Stator Core Shift	Uneven Air Gap
Guide Bearing Vibration (Runout)	*	*	*	*					
Thrust Bearing Oil Film Thickness			*						
Guide Bearing Temperature									
Thrust Bearing Temperature									
Once per Rev / reference pulse	*	*	*	*		*		*	*
Head Cover/ Draft Tube Vibration	*				*				
Seal Ring/ Blade Tip Clearance									
Generator Air Gap						*		*	*
Stator Frame Vibration								*	*
Generator Temperature									
Process Variables		●	●		●				
Generator Partial Discharge							*		
Wicket Gate Position	●	●			●				
Stator End Winding Vibration							●		
Stator Bar Vibration							*		
Brush Monitoring									

* vibro-meter sensors and monitoring hardware

Unbalanced Air Gap Forces	Insulation Fault	Excitation Fault	Seal Ring/Discharge Ring Distortion	Excessive Turbine Vibration	Bearing Overload or Fatique	Insufficient Bearing Lubrication	Stator Insulation Deterioration	Stator/Rotor: Out of Round, Concentricity	Stator Flexing	Loose Stator Laminations	Plugged Stator Coolers	Blocked Stator Ventilation Ducts	Stator Core Overheating Stator Coil Shift
					*	*							
					*	*							
					●	●							
					●	●							
*			*	*				*	*				
			*	*									
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*										*			
											●	●	●
	*						*						
	●						●						
	*						*						
		●											

● Third-party sensors; fully compatible with vibro-meter hardware/software

● Third-party sensors and monitoring hardware; data integration to VibroSight


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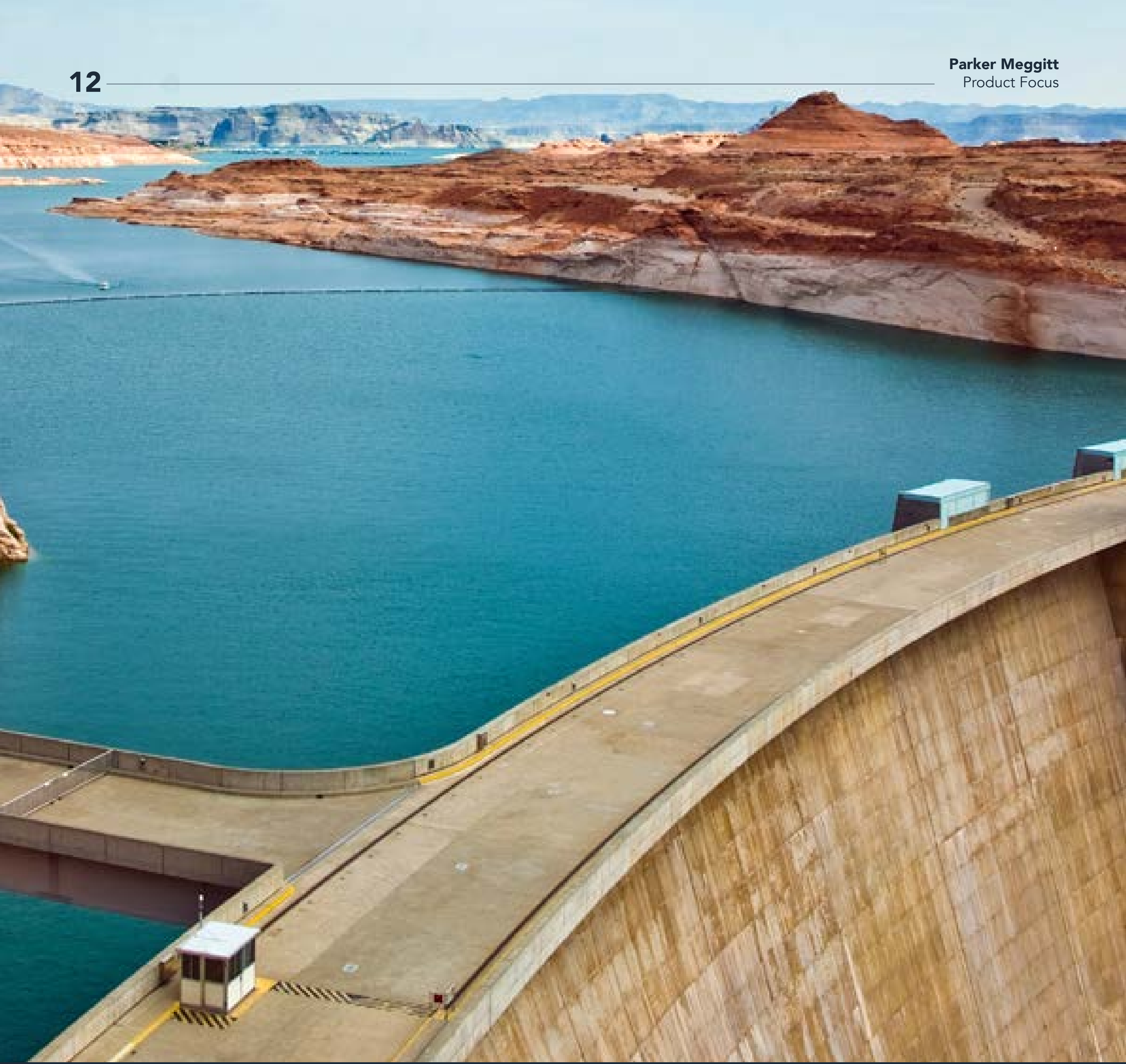


Whether a distributed or centralized architecture is right for you, the choice is yours with the VibroSmart and VM600^{Mk2} platforms from vibro-meter.

An endless battle

The debate over centralized versus distributed instrumentation architectures has been ongoing for more than 40 years, predating many of those reading this. Nor will it end any time soon. This is unfortunate because it is needless.

Rather than viewing these architectures as one versus the other it is helpful to view them as one plus the other. Both have their place. Both make sense when the application particulars dictate one approach in one situation and the other approach in another situation. For many manufacturers, however, their distributed offerings entail very different functionality and channel types than their centralized architectures, forcing customers to choose based not on the best architectural fit but the best feature set.
We have a refreshingly different perspective: give our customers a similar set of features and channels in each platform and let them choose based on the architecture that fits the application best – not the feature set. Nowhere is this more evident than in our hydro monitoring capabilities.

Uniquely Flexible Hydro Monitoring Solutions

For applications that can best be addressed by a distributed architecture, we're pleased to offer our VibroSmart platform. And for applications that can best be addressed by a centralized architecture, we're pleased to offer our VM600^{Mk2} platform.

"The total installed cost of wiring typically runs about €16 per meter per point and is often the single most costly part of a monitoring project."

Distributed or Centralized?

If you have never actually installed a monitoring system (or had to pay for it), it is easy to think that the preference for one of the two architectures might boil down simply to subjective factors. But in reality, it primarily boils down to something quite objective: *installation costs.*

Consider this important fact: the total installed cost of wiring typically runs about €16 per meter per point and is often the single most costly part of a monitoring project.
To make this more tangible, let's consider two scenarios. The first is three machines with 8 monitored points each, located 250m from a control room but for which wiring already exists and with an existing monitoring system that is obsolete and ready for replacement.
The second scenario assumes the same three machines but will use a distributed system. This is depicted in Figure 1.

If we had to install the wiring in scenario #1 from scratch using today's prices, the cost would be about €96,000. Fortunately, the wire is already in place and can be reused. In this case, we might simply choose a solution that can be mostly easily mounted in place of the outgoing system – also in a 19" EAI rack-mounted form factor – and the VM600^{Mk2} with its centralized architecture would be a good fit.

In scenario #2, selection of a centralized architecture has a very different outcome. As in scenario #1, the wiring costs would be about €96,000 if the wiring for each and every sensor went to a system located in the control room. However, by use of a distributed monitoring system we now have an option that allows us to keep individual sensor wiring for each system to no more than 10m (assuming we mount the distributed systems at each hydro unit) and then to run redundant network cables back to the control room where a human-machine interface (HMI) will be located. In this instance, we now have two cables that run 280m (250 + 15 +15) and 24 cables that run 10m each. Total wiring cost using a distributed architecture becomes €12,800. Or in other words, a savings of 87%! This is substantial and underscores why a customer would have a compelling reason in some applications to choose a distributed versus centralized architecture. It is recognized that each distributed monitoring system must generally be mounted in its own simple junction box, but this will rarely eclipse the savings enabled by shorter wiring runs and becomes more acute for longer runs.

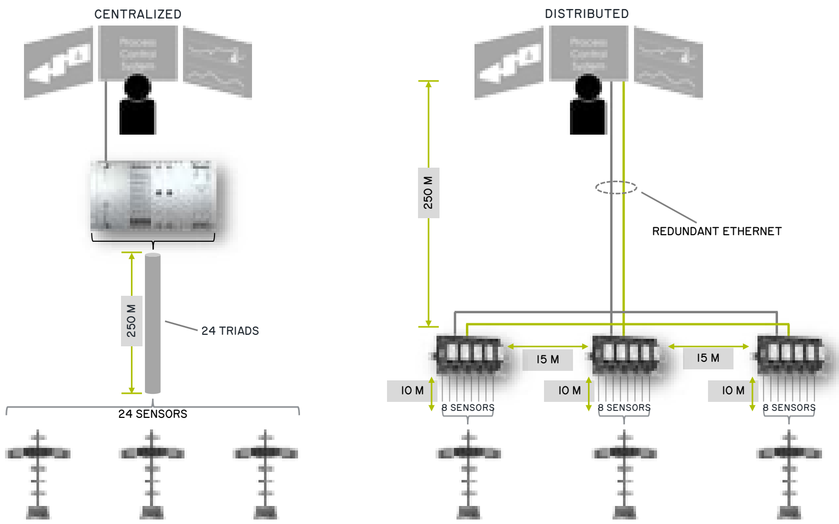


Figure 1: Centralized versus distributed architectures can result in dramatically different field wiring costs for some applications. In this instance, the wiring costs for a centralized approach are 87% more than those for a distributed approach.

Taking a distributed architecture further

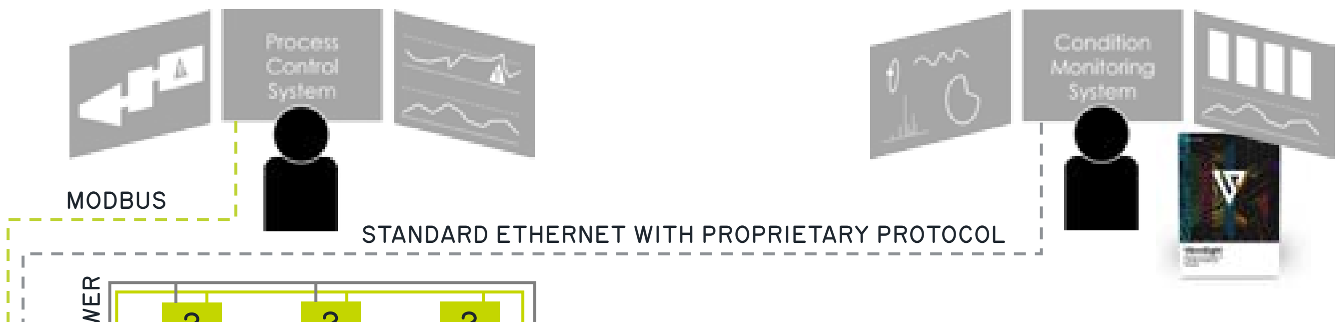
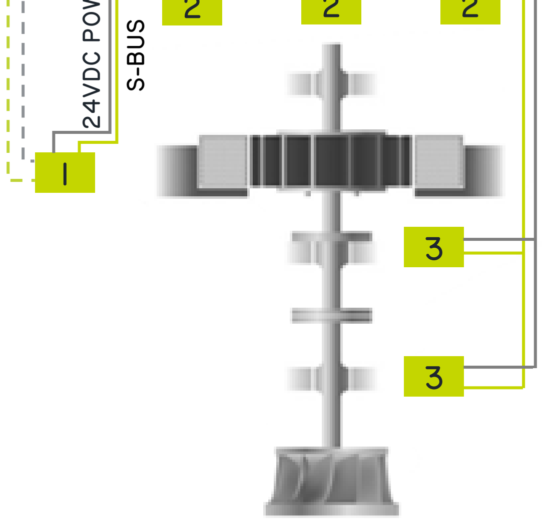
Above, we showed how a distributed architecture could dramatically reduce wiring costs in a scenario with three machines. This can also hold true for a *single* machine where the VibroSmart system is distributed around the machine to keep wiring runs very short. The VibroSmart architecture incorporates a virtual backplane that can be created both by plugging modules side-by-side using special connectors on the terminal bases, and/or by running Ethernet cables between the modules. This is called the "sidebus" (or S-bus) in the VibroSmart system and allows adjacent modules to be connected side-to-side using the special S-bus connectors and non-adjacent modules to be connected via conventional Ethernet cabling.

