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Experimental Pressure Measurements on Hydropower Turbine Runners

A Review of In Situ Methods to Quantify Hydropower Turbine Blade Pressures at Model and Prototype Scales

December 2016

SF Harding
MC Richmond

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Summary

The range of hydrodynamic operating conditions to which a hydropower turbine is exposed results in significant pressure fluctuations on both the pressure and suction sides of its blades. Understanding these dynamic pressures and their effects has a range of applications.

- Structurally, the resulting dynamic loads are significant in understanding the design life and maintenance schedule of the bearing, shaft, and runner components. The pulsing pressures have also been observed to have a detrimental effect on the surface condition of the blades.
- Biologically, the pressure gradients and pressure extremes are the primary driver of barotrauma for fish passing through hydropower turbines.
- Improvements in computational fluid dynamics (CFD) modeling can be used to simulate such unsteady pressures in the regions of concern. High-frequency model-scale and prototype-scale measurements of pressures at the blade are important in the validation of the CFD models.
- Experimental characterization of pressure fields over hydropower turbine blades has been demonstrated by a number of studies that have used multiple pressure transducers to map the pressure contours on the runner blades. These studies have been performed at both model and prototype scales, often to validate computational models of the pressure and flow fields over the blades.

This report provides a review of existing studies in which the blade pressure was measured in situ. The report assesses the technologies for both model- and prototype-scale testing. The details of the primary studies in this field are reported and used to inform the types of hardware required for similar experiments in the US. Ice Harbor Dam, owned by the U.S. Corps of Engineers, on the Snake River in Washington State is used as an example in this report. Such a study would be used to validate the CFD modeling performed for the biological performance assessment (BioPA) method developed at the Pacific Northwest National Laboratory (PNNL).

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Acronyms and Abbreviations

°C	degree(s) Celsius
CFD	computational fluid dynamics
DAQ	data acquisition
EPFL	Swiss Federal Institute of Technology
Hz	hertz
IMHEF	Institute of Hydraulic Machines and Fluid Mechanics
kHz	kilohertz
m	meter(s)
mbar	millibar
Mbps	megabytes per second
NI	National Instruments
NTNU	Norwegian University of Science and Technology
PTFE	polytetrafluoroethylene
RPM	revolutions per minute
USACE	U.S. Army Corps of Engineers
USB	universal serial bus
V	volts
WLAN	wireless local area network

Contents

Figures

Tables

1.0 Introduction

Hydropower represents a renewable energy source that has the unique ability to complement more intermittent methods of power generation through control of the plant output at off-design operating points. The inflow characteristics of hydropower turbines are highly variable and unsteady as a result of complex fluid-structure interactions and high pressure gradients through the machine. The range of hydrodynamic operating conditions to which a turbine is exposed results in significant pressure fluctuations on both the pressure and suction sides of the blades. Understanding the resulting dynamic loads and their effects are significant in determining the design life and maintenance schedule of the bearing, shaft, and runner components. The unsteady pressures detected at the runner also cause barotrauma for fish during their passage through a hydropower turbine (Richmond et al. 2014a).

Experimental characterization of pressure fields over Kaplan and Francis turbines blades is an inherently challenging exercise. This is a result of the limited access to the runner blade, the required modification of the runner blade to house pressure sensors, as well as the challenges of making measurements from a rotating component of the machine. While draft tube flow conditions have been investigated to identify the nature of the unsteady loads, the source of the disturbances is difficult to locate without the experimental mapping of pressure on the runner blades.

One continually improving technique for calculating the pressure distributions numerically is to use computational fluid dynamics (CFD) modelling. High-frequency in situ pressure measurements are able to refine and validate the numerical solutions calculated using CFD codes at the locations of the pressure sensors and, in doing so, they ensure the appropriateness of CFD for use in this application.

The instrumentation of hydropower turbine runners with pressure transducers has been performed by a number of research groups in recent years for both model and prototype scale blades[1]. The primary difference between these two scales of study is the available surface area on the blade for the array of pressure taps. A significant number of pressure taps are required to capture the spatial variability of the pressure distribution on both the pressure and suction side of the blade (Figure 1). In the case of the model-scale devices, this spatial resolution of pressure taps cannot always be implemented on a single blade. To resolve this issue, multiple blades can be instrumented and the measurements from a number of blades can be phase corrected to infer the pressures with increased spatial resolution on a single blade.

This report provides a review of existing studies in which the blade pressure was experimentally measured and provides an assessment of the technology for both model- and prototype-scale testing. This overview presents the range of existing approaches to in situ blade pressure measurements and will be used to inform the design of similar experimentation for the validation of the CFD modeling performed for the biological performance assessment (BioPA) method developed at the Pacific Northwest National Laboratory (PNNL) (Richmond et al. 2014b; Richmond et al. 2015). This method uses CFD simulations to model the three-dimensional flow through the hydropower turbine unit, allowing the hydrological stressors (of which pressure is one) to be extracted throughout the hydropower turbine unit. These stressors are related to biological performance of fish through dose-response models in the BioPA method.

[1] In the case of model-scale blades the geometry featured reduced dimensions relative to the full-scale device; while in the case of the prototype-scale blades the geometry featured dimensions equivalent to the full-scale device.