This granularity of distribution can be especially advantageous in applications such as hydro where vertical machines may span multiple floors of the power hall and a small junction box with one or more VibroSmart modules can be mounted very close to each cluster of desired sensors. As shown in Figure 2, this can be a very small junction box to accommodate just one or two VibroSmart modules; the power can be supplied remotely, meaning the junction box does not even need to hold individual power supplies. A single Ethernet cable can be run between each junction box to create this virtual backplane (S-bus) and a single twisted pair can carry the required 24Vdc power needed for each junction box.

Channel Types

As shown in Figure 3, Hydro machines have a number of special measurements such as air gap, magnetic flux, partial discharge, and cavitation – most entailing special sensors and corresponding special signal conditioning. They also have a number of conventional measurements such as temperatures, flows, thrust position, phase, casing vibration, and shaft radial vibration; however, there are special signal conditioning requirements for vibration on hydro units that are not characteristic of other machines.

One of these characteristics is a requirement for very low frequencies. Smaller units such as those incorporating Pelton wheels will often turn at several hundred rpm. While considered quite fast for hydro units, this would normally correspond to a very slow machine in and of itself – much slower than most motors, pumps, compressors, blowers, and gas and steam turbines. Even so, larger units using Francis and Kaplan type designs typically turn even slower and speeds of only 50-60 rpm are common. This means

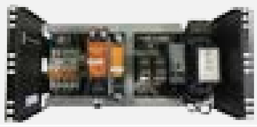
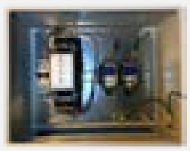
#	DESCRIPTION	IMAGE
1	24Vdc power supply for all distributed modules, remote relays, and VSI010 module for DCS communications	
2	Junction box with one (1) VSV301 module for two air gap points and two (2) ILS730 air gap signal conditioner modules	
3	Junction box with one (1) VSV301 module for two vibration points and two (2) IQS450 proximity probe signal conditioner modules	

Figure 2: The configuration shown here was provided for a hydro customer in eastern Canada, allowing consolidation of two separate systems (one for air gap and one for vibration) into the integrated environment provided by the VibroSmart platform. Modules were distributed around the machine to minimize wiring runs and keep installation costs correspondingly low.

the sensors and monitors must have a frequency response down to 1 Hz just to capture rotational speed, let alone sub-harmonic frequencies. For which fractional frequencies down to 0.1 Hz would be required.

Another characteristic behavior of hydro units is so-called "rough load zone" (RLZ) that corresponds to turbulent flow conditions when bringing a unit online and adjusting flow via the wicket gates. It is typically detected from the vibration signature by removing the 1X component from the overall broadband signal, resulting in a measurement known as NOT 1X. Operators required rapid feedback from a monitoring system when a machine is in RLZ because it can inflict significant damage if left in the condition for too long.

Some hydro units are part of pumped storage schemes whereby power is generated during periods of peak demand by allowing it to flow out of a reservoir, spinning the turbine and connected generator normally. However, during periods of low demand, this water is pumped back up into the reservoir by running the generator as a motor and the turbine as a pump. This allows the hydro plant to act as a "battery" by charging and discharging. Charging the battery occurs by pumping, storing the power as potential energy by virtue of elevation of the water in the reservoir. The battery can then be discharged when required by allowing the water to flow back through the turbine, spinning the generator and producing power. This cycle usually continues daily to charge during off times and discharge during peak demand times. Such plants require special monitoring schemes that can detect when the machine is running in generating mode versus pump mode because the alarm setpoints will be different. This is so-called "state-based" monitoring that recognizes the operating state the machine and adjusts the setpoints accordingly.

> "One of the substantial advantages of the vibro-meter approach is that these hydro measurements [...] can be made in both the VM-600^{Mk2} and the VibroSmart platforms."

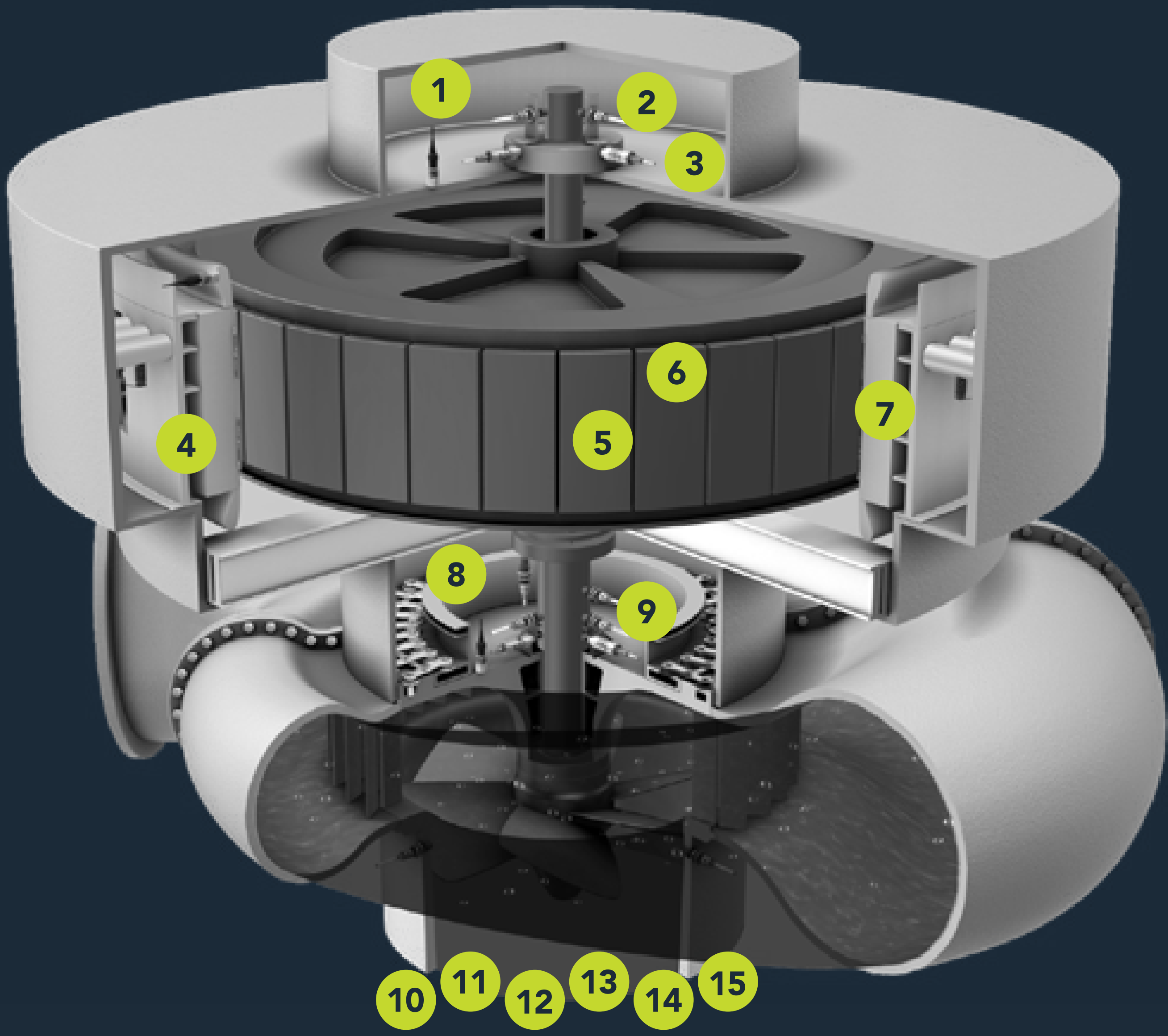
"One Card Does It All"

One of the substantial advantages of the vibro-meter approach is that these hydro measurements – and many others for other machine types – can be made in both the VM600^{Mk2} and the VibroSmart platforms. This ensures that you can choose your platform based on what architecture works best for your application – not because the necessary functionality is available in one platform but not the other. This is enabled by vibro-meter's "one card does it all" approach to signal processing. When we designed the original VM600 back in the late 1990s and launched it to the market in 2000, we made a ground-breaking decision to create a truly universal monitoring card that could make any vibration, position, or speed measurement – and indeed any dynamic or quasi-static measurement – in a single module. This was known as the MPC4 (Machine Protection Card – 4-channel) and it revolutionized the industry. That same approach was used in the design of the VibroSmart platform where a single module type (VSV30X) could be used universally for any conventional dynamic or static machinery measurement – whether vibration, air gap, cavitation, magnetic flux, etc. This is done by allowing the user to fully customize the transducer type and the measurement particulars.

It is this approach that allows both the VM600 and the VibroSmart systems to be used across virtually any machine type for any necessary sensor input. In addition, both platforms now combine the condition monitoring functionality and machinery protection functionality in the same module/card, reducing the burden of spare parts even further with a truly universal approach. They also incorporate integral relays, eliminating the need for separate modules to provide discrete outputs.

Figure 4: The universal "one card does it all" approach of the MPC4 in the VM600 platform was used as the basis for the VibroSmart platform as well. The VSV30X module is a universal module that provides all measurements with two universal dynamic channels and one speed/auxiliary channel.

Hydro Tubine Monitoring



1. Casing Vibration
2. Shaft Vibration (Relative)
3. Bearing Vibration (Seismic)
4. Stator
5. Partial Discharge
6. Magnetic flux
7. Air Gap
8. Trhust position
9. Speed / Phase
10. Temperatures *windings, bearings, etc.*
11. Pressure
12 Level
13 Wicket Gate Position
14 Cavitation
15 Foundation Vibration

Figure 3: Hydro turbine-generator machines have a number of conventional as well as specialized measurement requirements. Even on conventional measurements, such as radial vibration, requirements are different than on other machine types such as the need to address very low frequencies (down to 0.1 Hz) and the ability to provide signal conditioning such as NOT 1X that can detect the presence of rough load zone.

> “A **defining characteristic** of vibro-meter’s monitoring architectures is **simplicity**. This is evident not only in the “***one card does it all***” universal approach to channel types, but also in the relatively small number of other modules required.”

Simplicity

A defining characteristic of vibro-meter’s monitoring architectures is simplicity. This is evident not only in the “one card does it all” universal approach to channel types, but also in the relatively small number of other modules required.

For the VM600 platform, there are only five other modules: temperature, power, CPUM (communications), RLC (additional relays), and XMV/XMC[1](condition monitoring).

In the VibroSmart platform, it is even simpler and consists of a single additional module type: the VSI010. This module supports both serial and Ethernet-based communications with automation and control platforms using protocols such as Modbus, Profibus, and GOOSE. This allows compatibility with older machinery control and process control environments using serial communications as well as newer environments with Ethernet-based communications infrastructures. The module also supports full network redundancy to ensure that communications are never interrupted.

Accessories are available such as network switches and BNC patch panels.

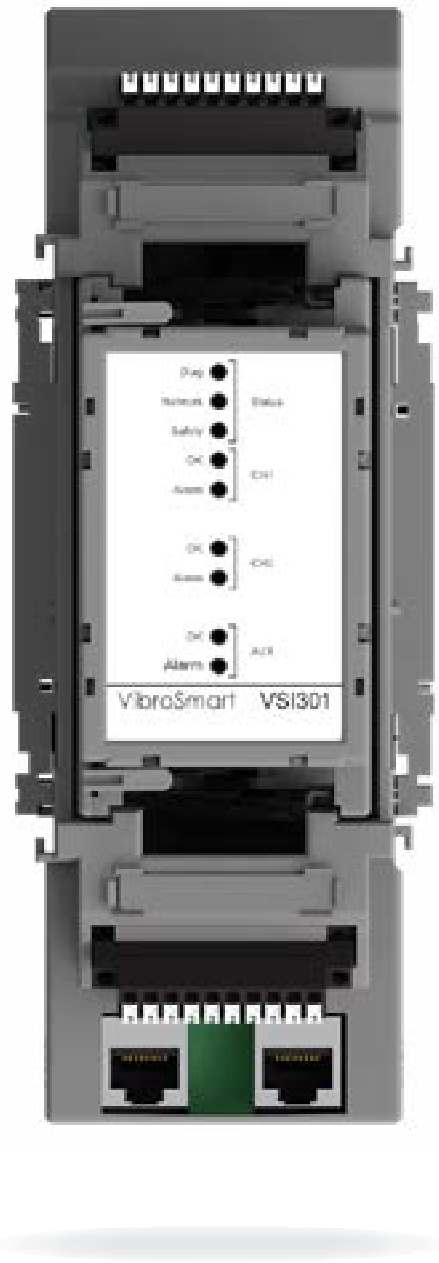


Figure 5: The simplicity of the VibroSmart system is evident in a system that requires only two module types: one for communications (shown here) and one for universal signal processing applications including the suite of measurements used for hydro machinery.

Software Considerations

The agnostic approach taken by vibro-meter in its hardware platforms also extends to the software connectivity. Both platforms are fully supported in our VibroSight suite supporting configuration, condition monitoring, decision support, data import/export, and more. This ensures that a single software environment can unify all of the monitoring hardware you use across your operations, allowing you to mix and match hardware based on the particulars of your operations, machine locations, and new versus retrofit installations. VibroSight also contains the specialized plot types used on hydro machines such as air gap and magnetic flux. This ensures a comprehensive solution for hydro machinery that incorporates all measurement types – not just conventional vibration and position.

Comprehensive Solutions

Our ability to address the hydropower market extends beyond just the flexibility of both centralized and distributed monitoring systems, and corresponding software with our VibroSight suite. We also offer the specialized sensors that are routinely employed on hydro turbines and generators, along with conventional acceleration and proximity sensors. You can learn more about both the VibroSmart and VM600^{Mk2} platforms in our online product catalogue or by contacting your nearest vibro-meter sales and service professional.

i XMV/XMC modules are 16-channel devices and required only when condition monitoring is required and machinery protective functions are not needed. When machinery protection is required, the MPC4^{Mk2} modules are used and provide integrated protection and condition monitoring, eliminating the need for a separate module such as the XMV.

Figure 6: The VibroSmart and VM600 platforms are fully supported by VibroSight software including the diagnostic rule box "decision support" capabilities (top) and the specialized plot types such as air gap (bottom) unique to hydro machines.

1. Low-Frequency Velocity
2. Proximity
3. Low-Frequency Acceleration
4. Air Gap

Figure 7: In addition to monitoring systems, vibro-meter provides a complete complement of sensors for the aggressive environments, low frequencies, and specialized measurements encountered on machinery in the hydroelectric industry.

Notes

1. XMV/XMC modules are 16-channel devices and required only when condition monitoring is required and machinery protective functions are not needed. When machinery protection is required, the MPC4^{Mk2} modules are used and provide integrated protection and condition monitoring, eliminating the need for a separate module such as the XMV.

When it comes to machinery vibration, mathematical equivalencies are not the same as measurement equivalencies.

The physics of low-frequency measurements.

In this article, we examine the pros and cons of various sensors used for making low-frequency measurements. Although the hydro power sector is one of the most common industries where such measurements are required, this is by no means the only industry where such applications are found. The pulp & paper, metal, mining, cement, water treatment, and petrochemical sectors also find applications where low-frequency measurements are necessary such as on rolls, mills, rotary kilns, agitators, pelletizers, extruders, and other slow-speed machinery.

We focus on the physics of low-frequency measurements, allowing a better understanding of why some sensors are inherently more sensitive than others and why simply mathematical integration of a signal does not automatically mean that an accelerometer is the right choice for any and all applications. In part 2, we focus on the other aspects of sensor selection and why sensitivity alone is not the sole criteria.

Low-Frequency Measurements

Introduction

Those new to the field of vibration – particularly if their learning is not reinforced with practical experience in the field – will often make the mistake of assuming that mathematical equivalencies translate into measurement equivalencies. Nowhere is this more common than in the physics of motion.
More than 300 years ago, Newton showed that displacement, velocity, and acceleration are mathematically related to one another through the processes of differentiation and integration. As a refresher, the basic relationships are as follows:

$$v(t)=dx(t)/dt$$

$$a(t)=dv(t)/dt= d^2x(t)/dt^2$$

$$v(t)= \int a(t)\, dt$$

$$x(t)= \int v(t)dt= \iint a(t)dt$$

Where,
t = time, x(t) = displacement as a function of time, v(t) = velocity as a function of time, a(t) = acceleration as a function of time

In words, we can integrate an acceleration signal to obtain velocity; we can integrate a velocity signal to obtain displacement; and, we can double integrate an acceleration signal to obtain displacement.

Because these mathematical relationships are exact and not approximations, it is reasonable at first glance to assume that we need only a single type of sensor for all vibration measurements: an accelerometer. To obtain velocity, we merely integrate the acceleration signal and to obtain displacement we merely double integrate the acceleration signal. However, as we noted earlier, while such relationships may indeed exist mathematically, this does not mean that the practical realization of these relationships in sensor technology is flawless. Quite to the contrary, it can be fraught with practical difficulties due to the underlying physics.

This leads to a very fundamental rule-of-thumb in the vibration world: it is generally best practice to choose a sensor with a **native output** that matches the **physical parameter** you are trying to measure. In other words, if you are trying to measure displacement, select a displacement transducer, if velocity a velocity transducer, and if acceleration, an acceleration transducer.

Like many rules, there are exceptions and part of the science of vibration measurement is knowing when the exceptions are warranted and when they are not. Here, we will outline two such exceptions:

1. If the acceleration levels themselves provide a reasonably strong signal that is not close to the noise floor of the sensor, velocity can be measured via an accelerometer signal that is integrated.

2. The measurement of casing displacement (not shaft-relative displacement) is made most practically by means of a velocity sensor – not a displacement sensor.

We next examine each of these two exceptions in greater depth as they pertain to low-frequency measurements in general, and to hydro measurements in particular.

"Vibro-meter is committed to **offering a broad selection of low-frequency seismic sensors** ranging from moving-coil designs to piezo-velocity designs to conventional piezo-electric accelerometers, and with the option for either voltage-mode signal transmission or current-mode signal transmission. "

True Velocity versus Integrated Acceleration

The only type of industrial vibration sensor providing a true (or "native") velocity output is a moving-coil device[1].

The principle of operation is quite simple and involves a coil of wire encircling a magnetic core. Relative motion between the coil and the core induces a voltage in the coil that is proportional to the relative velocity between them. It doesn't matter whether the coil is stationery and the core moves or vice-versa. However, it is generally more practical to construct a sensor in which the coil is supported on springs and stays relatively motionless while the core itself is rigidly attached to the sensor housing and thus moves as the sensor moves[2]. In this manner, machinery casing vibration can be measured and the output is thus indicative of the casing or structure vibration velocity.

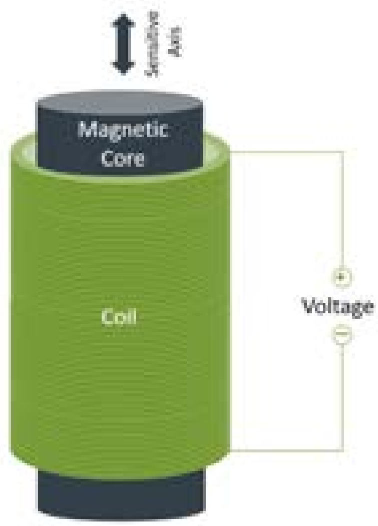
The VE210 is an example of a moving-coil velocity sensor.

Such sensors can be constructed to give a relatively strong output, and this is particularly true of those that measure down to low frequencies because the sensor geometry is physically large, leading to coils and magnets that are themselves relatively large and thus provide large outputs.

As an example, consider vibro-meter's VE210 velocity sensor. It is able to measure frequencies down to 0.5 Hz (30 cpm) with a sensitivity of 50 mV/mm/s (1270 mV/in/s).

Considering that most commercially available velocity sensors (whether moving coil or piezo-velocity) have an output sensitivity of only 100mV/in/s – and occasionally 500 mV/in/s – the VE210 provides an output amplitude for the same excitation that is anywhere from 2.5 to 12.7 times stronger, ensuring that very small velocity levels are easily detected, even in the presence of electro-magnetic noise and interference.

In contrast, consider so-called "velocity output" or "piezo-velocity" accelerometers that natively measure acceleration and then integrate the signal using integral electronics to produce a velocity output. The vibro-meter PV660 piezo-electric velocity sensor is such a device and provides an output of 4 mV/mm/sec at frequencies down to 1.9 Hz (114 cpm). For equivalent excitation of 1 mm/s at 1.9 Hz, the VE210 will produce an output of 50mV while the PV660 will provide an output of only 4mV. However, there is more to the picture than just the output sensitivity. To understand this, we will look at the vibration nomograph chart below.



In a moving-coil velocity sensor, the coil and core move relative to one another and produce a voltage directly proportional to the relative velocity. They are usually constructed such that the core moves with the sensor housing while the coil is supported on springs and remains relatively motionless.

Reading a Vibration Nomograph

A nomograph is a graphical calculation chart introduced in the early 1900s that has primary value today for visualizing the qualitative relationships between variables rather than quantitative – given the availability of modern calculation engines such as spreadsheets and apps for computing exact values.

Many times, logarithmic scales are used so that non-linear relationships become linear and thus easier to visualize. A vibration nomograph is commonly used to compute acceleration, velocity, or displacement amplitude given a particular vibratory frequency and one of the three vibration amplitudes. The chart assumes a single, sinusoidal vibration frequency – not complex vibration composed of multiple frequencies (see below).

Notice first that the orange dot corresponds to the excitation described in the preceding section.

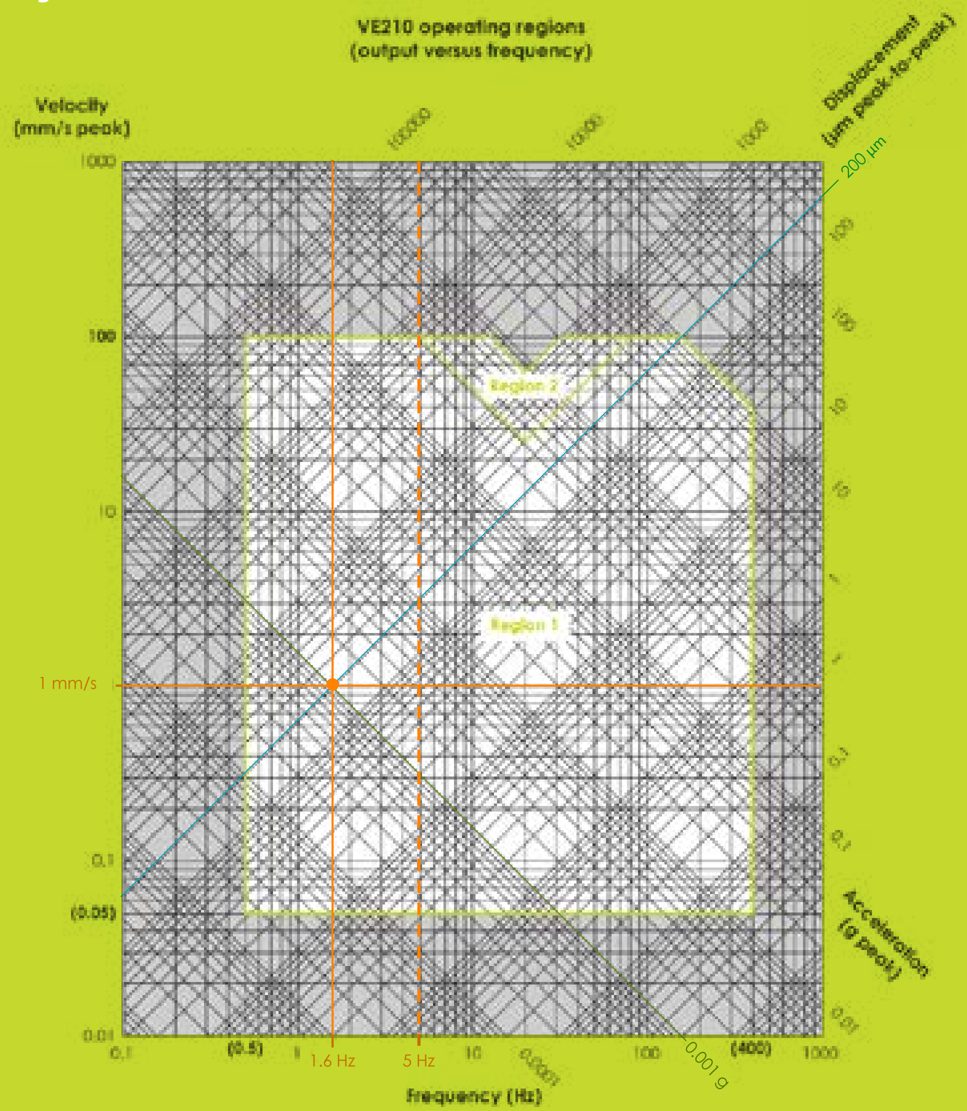
Namely, velocity of 1 mm/s (0-pk) at 1.6 Hz. Next, notice that this corresponds to a very large displacement amplitude of 200 µm (pk-pk) but an extremely small acceleration amplitude of only 0.001 g (0-pk).
To put this in perspective, a typical displacement sensor (eddy current proximity chain) has a sensitivity of 4mV/µm and would give an output of 800 mV pk-pk for 200 µm of displacement. In the instrumentation world, this is a very strong signal.
In contrast, consider the output of an acceleration transducer with a typical sensitivity of 100mV/g. There is only 0.001 g of vibration present which corresponds to 0.1 mV (100 µV).
This is a very weak signal in the instrumentation world and will often be at or below the noise floor. Lastly, consider the outputs from the velocity sensors we conveyed earlier.
For a typical piezo-velocity sensor, the output will be 3.9mV – approximately 80X lower than the output of the displacement transducer but 40X larger than the output of the accelerometer. However, when we use a moving-coil sensor such as the VE210, we get an output of 50mV which is excellent.
What the preceding discussion shows is the limitation of the physics involved. When looking at vibration occurring at very low frequencies, displacement levels are very high while acceleration levels are very low. Velocity, on the other hand, tends to be relatively independent of frequency and indeed, this is why the velocity amplitudes are shown as horizontal lines on the nomograph – they don't show nearly the dependence on frequency as do acceleration or displacement. Thus, no matter how low our sensor is ca-

Sinusoids versus Complex Signals

Using a nomograph properly.