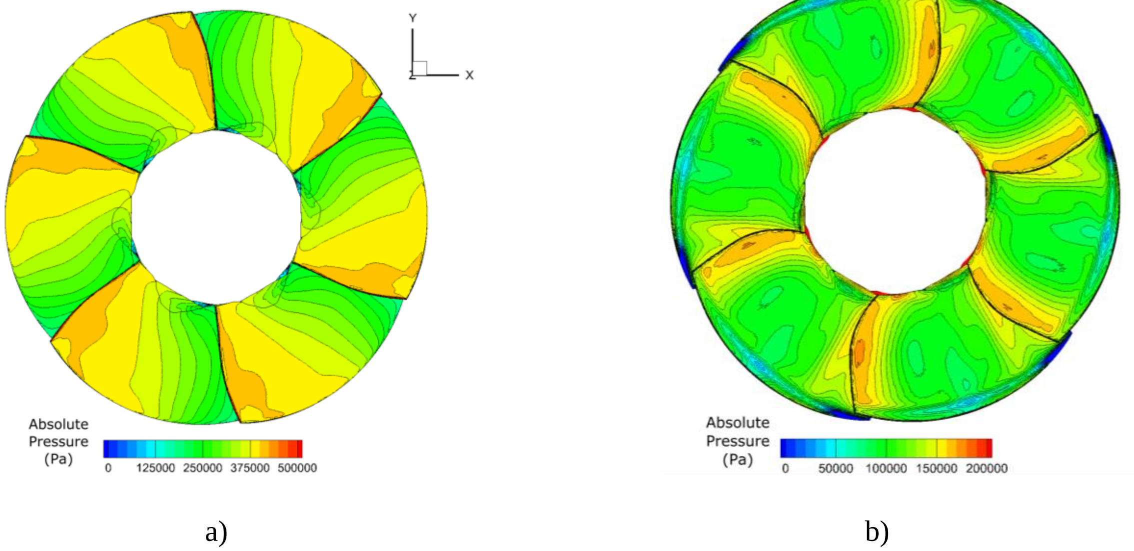


Figure 1. CFD-derived pressure distribution on a) the pressure side and b) the suction side of a Kaplan runner at Ice Harbor Dam, in Washington State.

2.0 Review of Recent Studies

This section provides a review of the technologies and methods used in recent studies to increase understanding of the effects of unsteady pressures on runner blades. The list of studies is not exhaustive, rather it represents those most relevant to the present topic. A summary of the studies is presented in Table 1. The study technologies and methods for both model- and prototype-scale testing are described in greater detail below the table.

Table 1. Summary of recent studies.

	Research Facility	Papers	Turbine Type	Prototype Design	Model Scale/ Output	Turbine Diameter
Model Scale	Luleå University of Technology, Sweden & Vattenfall Älvkarleby, Sweden	Amiri et al. 2015	Kaplan: Porjus U9	Kvarner AB (Andritz Hydro)	1:3.1 Model	0.5 m
Model Scale	Waterpower Laboratory, NTNU, Norway	Trivedi et al. 2013 Kobro 2008	Francis	Andritz Hydro AG and Kværner Brug	1:5.1 Model	0.35 m
Model Scale	Laval University, Québec, Canada	Houde et al. 2012a Houde et al. 2012b Deschênes et al. (2010).	Propeller: AxialT	1950s era propeller turbine	Model	~ 0.3 m
Model Scale	EPFL-IMHEF, Lausanne, Switzerland	Avellan et al. 2000	Francis	-	Model	0.3 m
Prototype Scale	Tokke Power Plant, Norway	Kobro, 2009	Francis	Andritz Hydro AG	Prototype	1.8 m
Prototype Scale	Porjus Hydropower Centre, Sweden	Jansson and Cervantes 2007 Cervantes et al. 2008	Kaplan: Porjus U9	-	Prototype	1.55 m

2.1 Model- Scale Experiments

2.1.1 Luleå University of Technology, Sweden

Twelve piezo-resistive pressure sensors (Kulite® LL-080 series, shown in Figure 2 and Figure 3) were installed on the model runner blades, flush with the surface. Six of the sensors were mounted on the pressure side of one blade (Blade 1), and six were mounted on the suction side of the following blade (Blade 2). The sensor locations are defined by the vertices of the 1/3 and 2/3 span lines and the 1/4, 1/2, and 3/4 chord lines (Figure 3b).

The pressure range of the sensors was 0–7 bar to account for transient pressures during startup, which were expected to be greater than the transient pressures during normal operation. The natural frequency of the selected pressure sensors was 380 kHz, which significantly exceeded the expected excitation frequencies of the experiments.

The measured pressure data is transmitted during the experiment using a dedicated telemetry system. This technique allows the measured pressure data to be transmitted wirelessly from the rotating blades to a fixed receiver and recorder. The telemetry system, made by Summation Research Inc. (Figure 4), was installed for each blade to transmit pressure data from the rotating shaft to a stationary receiver. The telemetry system had a data transfer rate of 17 kHz. The transmitter component of the telemetry system was installed on the rotating shaft and transmitted the measured pressure signals to the stationary receiver through the model walls.

The receiver model was connected to a National Instruments (NI) data acquisition (DAQ) system (PXI chassis with four NI-4772 DAQ Cards) that had 24-bit resolution and recorded pressure data over an acquisition period of 5 minutes at a sampling frequency of 4 kHz.

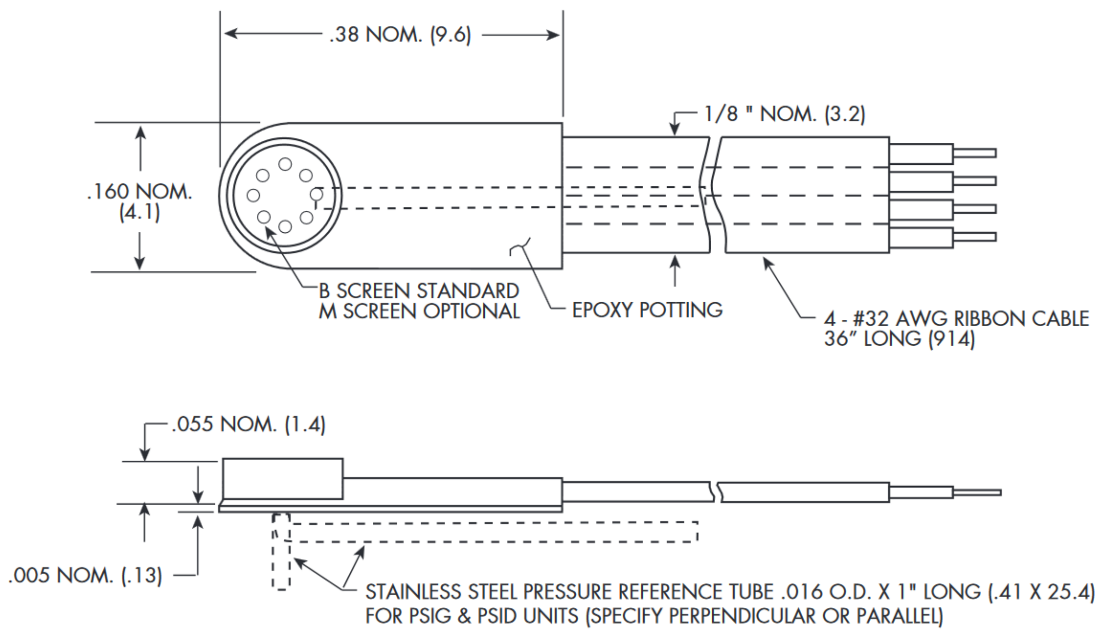


Figure 2. Schematic of a Kulite® LL-080 Series thin line pressure transducer (Kulite 2016). Dimensions are in inches. Dimensions in parenthesis are in millimeters.