It is extremely important to note that the nomograph shows the relationships between acceleration, velocity, and displacement for ONLY a single, sinusoidal frequency. It CANNOT be used to describe the relationships between vibration signals with complex frequency content consisting of multiple sinusoids.

In fact, this is a very common misuse of such charts by those new to the field of vibration. They look on an instrument or monitoring system at the amplitude of a complex vibration signal, erroneously use the chart to try and convert from one parameter to another (such as acceleration to velocity), and then become confused when the actual measurement amplitude fails to agree with the amplitude given by the chart.



pable of measuring, the amplitude of the acceleration itself may be so low as to be miniscule. We end up trying to measure a physical parameter that is too small at the frequency of interest and are better served by measuring a different parameter (such as velocity or displacement). This is intuitively obvious when we think of forces. If you move your arm up and down in a flapping motion once per second, it doesn't take much force and the displacement can be quite large – you can easily move your arm with a displacement of 50 cm once per second.
However, try now to move your arm that same distance, but 1000 times per second (1 kHz). Even under the assumption that your musculature was capable of such movement (and it is not), the forces to create this displacement at this frequency would break the bones in your arm because the acceleration levels are so high. Indeed, your arm has to change direction 1000 times per second and this requires tremendous force[3]. It can be shown mathematically, in fact, that 50 cm of displacement at 1 kHz corresponds to more than one million g's! Conversely, make your arm vibrate five times per second and you can probably sustain amplitudes of 1-2 cm as this corresponds to only 1g.

> "There are **additional criteria to consider when selecting a sensor for low-frequency measurements.** While a moving-coil device will sometimes be the right sensor, it will not always be the right sensor because its superior sensitivity comes at the expense of lower reliability due to its moving parts."

Machinery is subject to those same laws of physics; namely, large displacements and moderate velocity amplitudes occur at low frequencies but these correspond to extremely small acceleration levels. Indeed, as we decrease in frequency, the acceleration decreases with the square of the frequency compared to displacement. Thus, using the nomograph, a displacement of 200µm at 5 Hz corresponds to approximately 0.01 g's while the same displacement at 1 Hz corresponds to only 0.0004 g's (25X less). This is precisely why we tend to avoid accelerometers at very low frequencies: the acceleration levels themselves are often many orders of magnitude smaller than the corresponding displacement or velocity levels. And, the situation becomes even more pronounced as we go increasingly lower in frequency. Using velocity, the acceleration levels decrease in a manner inversely proportional to frequency. A velocity of 1 mm/s at 5 Hz corresponds to 0.003 g's (an already small value) while the same velocity at 0.5 Hz corresponds to just 0.0003 g's (10X less).

As a consequence, even though accelerometers with very low frequency response are available, one should carefully consider the actual acceleration amplitudes at such frequencies. It is not uncommon for the acceleration levels at low frequencies to be several orders of magnitude smaller than the velocity levels. While this can sometimes be offset by using an accelerometer with higher sensitivity (gain), it is important to avoid trying to measure acceleration amplitudes that approach the noise floor of the transducer. In addition, when an accelerometer is used and the signal strength is quite weak, if a measurement in velocity units is required, one must then integrate this very weak acceleration signal to velocity in the monitoring system. This can contribute additional error due to the noise that may be present and the realities of integrating very low frequencies[4]. The situation becomes even worse if we want units of displacement and must therefore double integrate the acceleration signal[5].

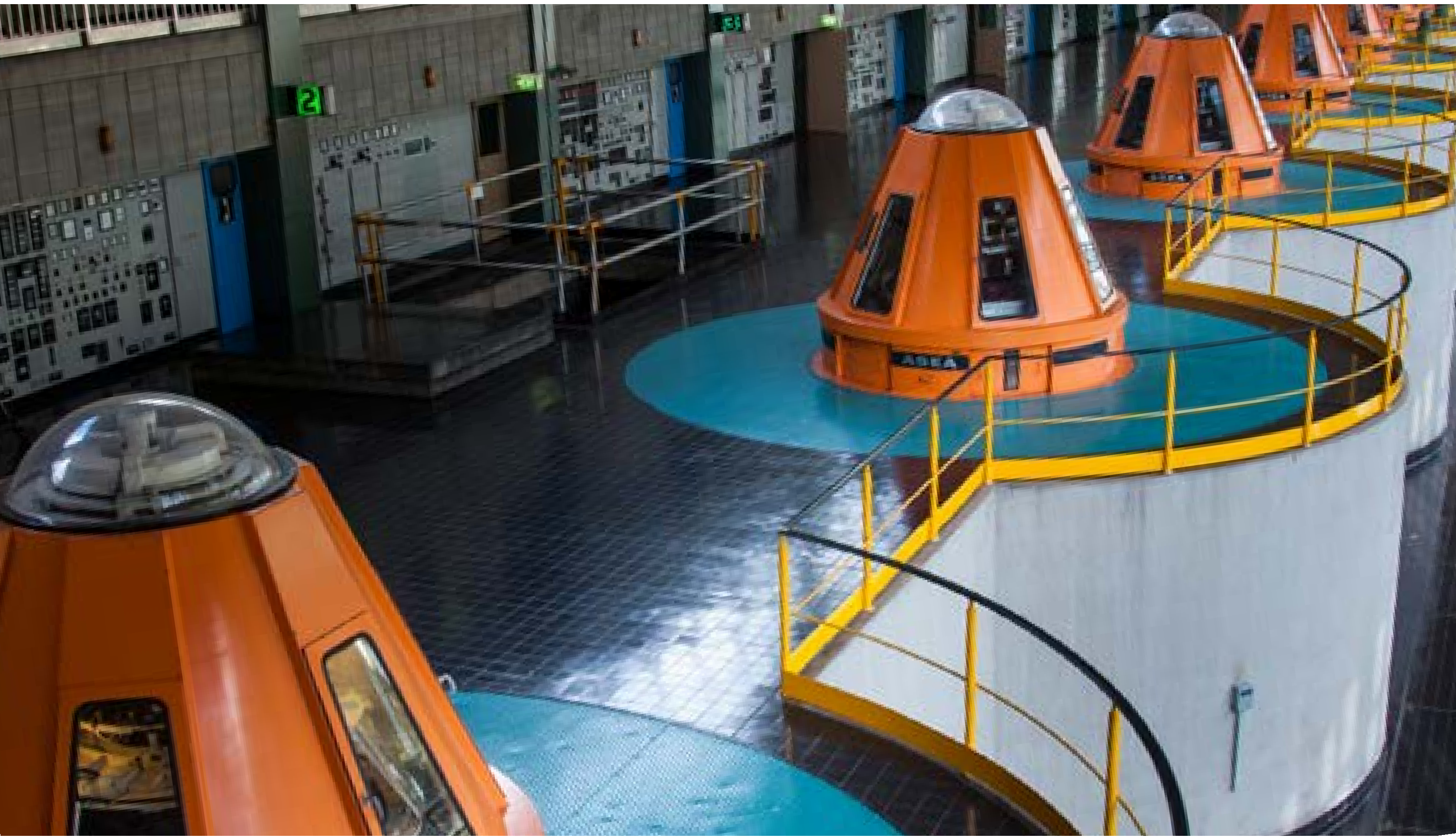
As one final example, we consider another provider's low-frequency accelerometer. It has a -3 dB frequency response down to 0.2 Hz and provides an output sensitivity of 500 mV/g. However, as we showed earlier, a 1 mm/s velocity signal at 0.5 Hz corresponds to 0.0003 g's – an extremely small amplitude. Even at a sensitivity of 500 mV/g, this still provides a signal of only 150 µV. Additionally, this small signal must then be converted to velocity through integration which will generally introduce more errors – particularly at such low frequencies. In contrast, the VE120 would provide an output of 50 mV (more than 300X stronger) and would require no integration. The PV660, however, could not be used because although it provides a velocity output, its frequency response does not extend down to 0.5 Hz.

Other Considerations

Based on the foregoing discussion, it would be easy to conclude that a moving-coil device is always the right sensor for velocity measurements. However, we have thus far examined only two of the considerations when choosing a sensor: the underlying physics and the transducer sensitivity (output strength versus vibration amplitude). There are additional criteria to consider when selecting a sensor for low-frequency measurements. While a moving-coil device will sometimes be the right sensor, it will not always be the right sensor because its superior sensitivity comes at the expense of lower reliability due to its moving parts.

Notes

1. Strictly speaking, laser surface velocimeters (LSVs) also measure velocity natively but are currently used only in laboratory settings – not for industrial machinery vibration measurements.
2. It is indeed more appropriate to think of most "moving-coil" velocity sensors as being "moving magnet" because the design is such that the magnetic core moves with the sensor's housing while the coil itself remains motionless. It is analogous to the suspension on a car consisting of coil springs and damping where the goal is to keep the car's frame stationary while the wheels themselves move up and down on bumpy roads, thus keeping the passengers relatively still and comfortable.
3. Recalling from physics that force (f) = mass (m) x acceleration (a), high forces for a given mass require high sinusoidal acceleration amplitudes.
4. For additional information, SKF Technical Bulletin TB02003 "Integration of Vibration Signals" provides a helpful overview of the challenges inherent in signal integration
5. Double integration is rarely advisable. Consult vibro-meter for additional application-specific guidance.



Shaft-Relative Displacement versus Casing Absolute Displacement

The direct measurement of casing displacement vibration with a sensor that has a native displacement output entails use of a proximity probe rigidly mounted so that it does not move relative to free space and observing a suitable target on the vibrating surface. While this is easy enough to describe verbally, it is often impractical for machinery. It is almost always easier to use a seismic sensor and then integrate the signal to displacement. Such vibration measurements are very typical on hydro turbine generators where it is usually necessary to measure not only shaft-relative vibration at each bearing but also seismic vibration of the bearing caps. It is also typical to monitor stator frame vibration in both the radial and axial directions and sometimes even to measure the support structure vibration to ensure looseness or other problems are not occurring.

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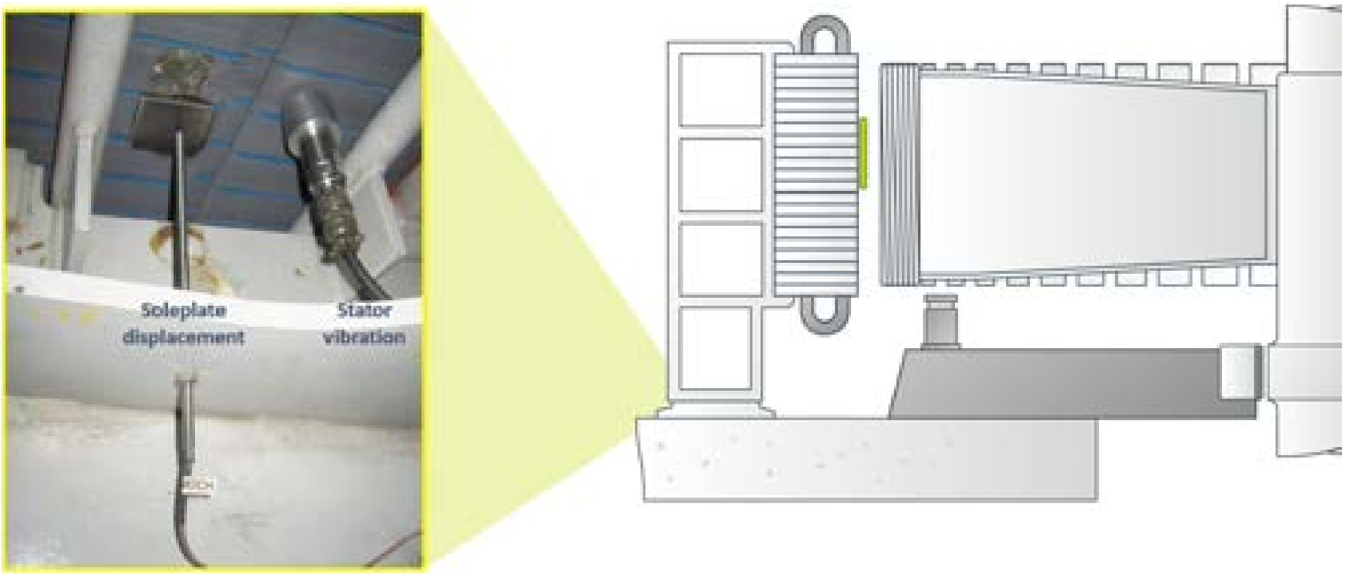


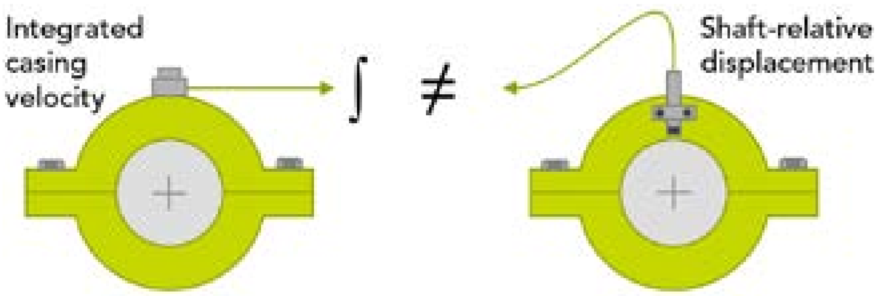
On this hydro generator unit, stator vibration is measured with a seismic sensor (right) while soleplate displacement (position of stator soleplate relative to the support structure) is measured with a proximity sensor (left). While position measurements such as soleplate displacement necessitate a proximity or other displacement sensor, it is rarely practical to measure casing vibration with a proximity sensor due to the complications of finding a mounting location that does not itself vibrate.

Soleplate displacement is another common measurement. However, it is fundamentally a position measurement – not vibration.

Seismic sensors are often used for casing vibration measurements rather than proximity sensors due to the complications in mounting the sensor on a structure that is truly motionless rather than vibrating since absolute (relative to free space) casing vibration is almost always desired rather than the relative vibration between the casing and the mounting surface. When a seismic sensor is used, it is usually one that provides a velocity output, whether native velocity from a moving-coil device (such as the vibrometer VE210) or integrated acceleration from a so-called "piezo velocity" device (such as the vibrometer PV660).

It is very important to note that the displacement obtained by integrating a casing velocity signal is not the same as displacement measured at the shaft via proximity probes. Shaft-observing proximity probes measure shaft-relative vibration. In other words, the relative motion between the vibrating shaft as it rotates and the bearing structure to which the probe is mounted. Whether the shaft moves or the bearing moves, the probe sees both sources of motion in what is effectively a composite signal. In contrast, a seismic velocity sensor sees only the vibration of the bearing housing or machine casing relative to free space.

When this signal is integrated, we obtain a displacement, but it is not shaft-relative displacement – it



Even when measured in the same axis, the integrated velocity signal from a casing absolute measurement is not the same as a shaft-relative measurement. Both may share displacement units, but one is a displacement relative to free space while the other is a displacement of the shaft relative to the probe's mounting surface.

The vibrometer PV660 is fundamentally a piezo-electric accelerometer with an internal integration stage to produce a velocity output. It has a frequency response down to 1.9 Hz (114 cpm) and an output sensitivity of 4mV/mm/sec.

is bearing (or structure) absolute displacement. Thus, hydro-specific vibration monitoring standards such as ISO 20816-5[6] that call for measurement of both relative vibration in displacement units (µm) and absolute vibration in velocity units (mm/s) require two different transducers – not just a single transducer (velocity) that has one path for velocity and one path for integrated velocity (displacement). The proximity probe measures relative vibration while the velocity sensor measures absolute vibration.

Sensor Reliability

When casing vibration measurements are required – whether on slow-speed machines or higher-speed machines – seismic sensors are almost always used as discussed in the previous section. Thus, the selection of a sensor for casing measurements is rarely about proximity versus seismic – it is instead about moving-coil versus piezo technology.

As we showed previously, when very low frequencies are involved, the output from a moving-coil sensor will almost always be stronger than from a sensor incorporating a piezo effect as its underlying measurement technology – whether piezo-electric (such as the vibrometer PV660) or piezo-resistive (such as the vibrometer SE120). If the decision was based solely on transducer sensitivity and the corresponding signal strength, a moving-coil device would thus be the obvious choice for low-speed measurements. However, moving-coil devices have a very fundamental, unavoidable limitation: moving parts and the corresponding degradation that occurs over time.

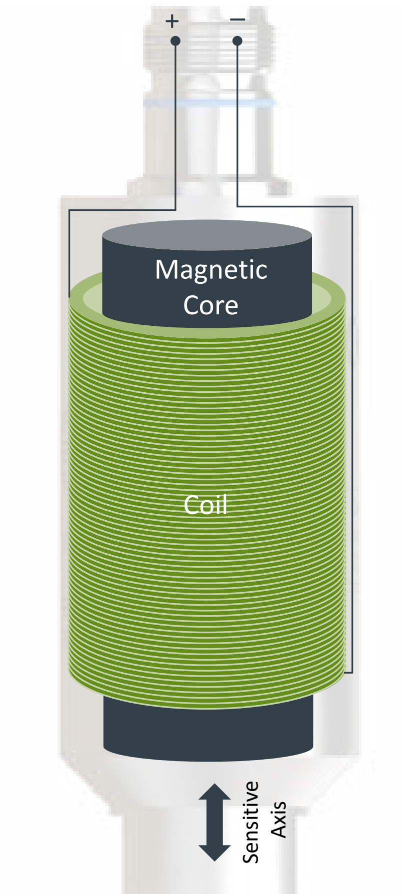
Consider the vibrometer VE210 pictured above and conceptually showing its internal construction. The coil is supported by springs and is designed such that the coil remains nearly stationary as the case of the transducer and its rigidly attached magnetic core move up and down in unison. The relative motion between the magnet and coil generates a signal that is directly proportional to velocity. As can be imagined, however, when the transducer is mounted horizontally rather than vertically, the springs behave differently due to the direction in which gravity acts. Many moving-coil devices thus exhibit restrictions on their mounting orientation. However, the VE210 is designed such that it can be mounted in any orientation from 0-360°.

Over time, the springs supporting the coil will wear out and the transducer will fail – generally without any advance warning such as a gradually degrading signal. Of particular concern is so-called "cross-axis" vibration; i.e., vibration perpendicular to the transducer's sensitive axis. This type of vibration can be especially fatiguing on the support springs and is characteristic of machines with passing vanes or blades such as gas turbines. Consequently, moving-coil devices are less reliable than piezo-effect

The vibrometer SE120 has a frequency response down to 0.2 Hz (12 cpm), an output sensitivity of 2mA/g, and uses piezo-resistive technology.

devices and should generally be replaced every 3-5 years. It is not possible to inspect them for wear due to the (usually) hermetically-sealed construction.
In contrast, piezo-type devices rely on the alternating compression and tension of a piezo-electric crystal and the signal it generates proportional to force (and thus acceleration). There are no moving parts to wear out and such devices can last decades.

When reliability is a concern and/or the device will be inaccessible for easy replacement, a piezo-type sensor may thus be a better choice.



The vibrometer VE210 is an example of a moving-coil velocity sensor where relative motion between the magnetic core and a spring-supported coil generates a signal directly proportional to velocity. Because the device has moving parts, it is subject to wear over time – unlike solid-state devices that rely on a piezo-electric or piezo-resistive effect. Also, the construction of a moving-coil device limits its mounting orientations, unlike piezo devices that can be oriented in any direction.

Although it may not generate an output signal that is as strong as a moving-coil device at low frequencies – because the acceleration levels may be appreciably smaller than the corresponding velocity levels – they will often be capable of generating a signal that is sufficiently strong for reliable monitoring and diagnostics. The vibrometer SE120 is an example of such a device and can monitor frequencies as low as 0.2 Hz (12 cpm). However, because it produces an acceleration output, the signal must be integrated to velocity units at the monitor. The vibrometer PV660 is another example. It provides internal integration and thus a velocity output. However, it is rated only to 1.9 Hz and thus not suitable for frequencies below 114 cpm.

Comparisons

Cost, frequency response, reliability, and signal strength are all considerations that factor into the decision of which transducer is best for a particular low-frequency application.

Comparison of our vibrometer low-frequency seismic sensor on the next double page

Long Cable Runs

In instances where long cable runs must be supported (up to 1km or greater), a sensor with a current output should be selected. They are less susceptible to noise (which is inherently a voltage rather than current disturbance) and offer other advantages6. vibrometer models such as the VE210 and SE120 directly provide a current-mode signal modulation output to support long cable runs. Models with only a voltage-mode output can also be used, but require our IPC 707 signal conditioner to convert from voltage mode to current mode.

Summary

As we have shown, the selection criteria for casing vibration sensors on low-speed machinery such as hydro turbine generators has multiple facets. We examined the physics of low frequency measurements and the many orders of magnitude that separates units of displacement, velocity, and acceleration when frequencies are below 1 Hz. Thus, when accelerometers are used, the sensitivity must be relatively high because the acceleration amplitudes are quite small at such low frequencies and the quality of the sensor must be quite high to ensure that its noise floor is suitably low and the high gain of the sensor does not simply amplify noise. In contrast, velocity sensors using a moving-coil design generally provide a very strong signal at low frequencies. Then, we continued the examination of selection criteria by showing that signal strength alone does not address all aspects that may be important for the application. Sensor reliability may often be of paramount concern along with secondary factors such as initial cost, broad frequency response rather than simply good low-frequency response, an output that may or may not require integration, and a signal output format that lends itself to very long cable runs.

For all of these reasons, vibro-meter is committed to offering a broad selection of low-frequency seismic sensors ranging from moving-coil designs to piezo-velocity designs to conventional piezo-electric accelerometers, and with the option for either voltage-mode signal transmission or current-mode signal transmission. You can explore the full range of these sensors in our catalog sections for vibration sensors with integrated electronics and velocity sensors. We also have the expertise to assist you in selecting the right sensor for your application. Use this page to find your nearest factory-direct sales and service office or vibro-meter representative office.

Notes

6. ISO 20816-5: 2018 "*Mechanical Vibration – Measurement and evaluation of machine vibration – Part 5: Machine sets in hydraulic power generating and pump-storage plants*"
7. A piezo-velocity device is inherently a piezo-electric accelerometer with an internal signal integration stage to produce an output in velocity units.
8. Although the VE210 can be mounted in any orientation, this is not generally true of moving-coil devices from other manufacturers or for all vibro-meter moving coil devices. For example, the vibro-meter CV213 is restricted to ±100° of vertical.
9. For additional information, SKF Technical Bulletin TB02003 "*Integration of Vibration Signals*" provides a helpful overview of the challenges inherent in signal integration.
10. Double integration is rarely advisable. Consult vibro-meter for additional application-specific guidance.
11. You can read more in vibro-meter Application Note via our website "*Cable length and attenuation in frequency for vibration measuring chains*".

Comparisons of vibrometer low-frequency seismic sensors

	VE210	SE120
Operating Principle	Moving-coil	Piezo-resistive
Advantages	• Signal strengh at low frequencies • Available in either voltage or current output; current output supports long cable runs and is less susceptible to noise • Native velocity output	• No moving parts • Signal strengh at low frequencies • Excellent low-frequency response (0.2Hz) • Current output to support long cable runs
Disadvantages	• Mounting orientations • Moving parts to wear out • Larger physical size • Cost • Larger physical size • Poor upper frequency response (400 Hz max)	• Acceleration output; requires integration to velocity or double integration to displacement • Cost • Not available with voltage output; current output only • Poor upper frequency response (350 Hz max)
Frenquency (-3 dB)	0.5 Hz	0.2 Hz
Dynamic Range	100 mm/s (pk)	±4 g (pk)
Sensitivity	50 mV/mm/s	2 mA/g
Relative cost	2X	2.3X

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CE620	PV660
Piezo-electric	Piezo-velocity
• No moving parts • Cost • Moderate upper frequency response (3.7 kHz) • Excellent low-frequency response (0.2Hz)	• No moving parts • Cost • Native velocity output • Compact size • Good upper frequency response (7kHz)
• Acceleration output; requires integration to velocity or double integration to displacement • Signal strengh at low frequencies • Not available with voltage output; current output only	• Signal strengh at low frequencies • Not available with current output to support long cable runs; voltage output only • Not available for frequencies below 1.9 Hz (114 cpm)
0.2 Hz	1.9 Hz
±16 g (pk)	1250 mm/s (pk)
500 mV/g	4 mV/mm/s
1X	1X

"Cost, frequency response, reliability, and signal strength are all considerations that factor into the decision of which transducer is best for a particular low-frequency application."

For additional information, SKF Technical Bulletin TB02003 "Integration of Vibration Signals" provides a helpful overview of the challenges inherent in signal integration. Double integration is rarely advisable. Consult vibro-meter for additional application-specific guidance.


vibro-meter

Vibro-meter's air gap monitoring capabilities extend from the sensing chain to the monitor to the condition monitoring environment and are thus comprehensive.