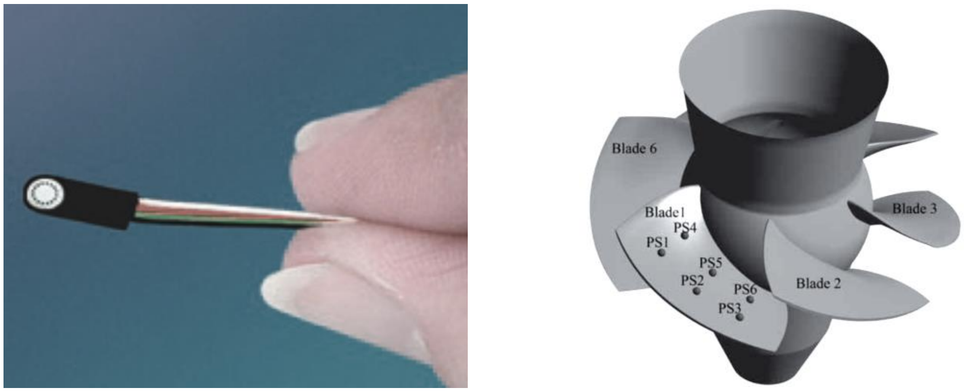


Figure 3. Representative location of pressure transducers (left) on the model turbine blades (right) (Kulite 2016 and Amiri et al. 2015).

Figure 4. Summation Research Inc. 500e Series telemetry system receiver (a) and transmitter (a and b) (SRI Inc. 2016).

2.1.2 Waterpower Laboratory, NTNU, Norway

The work of Trivedi et al. (2013a) was performed in the Water Power Laboratory at NTNU (Norwegian University of Science and Technology), using the model-scale test rig, which allows scaled model testing at 1:5.1 scale of the prototype, with a runner outlet diameter of 0.349 m.

In this work on a Francis turbine model, pressure taps were mounted on the pressure side of a blade (2) and the suction side (1) as well as on the inlet pipeline (2), vaneless space (1), and draft tube cone (2). Pressure signal samples were logged at a frequency of 2083 Hz. The pressure sensors used in the runner blades were Kulite LL-080 devices (0-350 kPa abs), also used by Amiri et al. (2015). These sensors have a bandwidth of approximately 100 kHz and a natural frequency of 300 kHz.

As with the experiments of Amiri et al. (2015), a Summation Research SRI-500e wireless telemetry system was used to transmit data from the miniature sensors on the rotating runner to the stationary receiver outside the test rig. Analog data were sent through a HBM DC voltage amplifier (10 kHz) to a NI2939 input module (50 kHz) in a NI universal serial bus (USB) DAQ (cDAQ9172, 400 kHz).

The logging frequency was selected based on the following factors:

- maximum possible blade passing frequency
- at least one sample per degree of runner rotation
- communication between transmitter and receiver of telemetry system was possible without loss off data or delay in transmission.

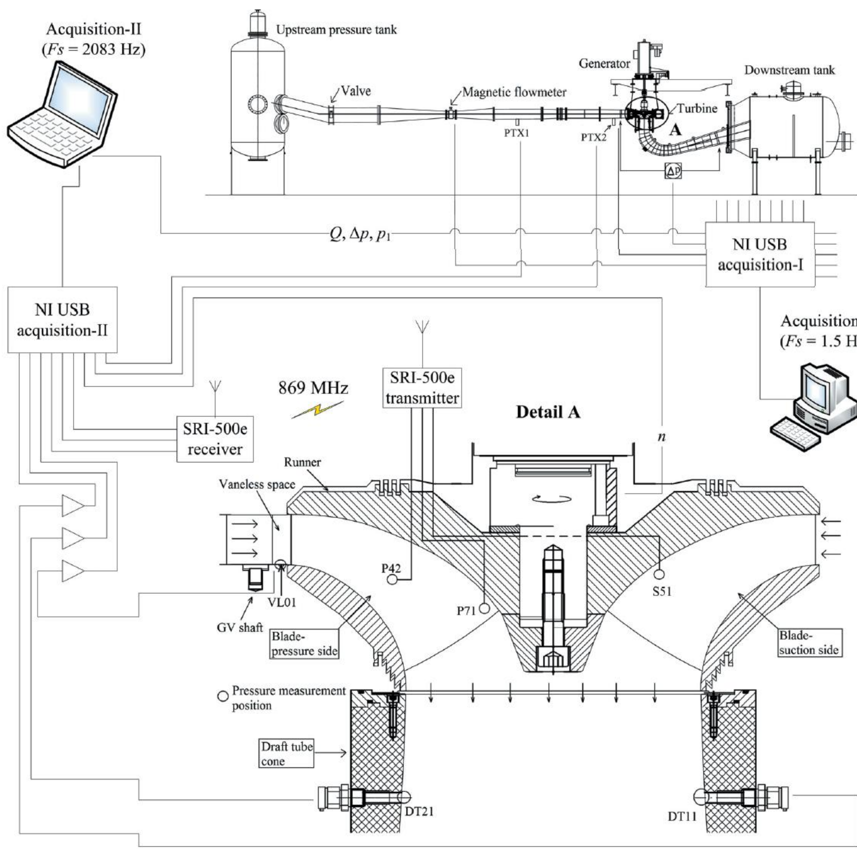


Figure 5. Schematic of experimental test rig and data acquisition systems showing locations of pressure sensors: P42, P47, and S51 (Trivedi et al. 2014).

The work of Kobro (2008, 2009) was completed at the same laboratory during a time when the Tokke power plant in Telemark, Norway, was being refurbished. This allowed the opportunity for both model- and prototype-scale instrumentation of hydropower turbines in collaboration with Andritz Hydro AG.

The 5:1 model-scale measurements were performed at NTNU in the Waterpower Laboratory using two model Francis turbine runner designs—one designed by Andritz Hydro AG (the VA Tech Hydro runner) and the other by NTNU.