Air Gap Measurement

Hydro turbine-generators represent a mix of conventional radial vibration, thrust, and phase trigger measurements along with several measurements that are generally unique to hydro. In this article, we explore one such measurement – air gap – explaining what this measurement is, how it is made, and why it is important.

Hydropower is a significant part of the world's energy supply and the renewable portfolio. Indeed, approximately 7% of the world's electricity is produced by hydropower and nearly a dozen countries generate more than a quarter of their power from this renewable resource (Figure 1).

While these percentages are important, they tell only part of the story: the percentage of a country's energy portfolio coming from hydro. Table 1 conveys the rest of the story by showing the top 5 countries for hydropower based on installed generating capacity. As can be seen, even countries with a relatively small percentage of their power coming from hydro can still

Air Gap Measurements

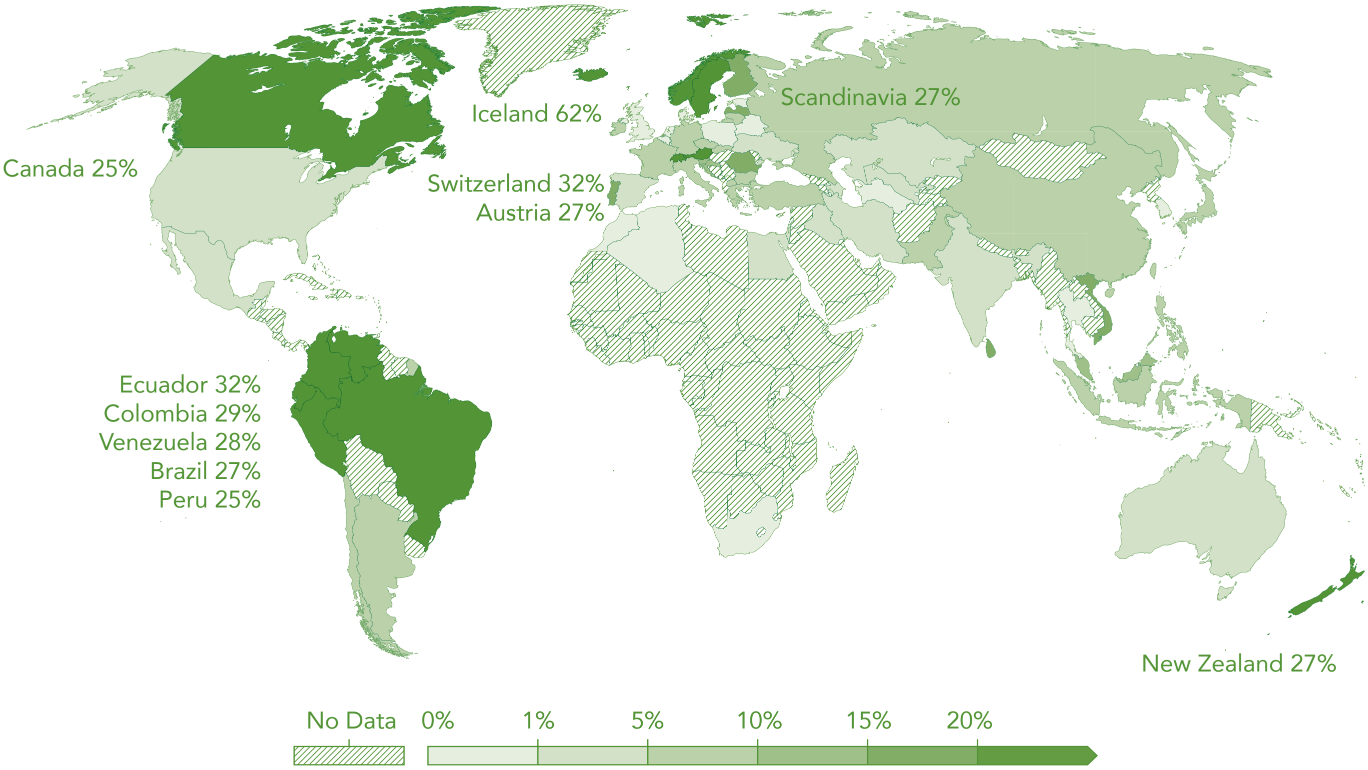

Figure 1: 2021 hydropower as a percent of total generating capacity by country. Countries generating more than 20% of their power via hydro are explicitly noted. Although some countries – such as the United States, China, and Russia – represent small percentages (2.6%, 7.8%, and 6.5% respectively), this still equates to a sizable number of machines and GW of production. For example, China represents more than 370GW of hydropower capacity – far exceeding countries with higher percentages yet smaller capacities.
Source: ***OurWorldInData.org/energy***

represent a very large installed base of generating capacity and thus numbers of machines.

We provide this preamble to underscore that there are many hydropower generators around the world and many of those are monitored by vibro-meter technology. While radial vibration, thrust, and phase trigger measurements are generally well-understood because they are present on most other machine types, air gap is less understood because it generally appears only on hydro units[1].

Table 1

Top 5 Hydropower National Capacity

Rank	Country	Installed Capacity
1	China	370.2 GW
2	Brazil	109.3 GW
3	USA	102 GW
4	Canada	82 GW
5	India	50.5 GW

Source: 2021 Hydropower Status Report, International Hydropower Association (hydropower.org)

Machine Size Implications

Although some hydropower is generated by smaller[2], units (usually horizontal and may even use a gearbox[3] between turbine and generator), as of 2022, a relatively small percentage[4] (15%) of global hydropower comes from such machine trains. Also, they are not generally candidates for continuously monitored air gap due to the much smaller sizes of their generators. As such, those machines are not addressed in this article.

Instead, most hydro plants are large in scale – often marvels of civil engineering – featuring large dams and massive vertical turbines with salient pole generators and corresponding rotors that may exceed 10m in diameter and 450 tons (Figure 2)[5]. These machine trains are indeed among the largest on the planet in terms of both power output and physical size, some capable of 1GW from a single train – only exceeded in power output by the steam turbines in most nuclear plants and a small number of conventional thermal plants[6].

The size of these units means that the bearings carrying radial and axial loads are fluid-film type and thus use proximity probes for monitoring radial vibration and thrust position. Phase triggers are also used to provide a once-per-turn timing mark used in certain measurements (such as air gap profiles) that must be referenced to a precise location on the shaft. Although phase (degrees of rotation from the mark) can sometimes form part of a protective measurement, it is always valuable for condition monitoring and diagnostics and should thus be included on every machine regardless of size and regardless of whether air gap measurements are present.

The size of these units also means that the ramifications of mechanical failures can be very serious, as this series of before and after photos from the Sayano-Shushenskaya hydroelectric dam accident[7] soberly convey.

Lastly, as we will show next, the size of these units also results in numerous sources of static and dynamic movement that must be understood and are often best measured by air gap and a suite of other measurements that help isolate and identify the underlying cause of changes in air gap. But first, we must define air gap.

What is Air Gap?

Air gap is simply the instantaneous gap between generator rotor and stator as shown in Figure 3. However, it will not necessarily be uniformly circular and must thus be measured using multiple, uniformly

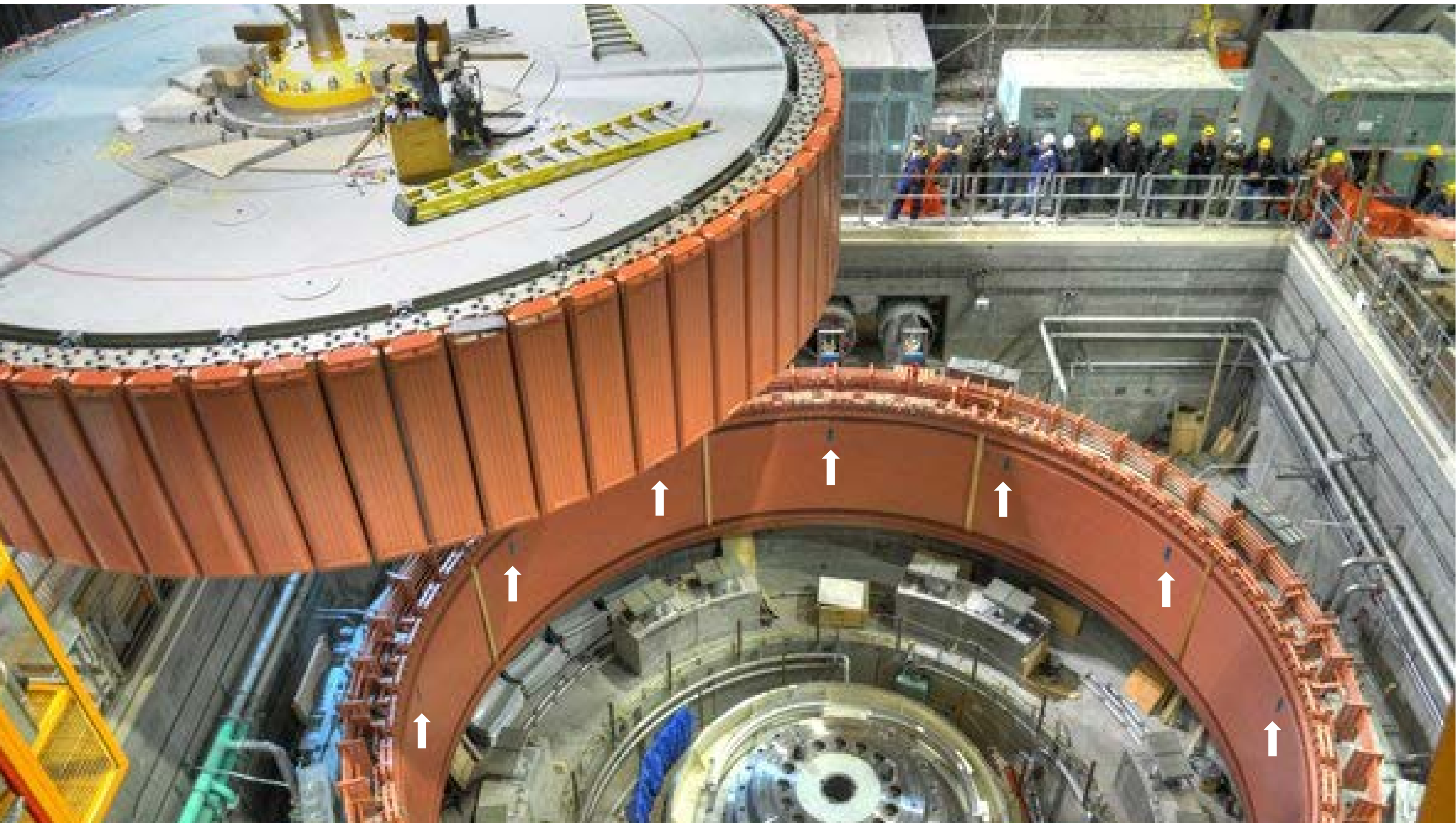

Figure 2: A hydro generator rotor being lowered into place. Note the relative size of the ladder atop the rotor and of the workers along the railings. Such massive sizes are quite common in many hydro plants where vertically oriented turbine-generator units are used. Note also the single layer of stator-mounted air gap sensors (seven are visible) as indicated by the white arrows.

spaced sensors around the stator periphery so that a complete picture of rotor and stator shape and clearances (air gap) can be determined. Figure 4 is an example of one such plot (rotor profile) available from suitable air gap sensor data.

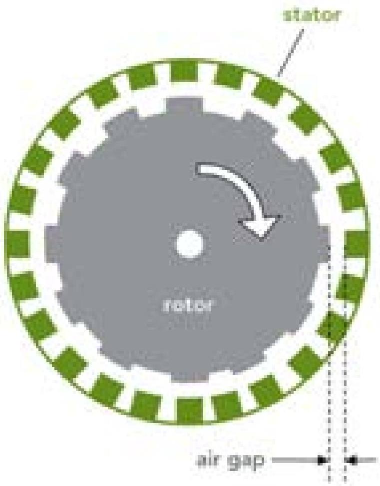

Figure 3: Air gap in a generator.

Why Measure Air Gap?

Air gap is at the heart of the turbine-generator because it is where the mechanical forces and electromagnetic forces intersect. Changes in air gap are indicative of many different problems and it is thus an important measurement that provides insight into more potential problems in a hydro unit than almost any other single measurement – more than even radial vibration.

Figure 5 shows the key components in the generator[8] rotor/stator assembly while Figure 6 superimposes onto the same illustration the numerous areas in which relative movement between the two can occur, resulting in a non-uniform air gap.

Other sources of non-uniform air gap include constantly varying centrifugal, thermal, and magnetic forces that are capable of distorting the stator and rotor of the generator. For this reason, air gap cannot simply be measured on the unit at rest because there are dynamic contributions – not just static. Lastly there is the issue of manufacturing and assembly tolerances that cannot be precise enough to result in rotors and stators of such large geometries that are perfect in concentricity, circularity, alignment, and all other aspects.

As the size of a hydro-generator increases, all of these contributing factors become more pronounced and the need for monitoring air gap becomes more acute. This explains why air gap measurements are generally warranted on hydro units above 50 MW in size[9].
Air gap is thus a combination of contributing factors that may act in isolation or interact in complex fashion. Root cause could be anything from a loose pole to a shifting foundation to a thermal hot spot, or a combination of factors.

While non-uniform air gap reduces operational efficiency, this is not the only reason (or even primary reason) it is monitored. Instead, non-uniform air gap can be indicative of more serious problems that lead to potentially catastrophic breakdowns if the causes are not understood and corrected. Consequently, the incentives to monitor air gap entail far more than simply optimizing maintenance intervals – they include the avoidance of catastrophic failures and the associated safety and economic consequences.

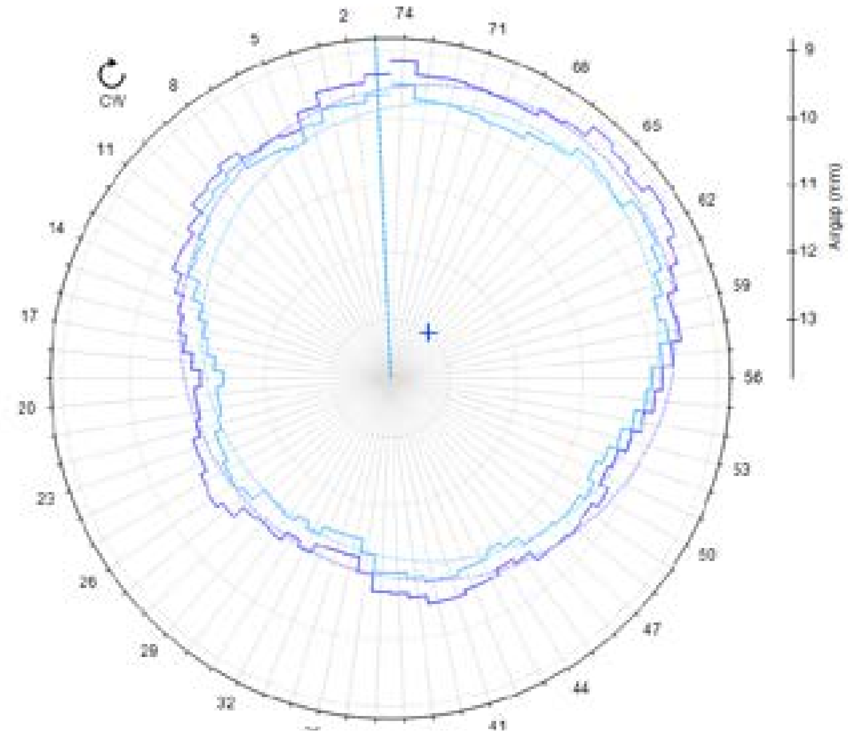

Figure 4: Air gap data is collected via multiple sensors placed at uniformly spaced intervals around the stator and allows the creation of plots such as this rotor profile. The data can be used to generate other important plots and information including rotor circularity, rotor eccentricity, min/max/average air gap, and more.

> "Vibro-meter's air gap sensing chain consist of two components:
>
> a sensor with 5m or 10m of integral cables and a companion signal conditioner "

How to Measure Air Gap? Sensing Chain

Vibro-meter's air gap sensing chain consist of two components: a sensor with 5m or 10m of integral cables and a companion signal conditioner. The two required cables (transmit and receive) are provided with separate connectors but within a single jacket. The 5m and 10m length options allow sufficient length to connect the stator-mounted sensor to its associated signal conditioner, located in a nearby junction box. The 10m length is used on stators where the additional length is needed to exit the machine, or where the junction box is not immediately adjacent.

While the sensor is designed to withstand the large magnetic fields[10] inside a generator, it is important to note that it is intended only for air-cooled generators – not the hydrogen-cooled generators typically associated with large steam turbine-generator trains.

Two sizes are offered. The LS120

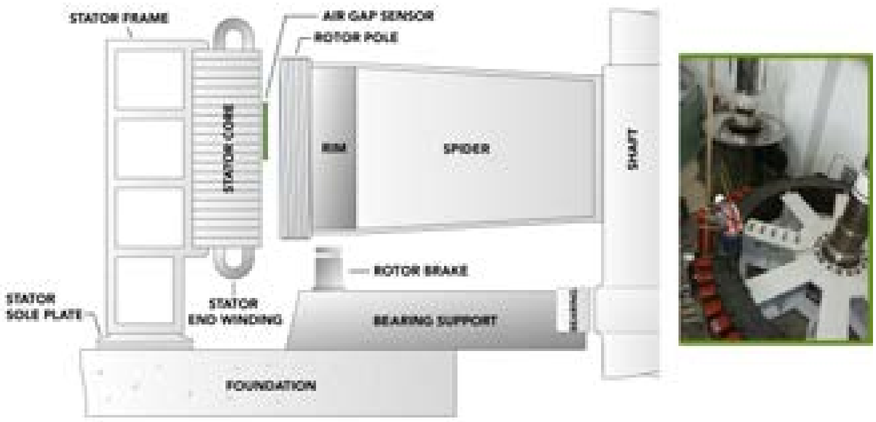

Figure 5: Cross-sectional diagram of a vertical hydro-generator rotor, stator, and supports. The inset photo shows a comparatively small unit where workers are installing rotor pole pieces with the aid of a crane. The spider (gray) is clearly visible as is the shaft, the rim (black), and the pole pieces (red).

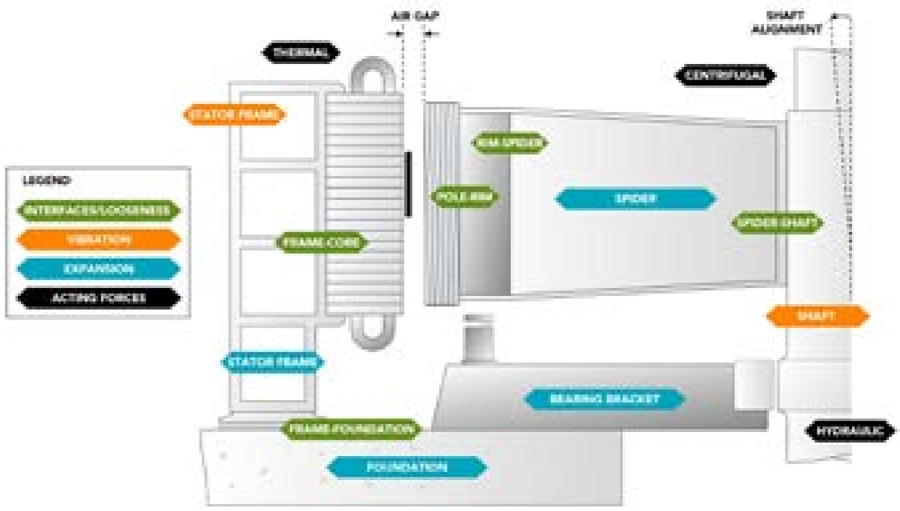

Figure 6: Multiple sources of static and dynamic movement exist in large hydro-generator assemblies resulting in non-uniform air gap. Continuous measurement of air gap around the entire periphery of the rotor allows problems to be detected and isolated.

is designed to measure air gaps between 5mm and 30mm while the LS121 is designed to measure air gaps between 20 and 60mm as encountered on larger generator geometries[11]. Each size has its own corresponding signal conditioner – the ILS730 and the ILS731.

Mounting

Air gap sensors are affixed to the stator and the measurement is thus sometimes referred to as "stator-mounted air gap" to distinguish it from rotor-mounted[12] air gap.

The sensors are placed uniformly around the stator periphery as shown in Figure 7. The recommended number of sensors is generally a function of rotor outer diameter and can vary from as few as 4 to as many as 12 (Table 2).

The number of sensors can also vary based on the height of the rotor pole pieces. However, the need for multiple layers tends to be more subjective based on customer preferences and practices, but is done to account for the tilt that can occur due to vertical misalignment and the corresponding differences in air gap between the top of the rotor versus the middle and bottom of the rotor. The sensors can thus be arranged in layers, allowing multiple profiles – one for each layer. A very large machine with a rotor diameter of 13m and a height of 2m might thus have 3 layers of sensors with 12 sensors per layer for a total of 36 air gap sensors. Profiles would then be available for three vertically spaced layers: top, middle, and bottom. Other machines might require only a single layer and still others only two layers. The upper-most layer is the most important in protecting against rotor-to-stator rubs.

Table 2

Recommended Quantity of Air Gap Sensors versus Rotor Diameter

Generator Rotor Diameter	Number of sensors
< 7 m	4 (every 90°)
7 - 10 m	6 (every 60°)
10 -13 m	8 (every 45°)
> 13 m	12 (every 30°)

Depending on height (H), multiple layers (horizontal planes) of air gap sensors may be required.

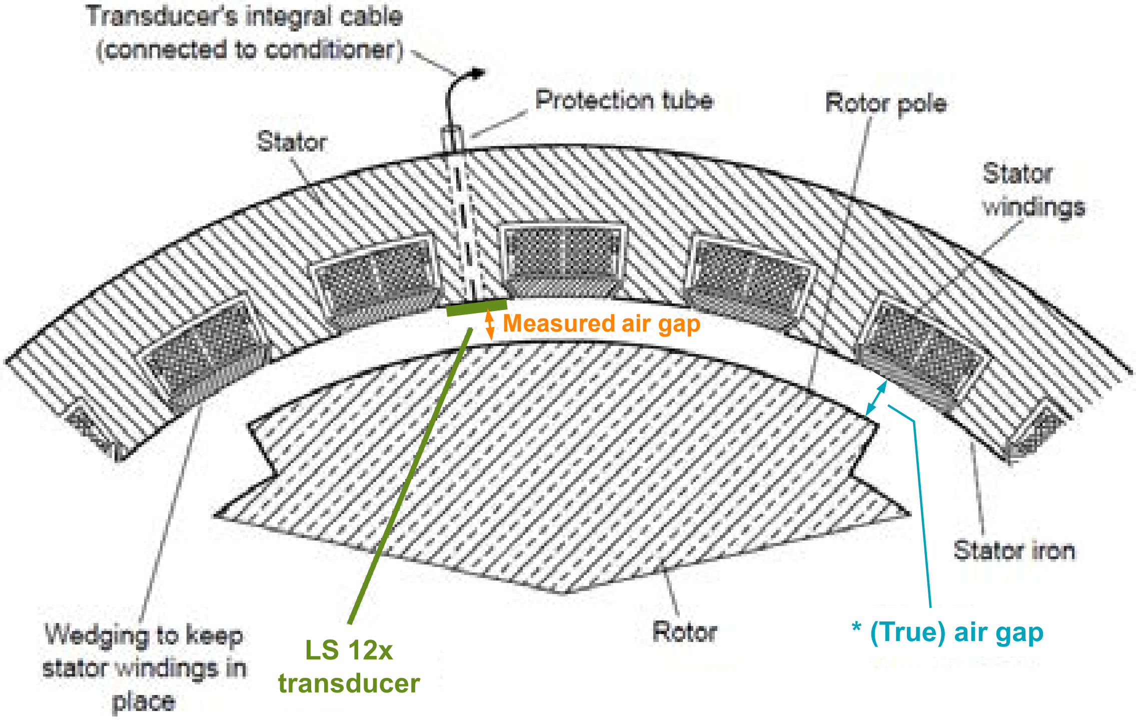

Figure 7: Air gap sensors are mounted on the stator at locations between its windings (see also inset photo showing three sensors in place on the stator). The number will depend on the rotor diameter and may be as few as 4 for small machines to as many as 12 for large machines. Although there is a difference between the measured air gap and the true air gap due to the thickness of the air gap sensor and the layer of adhesive affixing it to the stator, this difference is compensated for in VibroSight software, ensuring that plots and data always reflect the true air gap.

Signal Formats

The sensing chain's principle of operation is that as the distance (air gap) between the rotor and stator changes, the capacitive coupling between the transmitter and receiver elements of the sensor will change. This results in a modulated signal at the receiver, reflecting the instantaneously changing air gap – known as the pole profile – in the form of a time-varying waveform, similar to the output from any other dynamic sensor.

The signal conditioner also processes this waveform into two additional measurements: minimum gap and rotor profile. Minimum gap is exactly as would be expected: the smallest air gap regardless of where it occurs. It is typically used as the input to a protection system such as our VM600 or VibroSmart where it can be displayed, alarmed, and perhaps trended.

In contrast, the rotor profile signal is used primarily during system commissioning and verification. It is not further detailed here but is discussed at greater length in the product manual.