For the model-scale blade instrumentation, miniature Kulite LL080 strain gauge-based pressure transducers were selected rather than piezoelectric type transducers to allow the absolute pressure to be measured. The pressure signals were transmitted from the runner using the Summation Research PMD 500e with programmable gain and anti-aliasing protection, analog-to-digital (AD) conversion, and a multiplexer board. Power was supplied to this system using a 9 V battery. Grooves were milled into the blade to contain cables and were then filled with epoxy to maintain a smooth surface on the blade.

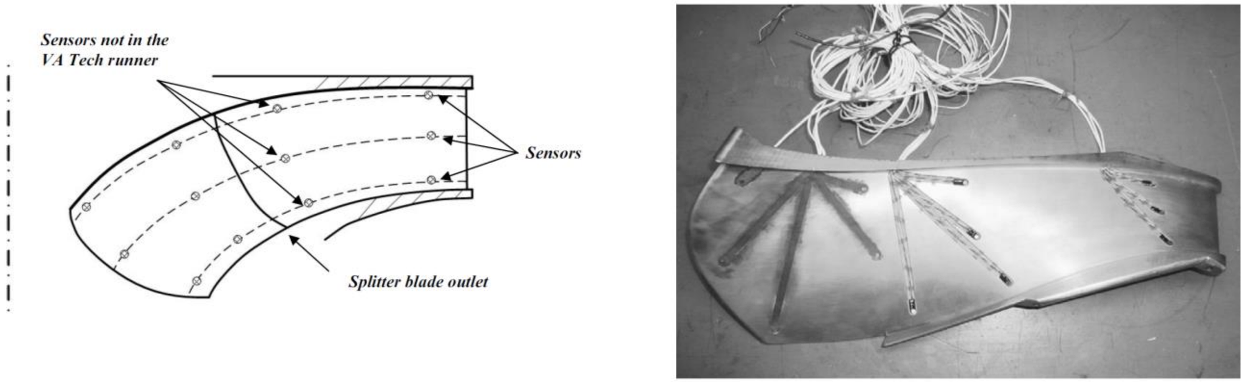


Figure 6. Sensor locations and installation on NTNU model runner blade (Kobro et al. 2008).

2.1.3 Laval University, Québec, Canada

The work at Laval University was carried out as part of an initiative instigated by the Consortium on Hydraulic Machines (of which the partners are Alstom Hydro, Andritz Hydro, Edelca, Hydro-Québec, NRCan, CanmetENERGY, Voith Hydro and Laval University). The Consortium was formed to create and maintain a major research center for the development of hydraulic turbines in Canada. For further background information on this project, refer to Deschênes et al. (2010).

The turbine being studied for the AxialT project was a six-bladed 1950s era propeller turbine that had a semi spiral casing and 24 guide and stay vanes (Houde et al. 2012b). As with Amiri et al. (2015), two adjacent blades were instrumented with pressure sensors. In this study, significantly more sensors were installed—9 on the pressure side of Blade 1 and 11 on the suction side of both Blade 1 and Blade 2. The placing of these sensors was nonlinear and followed the pressure gradients identified from CFD flow simulations with increased spatial concentrations occurring near the leading and trailing edges.

Again, a telemetry system was used to transmit the pressure sensor outputs from the rotating shaft to stationary data acquisition hardware. The telemetry system was a 32-channel, custom design by Atcom Telemetry, that had a sampling rate of 5 kHz. Power was provided to the system via an induction device rather than via conventional batteries. The data acquisition system was based on three 16-channel NI cards, with 200 kHz and 16-bit resolution capabilities.

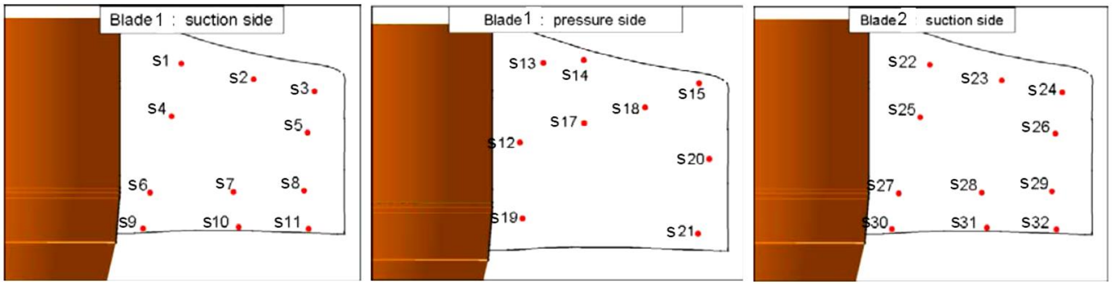


Figure 7. Pressure sensor locations on Blade 1 and Blade 2 (Houde et al. 2012b)

2.1.4 EPFL-IMHEF, Lausanne, Switzerland

Avellan et al. (2000) developed a procedure to instrument model turbine blades with miniature piezo-resistive pressure sensors (Figure 8). In this pressure sensor design, the surface of the blade was coupled to the sensor via a plastic compound that had the same acoustic impedance as water. Using this design approach the sensor could be installed below the surface of the blade with minimal geometric alteration to the blade surface. The measurement error of the design is quoted as being less than 1 mbar absolute pressure (Farhat et al. 2002b).

Because of the size of the model blades, the number of pressure transducers installed on each blade was limited to six. In total, four blades were instrumented with six pressure transducers on each. Two blades were instrumented on the pressure side and two on the suction side. An additional four transducers were mounted in the runner band. The cross section of the Keller pressure transducers used and a representative instrumented blade are shown in Figure 8. The pressure range of the transducers was 0–3 bar with a frequency range of up to 15 kHz. These were calibrated in a static rig at EPFL Laboratory and verified by the Voith Hydro test rig. Dynamic calibration was performed at EPFL using a Kistler high-precision transducer.

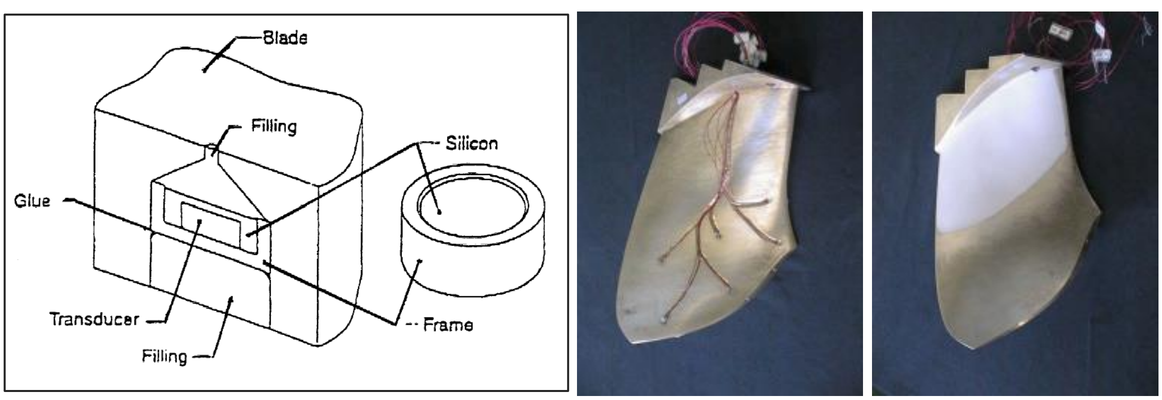


Figure 8. Schematic diagram of Keller miniature piezo-resistive pressure transducer and pressure sensor locations on single blade of the model Francis turbine showing the transducer mounting channels and finished blade surface (Avellan et al. 2000).

Transducers were wired to signal-conditioning modules on the model runner crown that were fed into eight data acquisition modules (Figure 9). These modules were able to store 32,768 samples per channel at 20 kHz and 12-bit resolution, which equated to more than 1 second of data.

After the data were acquired, they were transferred to the central laboratory computer through slip rings via an ARCnet (attached resource computer network) transfer protocol for further processing. This networking system is a local area network, similar to Ethernet services, that has data transfer rates of up to 2.5 Mbps.

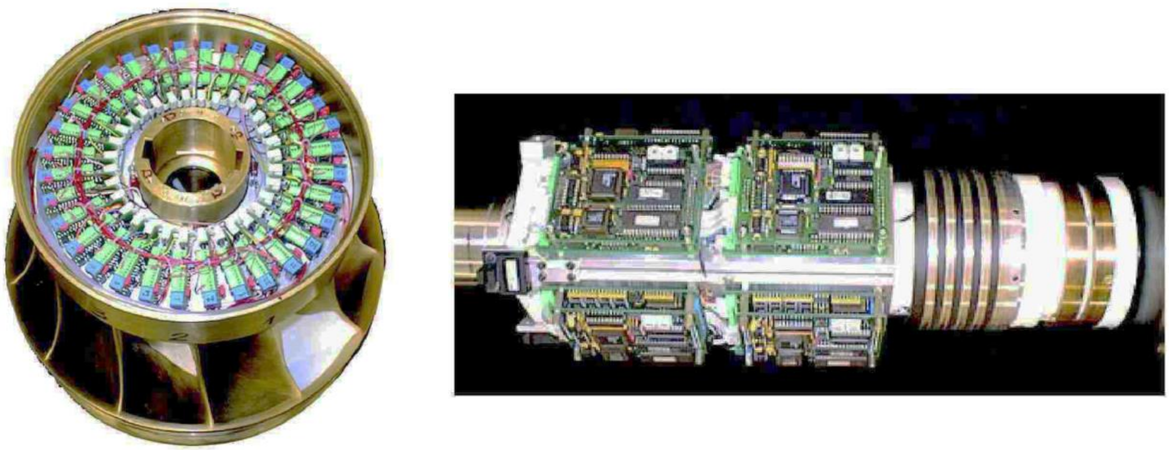


Figure 9. Conditioning electronics in the crown of the Francis turbine (left) and eight DAQ boards and slip ring for power and communications fitted on the turbine shaft (right) (Farhat et al. 2002b).

2.2 Prototype Experiments

2.2.1 Tokke Power Plant, Norway

During the refurbishment of the Tokke power plant, Statkraft, Andritz, and NTNU performed a collaborative research project on pressure pulsation. Statkraft funded the majority of the project (costs not disclosed). Andritz contributed to funding and project organization and worked with NTNU to instrument the runners. At the time of the experiments (to the knowledge of Kobro et al. (2009)), pressure measurements on the runner blades had not been performed on both the model-scale and prototype-scale designs of the same unit. As such the experiments performed in this study provided the unique ability to validate pressure measurements from a scaled model with a full size prototype of the same device.

Two types of pressure transducers were used in the prototype experiments. Three Kulite LL-080 sensors used in the model tests were installed at the runner blade outlet, while three Kistler 7037 Quartz pressure sensors were installed at the inlet (Figure 10 and Figure 11). Strain measurements were also taken on the runner blade outlet using 350Ω strain gauges at 16 locations; 10 in the radial direction and 6 in the tangential directions, with 14 of these on the suction side and 2 on the pressure side.

In the interest of minimizing the alteration to the turbine components, a high-frequency data-logging (rather than telemetry) system was used in the prototype-scale testing (Figure 12). In contrast to the telemetry techniques described in Section 2.1, which transmit the data to a recorder outside of the rotating reference frame, the data logger in this set of experiments is mounted in runner cone. As such, the recorded data is not accessible until the test is complete. The system consisted of a NI Compact-Rio 9014 Real-Time controller. The chassis housed seven modules (of the available eight slots), to collect both strain and pressure data. Two of these modules (NI 9237) were used to log the outlet pressure collected by the Kulite pressure sensors. A single NI 9239 module was used to acquire the amplified voltage signal from the Kistler pressure sensors at the inlet. The Compact-Rio was powered using a 24 V battery pack to avoid the need for external power and collected 24-bit resolution data at a frequency of 1613 Hz. As a prime number, this acquisition frequency was selected to reduce aliasing effects.