Lastly, the pole profile (waveform) signal is used in companion condition monitoring software such as our VibroSight suite where numerous plot types and measurement extractions are available along with supplementary software alarming. In those instances where continuous condition monitoring is not installed, the pole profile signal is available at the monitor's buffered output connector for access by portable instrumentation. It is worth noting that the minimum gap can be provided as a proportional 4-20mA signal[13] for connection to a PLC or other platform when a conventional vibration monitoring system is not used.

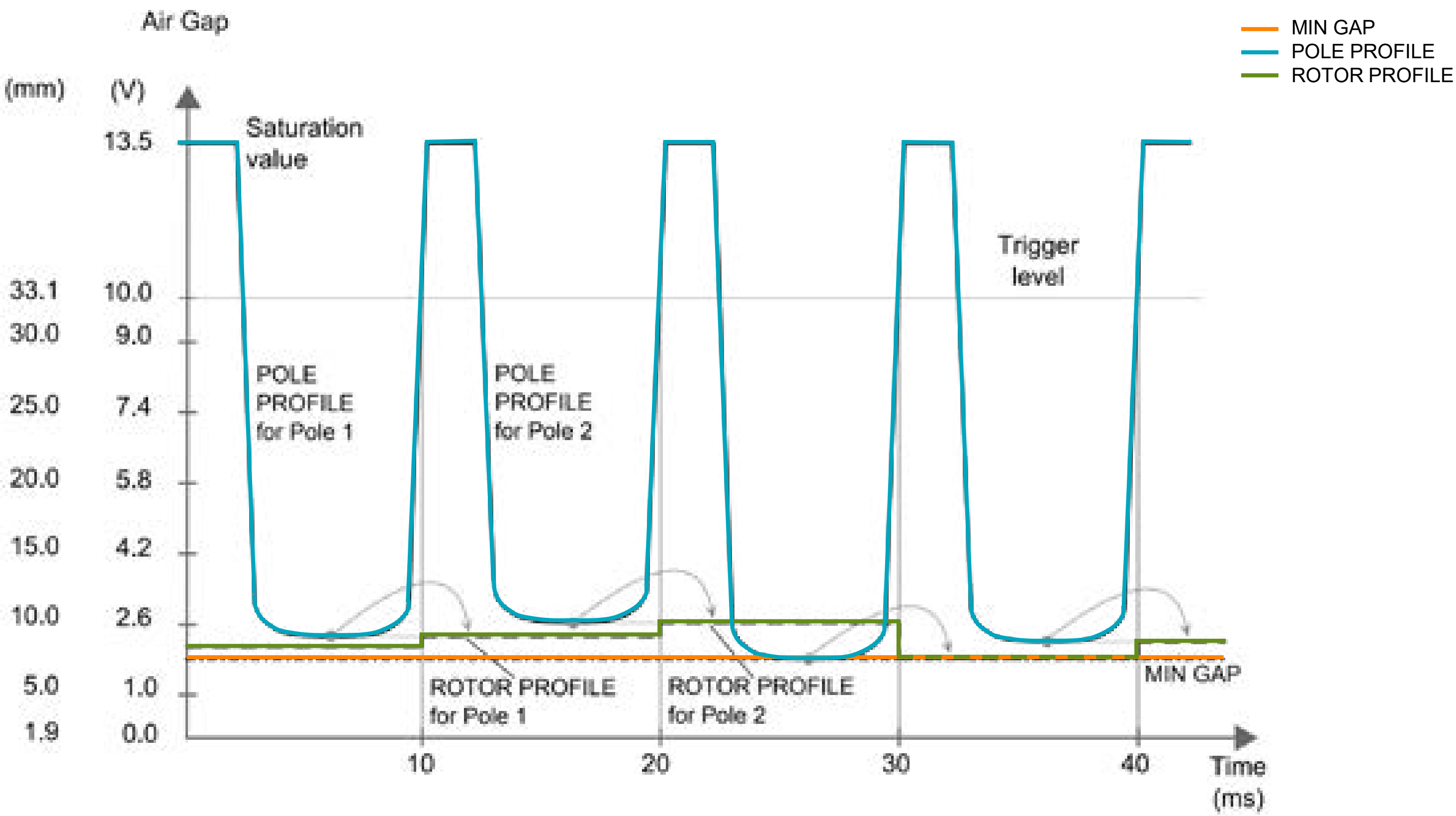

Figure 8: The signal conditioner takes the instantaneous raw sensor signal (pole profile) and generates two additional measurement signals useful for monitoring and alarming: rotor profile and minimum gap.

"The vibro- meter air gap measurement chains are the best on the market. The sensing technologu is better than the competitors in that it does not require lineariza-tion in the driver and that the driver outputs a processed signal like minimum gap as well as pole profile and rotor profile."

— Douglas E. Franklin
CIGOL CONSULTING LTD.

Differentiation

A significant part of vibro-meter's heritage is an emphasis on quality. Although it is embodied in all our products, nowhere is it more important than in our sensors given the harsh locations in which they must often survive. Unlike monitoring systems and software that can be addressed even when a machine is running, this is not the case for sensors such as air gap and robustness becomes even more important. Replacing an air gap sensor means not just stopping the unit, but pulling the generator rotor and thus entailing a major, planned outage.

Another area where our air gap sensing chain differentiates itself is in the signal quality. As was noted above, our air gap sensors output minimum air gap and rotor profile, not just the raw signal (pole profile). This means that they do not necessarily require an accompanying monitoring system to extract measurements from the raw pole profile signal and can thus be applied to smaller machines where monitoring might be done in a PLC using a 4-20mA signal. Also, our signal conditioner does not require special linearization[14] and ships from the factory already calibrated for use with the sensing element. In contrast, some competitors require field linearization and thus increased commissioning costs.

Monitoring

As was previously noted, the minimum gap is available directly from the signal conditioner as a proportional voltage and/or current and is frequently brought into a permanent protection system such as our VM600 or VibroSmart where it can be displayed and alarmed using adjustable ALARM and TRIP setpoints. The pole profile, on the other hand, is a dynamic waveform and is used in our VibroSight condition monitoring system to generate the various measurements and plot types useful for condition monitoring.

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Analysis

As has been conveyed, the air gap measurement is useful precisely because it reflects many different sources of static, quasi-static, and dynamic movements within the hydro-generator and its support structure. In this respect, it is like an audio waveform that may reflect the contributions of a 20-member band. To use this analogy further, the job of the analyst becomes that of extracting the guitar, the bass, the keyboards, the cymbals, the kick drums, etc. When air gap non-uniformities occur, it thus becomes necessary to determine what is contributing to the change and how to remedy the situation. In some cases, examination of the various air gap plots alone can isolate the issue. In other cases, supplemental measurements are needed. For example, if the stator has shifted, a soleplate displacement measurement can be helpful in isolating this. Or, if a preload exists on the shaft, X-Y radial vibration probes would allow shaft eccentricity to be correlated with generator rotor eccentricity as revealed by air gap sensors and profiles.

A discussion of the various data types, presentation formats (see Figure 4, for example), and interpretation thereof is beyond the scope of this article, but may be the topic of a separate future article. Suffice to say here that our VibroSight software possesses the capabilities (Table 3) to collect, process, extract, and display the air gap data necessary for proper analytics and can even be used to generate automated analytics using the Rule Box component of the software suite.

CEATI Conformity

Vibro-meter is active in numerous industry groups as it allows us to better understand the needs of our customers, industry trends, applicable standards, and evolving best practices. One such industry group is CEATI (Centre for Energy Advancement through Technological Innovation). CEATI has developed

Table 3
VibroSight Airgap Monitoring Capabilities

	Measurements	
Polar wavefront plot	**Layer Level**	**Sensor Level**
Dedicated polar wavefront plot for the display of hydro air-gap measurement such as rotor and signatures. Capability to store baseline profiles and overlay with other real time and saved profiles.	• Layer rotor signature • Layer pole gap (P*n*) • Layer max/min/avg gap • Layer rotor eccentricity • Layer rotor circularity • Layer rotor ellipticity • Layer stator shape • Layer stator eccentricity • Layer stator circularity • Layer stator ellipticity	• Rotor shape • Rotor signature • Pole gap (P*n*) • Max/min/avg gap • Rotor eccentricity • Rotor circularity • Rotor ellipticity

several thousand technical reports and guides over the years, including one dealing with alignment and circularity measurements in hydro generators[15]. We have produced a separate application note[16] on this topic which you are encouraged to download and read. It details the importance of such measurements and why adherence to this CEATI guideline is likewise important. The guideline reflects the combined experience and ensuing best practices compiled from dozens of hydroelectric operators, OEMs, and consulting engineers.

Figure 9: The guidelines in CEATI's documents are essential for properly computing hydro generator rotor circularity. As such, vibro-meter uses them in both our monitoring hardware and in our VibroSight® software. We have also published a companion application note with additional information on the topic of rotor circularity calculations.

Conclusion

Air gap is perhaps the single most useful measurement for assessing the overall health of large-diameter hydro turbine-generator units. That said, it is best used in conjunction with a suite of other measurements to provide total protection and condition monitoring capabilities.

Vibro-meter's air gap monitoring capabilities extend from the sensing chain to the monitor to the condition monitoring environment and are thus comprehensive.

This article has briefly explored what air gap is, how it is monitored, and perhaps most importantly, why it is monitored. You can learn more about not just air gap, but all the various hydro-related machinery measurements by contacting your local vibro-meter sales professional to learn about our portfolio of products and services. You can also visit our hydro application pages.

Notes

1 Continuous air gap monitoring is also used in other niche applications, such as the gearless drives for mills used in the mining industry and occasionally very large horizontally mounted generators driven by steam and gas turbines.
2 The definition of so-called "small hydro" varies by country but is generally deemed to be installations smaller than 30MW, whether from a single machine or multiple machines. Small hydro is considered to have a smaller environmental impact because it diverts only part of a stream or river rather than the entire flow and may even use existing irrigation canals or reservoirs.
3 Gearboxes are used to increase the speed from the turbine to a speed that allows a generator with fewer poles to be used. For example, if the turbine output speed is increased to 1500 rpm via a gearbox, a 4-pole generator can be used for 50Hz electricity. Gearboxes can be used on turbines up to about 10MW in size. Above that, the generator is directly driven by the turbine.
4 Source: GlobalData (www.globaldata.com), power industry database
5 Refer to this informative Quora post for a succinct description of why salient pole generators must be so large.
6 The largest machines by power output to-date are the 1770MW steam turbines provided to the Hinkley Point Nuclear Station in the UK. A small number of conventional thermal plants (such as Belews Creek in North Carolina) have steam turbines of 1GW or larger, but this is rare.
7 The exact root cause has been postulated but not conclusively isolated. What is known is that excessive vibration had been present for nearly a decade prior to the accident and that it had increased hours prior to the accident.
8 Because air gap measurements pertain to the generator (not the turbine), we confine ourselves to discussion of the generator in this article.
9 The importance of air gap measurement is actually more closely associated with generator rotor diameter than with power output. However, a general rule of thumb is that air gap is usually measured on units with power outputs of 50MW or greater because these units generally have generator rotor diameters large enough to warrant measurement. Regardless, there are notable exceptions such as the Bieudron Hydroelectric Power Station in Switzerland which has units that are each 423MW, but no corresponding need for air gap measurements because of the unique generator designs resulting in relatively small rotor diameters.
10 Up to 1.5 Tesla
11 Vibro-meter air gap sensing chains can also be used to measure extended ranges 25% larger than those shown here, which are the ranges for ±1.5% linearity. Consult the product datasheets for the transfer characteristics and linearity over these extended ranges.
12 Rotor-mounted air gap has been attempted over the years by others but is no longer commercially available. Rotor-mounted sensors are generally discouraged in machines due to complications in the supply of necessary power to so-called "flying electronics" along with the centrifugal forces generated by the spinning rotor that can make it challenging to the securely retain such sensors on rotating parts – particularly at the outmost diameter of a generator rotor where centrifugal forces are greatest.
13 A factory-changeable option also exists to use the 4-20mA output for the rotor profile or the pole profile; minimum gap, however, is the default and typical use of this output.x
14 The underlying operating prnciples of vibro-meter air gap sensors result in a signal that is inherently linear over the useful range. This allows sensors and signal conditioners to be easily interchanged, simplifying stocking and usage of spare parts. In contrast, the operating principles underlying competitive designs may require considerable linearization in the signal conditioner. In some cases, this can introduce interchangeability constraints and necessitate individual tuning and matching of sensors to signal conditioners, adding complexity and cost to spare parts strategies.
15 CEATI HPLIG Project T122700 0381 (May 2015), *Hydroelectric Turbine-Generator Units Guide for Erection Tolerances and Shaft System Alignment*. Montreal, Canada: Centre for Energy Advancement through Technological Innovation (CEATI)
16 *Rotor Circularity Calculation for Hydro Turbines*, vibro-meter application note (2016).


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