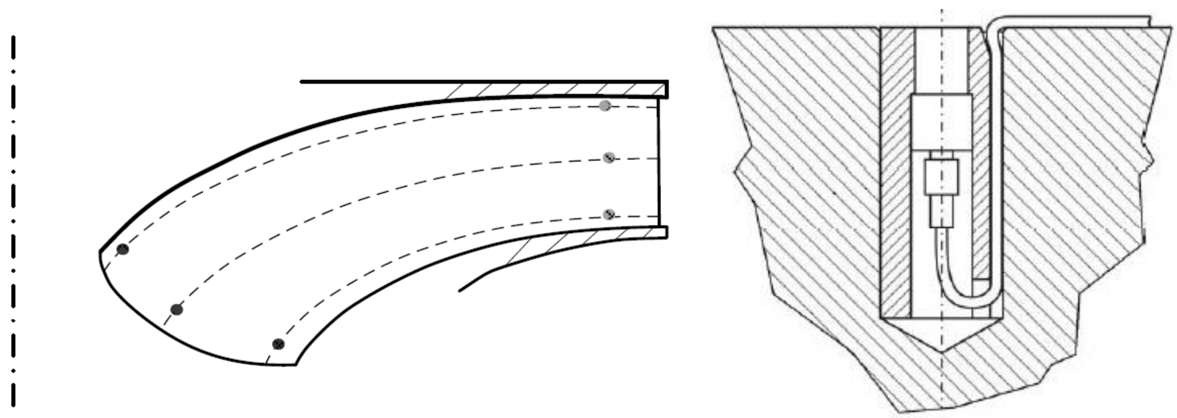


Figure 10. Sensor locations and installation on Andritz Hydro prototype runner blade. The light grey markers indicate the Kistler Quartz pressure sensors at the inlet (detailed right) and the dark grey markers indicate the position of the Kulite sensors at the outlet (Kobro et al. 2009).

The pressure transducers were mounted on the blades using a cyanoacrylate adhesive and the cable runs stayed downstream of the sensor heads. The cables were covered with polyester filler. The cables entered the watertight data-logger compartment through watertight holes.

The first experimental campaign used the original Kværner runner. No data were retrieved from these tests because the logger became flooded. The flooding of the data logger was not detected until after the experiments because, unlike the model-scale tests, no data were being transmitted from the unit.

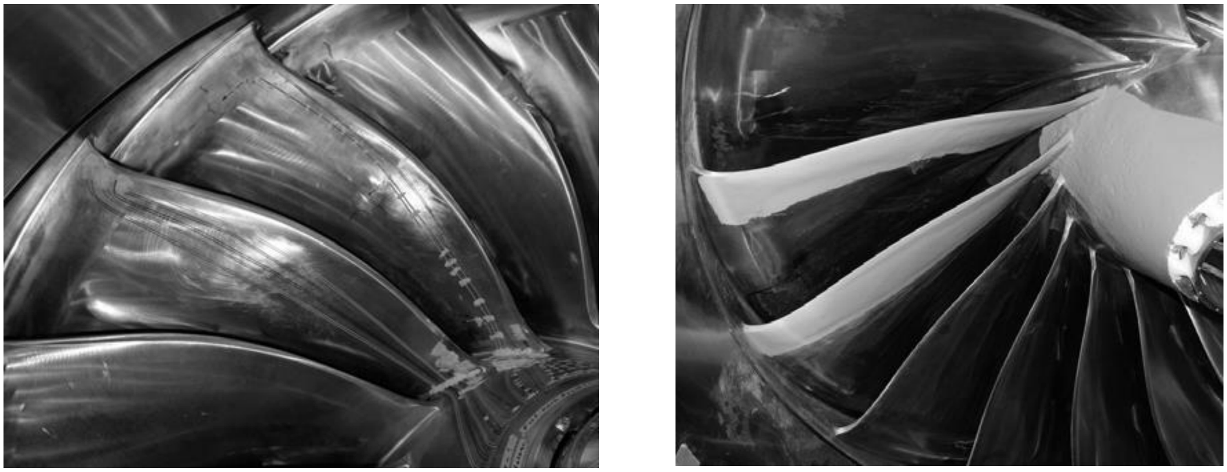


Figure 11. Sensor installation on blades before and after covering (Kobro et al. 2009).

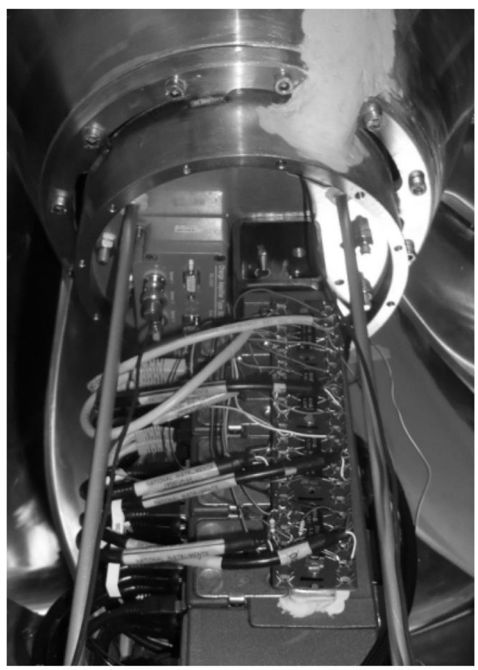


Figure 12. National Instruments Compact-Rio logging unit in the runner cone with the waterproof casing removed (Kobro et al. 2009).

The mixed success of data acquisition from this configuration highlights the risk of onboard data acquisition that cannot be verified until the experiment is completed. When the data are transmitted from a device in real time, damage to the data acquisition system can be detected immediately, which removes the risk of completing an experimental campaign without acquiring a successful data record.

2.2.2 Porjus Hydropower Centre, Sweden

In this study, piezo-resistive pressure transducers were mounted on both the pressure and suction side of 1 of the 6 runner blades with 20 sensors on each side as shown in Figure 13 (Cervantes et al. 2008). The locations of these pressure sensors were informed by CFD to locate the maximum and minimum blade pressures as well as regions of significant pressure gradients.

The installation objectives were a compromise between two specifications:

- to minimize machining of the blade to limit alteration of the mechanical properties of the unit, and
- to enable broken sensors and cabling to be replaced with relative ease.

To achieve the above-listed objectives the pressure sensor was mounted to a small metal flange which enabled it to be mounted onto the blade with two screws. The channels from the blade hub to the pressure sensors were fitted with a polytetrafluoroethylene (PTFE) conduit prior to filling them with resin so that the communication cables could be removed and replaced without affecting the blade surface.

The resonant frequency of piezo-resistive pressure transducers satisfies the condition of being greater than five times that of the measured frequency (Stoker 2005) due to its low mass and high stiffness. The high impedance of the pressure transducers allows them to be digitized further from the source than common strain gauges and in this setup the data acquisition system (NI cRIO-914) was located on the rotating shaft at the top of the generator. This location has easy access, low humidity, and low centrifugal loads.

In this case, a wireless local area network (WLAN) is used to connect the slave modules of the data acquisition system to the master computer using the angular position of the rotor to synchronize the signal from the total of five slave NI cards. The slave modules are powered through a slip ring to the rotating shaft.

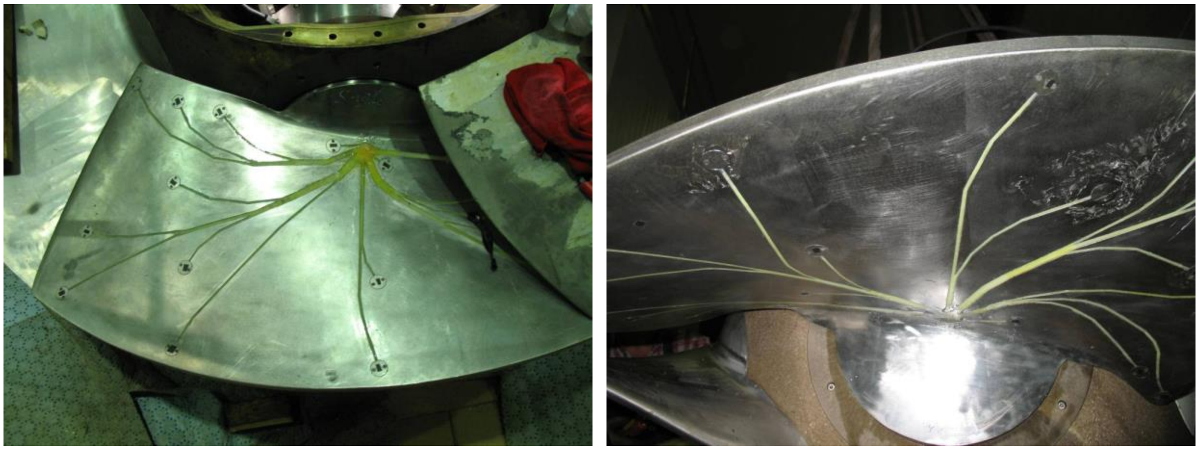


Figure 13. Pressure sensor locations on a single blade of a Porjus U9 turbine (Cervantes et al. 2008).

The pressor sensors are sensitive to water temperature, which in some rivers can range from 0–20°C (Jansson and Cervantes 2007). The pressure sensors must, therefore, be calibrated prior to every test. Unlike the model-scale blades, which can be placed inside pressure calibration chambers, the prototype-scale instrumentation must be calibrated on a sensor-by-sensor basis owing to the large geometry of each blade and the inherent difficulty associated with sensor removal and reinstallation. To do this, Jansson and Cervantes (2007) suggest a calibration system consisting of a pressure calibrator and suction cup (Figure 14). The portable pressure calibrator is used to supply a range of pressure levels in the range of 0–10 bar. This pressure is applied to the pressure sensor through the use of a suction cup, which surrounds the pressure sensor. The custom-made suction cup is fastened to the surface of the blade by drawing down the pressure in the outer region of the cup to below 0.4 bar.

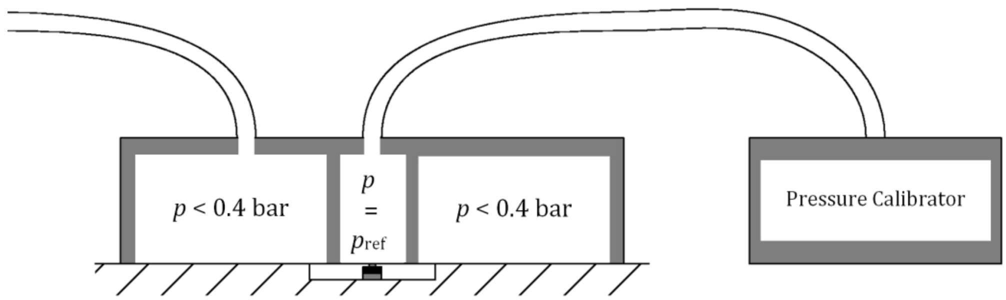


Figure 14. Calibration system for prototype pressure taps. Modified from Jansson and Cervantes (2007).

2.3 Summary of Recent Studies

The review of recent studies presented in this section is useful in identifying the challenges that are common to all such experiments and the varied approaches and successes in the approaches used.

All of the experiments reviewed achieved the installation of multiple pressure transducers on each blade, ranging from 3 to 20 on a single blade. All model-scale experiments distributed the pressure transducers over multiple blades to maximize the available area on the turbine runner. The pressure readings from different blades were synchronized through accurate encoder measurements in post-processing to allow the pressures measured from different blades to be considered together.

The pressure transducer layout ranged from a grid-like distribution of locations to irregular spacing. In the case of the latter, the location of the pressure transducers was informed by the pressure maxima, minima and gradients identified using CFD simulations.

The challenge of limited space for hardware installation and data acquisition was encountered by all tests and addressed in a variety of way. The majority of experiments used telemetry – the wireless transmission of data from the rotating runner to a fixed receiver – to transfer the data from the turbine. Not only does this remove the spatial constraints for the subsequent data acquisition hardware, but allowed real-time access to experimental data during the experiments. In a similar way, the EPFL-IMHEF experiments transferred data from the data acquisition units on the runner crown through slip rings via an ARCnet transfer protocol for processing outside of the turbine unit. In contrast to this, the prototype experiments at the Tokke Power Plant utilized an onboard data acquisition system whereby the data was acquired and stored in the runner cone and accessed at the conclusion of the testing.

3.0 Discussion

The following section presents a discussion of the implications and practicalities of conducting in-situ pressure measurements on both model- and prototype-scale hydropower turbines. To begin, the importance of the metric of pressure in the context of BioPA is summarized with emphasis on the validation on the CFD simulations developed (Section 3.1). Following this, a detailed discussion of the data collection methods reviewed in the previous section is presented (Section 3.2) and applied to an example hydroelectric power station of Ice Harbor Dam (Section 3.1). This discussion section of the report concludes by presenting cost estimates for model- and prototype-scale tests (Section 3.4).

3.1 Validation of CFD for BioPA

The in situ measurement of blade pressures is a valuable data set for the validation of the CFD performed for BioPA purposes for the following reasons:

1. Pressure is an indicator of flow quality. Knowledge of the pressure on the surface of the blades informs flow instabilities such as cavitation, separation, and unsteady flow conditions. The understanding of these flow conditions is critical to predicting the mechanical loads and hydrodynamic conditions that the blades must withstand. Such flow conditions are able to be predicted using CFD and therefore can be validated with experimental pressure data.
2. Pressure measurements are able identify symptomatic mechanical issues in turbine operation. A comparison of experimental pressure measurements with CFD models is therefore able to identify discrepancies in the mechanical operation and operating conditions of the two approaches.
3. Pressure is the stressor that has the most well understood biological impact on fish passage owing to the ability to observe dose-response relationships using currently available techniques (Brown et al., 2009; Brown et al., 2012). As such, the validation of the pressure measurements at the blade surface provides important input information for these experiments.

3.2 Data Collection

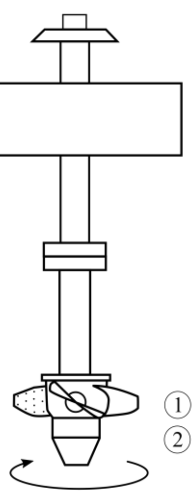
Following the literature review of Section 2.0, two distinct configurations of data collection can be classified (Table 2):

- Option 1: Onboard data storage in rotating turbine components
- Option 2: Real-time wireless data offload from the rotating to stationary regions of the turbine.

Kobro et al. (2009) preferred collecting the data onboard in rotating turbine components (Option 1, Table 2) to reduce the permanent alteration of the turbine that was required to implement telemetry. Specifically, onboard data collection does not require the pressure transducer wires to travel any farther than the hub cone. The primary limitation of this configuration is the restricted access to the data during and after testing. With the data acquisition hardware submerged in the hub cone (albeit in a waterproof casing), data collection malfunction cannot be detected until the test has been concluded and the data retrieved. This was observed in the experiments of Kobro et al. (2009), who were unable to recover the data from one full test schedule due to water intrusion that was not detected until the tests were concluded. The risk of this failure in an operational hydropower station is unlikely to be acceptable.

The second option mitigates these risks by installing the additional hardware that allows wireless real-time data transfer between the rotating and stationary regions of the turbine. The location of the wireless transmitter is required to be above the turbine, away from any humidity, which necessitates running the transducer wires up out of the hub cone. In this case a junction box in the nose hub was used by Cervantes et al. (2008) to simplify the wiring. It is typically a best practice to digitize an analog signal as close to the sensor as possible; however the pressure sensors have a very high impendance, which protects the signal from voltage loss and signal interference along a longer cable run (Cervantes et al. 2008). With this in mind, the data acquisition system can be mounted on top of the generator, in line with the rotational access of the turbine shaft—a dry location with minimal centrifugal loads induced by the shaft rotation. This location was chosen for the data acquisition system and WLAN transmitter in the Porjus U9 Kaplan turbine prototype experiments.

Table 2. Data acquisition configurations on the hydropower turbine prototype.

<table>
<tr><th colspan="2">Option 1:Onboard data storage</th><th colspan="2">Option 2:Real-time wireless data offload</th></tr>
<tr><td colspan="2">


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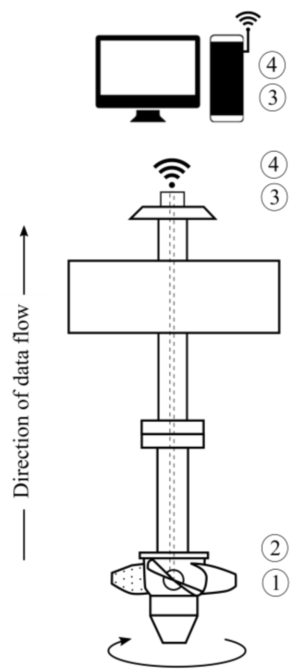

</td></tr>
<tr><th>Location</th><th>Component</th><th>Location</th><th>Component</th></tr>
<tr><td>1</td><td>Pressure sensors installed on blade</td><td>1</td><td>Pressure sensors installed on blade; wires fed through hole in trunnion to junction box in hub cone</td></tr>
<tr><td>2</td><td>Wires fed through hole in trunnion to DAQ system in waterproof casing in hub cone</td><td>2</td><td>Wires fed through hole in trunnion to junction box in hub cone</td></tr>
<tr><td></td><td></td><td>3</td><td>Conversion from analog to digital signals at DAQ in dry space above turbine</td></tr>
<tr><td></td><td></td><td>4</td><td>Digital signal transmitter</td></tr>
<tr><td></td><td></td><td>5</td><td>Digital signal receiver</td></tr>
<tr><td></td><td></td><td>6</td><td>Desktop computer</td></tr>
</table>

The frequency of data acquisition and transfer (if data are not stored on the rotating components) must be significantly greater than the frequency of rotor rotation in order to obtain the pressure information at each blade position with meaningful resolution. The rotor rotation rate of the previous model- and prototype-scale studies have ranged from 273–697 RPM as shown in Table 3. This corresponds to a rotation of 0.08°–1.44° between consecutive samples. In other words, a total of 250–4400 samples were acquired for each rotor revolution.

Table 3. Pressure data range and sample frequency details

	Research Facility	RPM	Pressure Range	DAQ Sample Frequency	Telemetry Transmission Frequency	Rotation Angle (°) per Sample
Model Scale	Luleå University of Technology, Sweden	696.3	0-7 bar	4 kHz @ 24 bit	17 kHz	0.25
	Waterpower Laboratory, NTNU, Norway	544	0-3.5 bar	2.1 kHz @ 16 bit	N/A	1.55
	Laval University, Québec, Canada	-	0-2 bar	200 kHz @ 16 bit	5 kHz	-
	EPFL-IMHEF, Lausanne, Switzerland	273	0-3 bar	20 kHz @ 12 bit	N/A	0.08
Prototype Model Scale	Tokke Power Plant, Norway	375	0-7 bar	1.6 kHz @ 24 bit	N/A	1.41
	Porjus Hydropower Centre, Sweden	600	0-7 bar	2.5 kHz @ 16 bit	WLAN	1.44

3.3 Application of in situ pressure instrumentation to Ice Harbor Dam

A representative case study was considered using the Ice Harbor Dam as the example facility. This facility was selected due access to an existing CFD model that could be used to look at typical pressure distributions and provide a realistic case for a study design. Ice Harbor was selected as a case study for the example study design and is not confirmed to be a final candidate for any possible field studies.

For the case of Ice Harbor Dam, which operates with a nominal rotation speed of 90 RPM (USACE 2016), the data acquisition rate to achieve a minimum resolution of 1440 samples per revolution (one sample for every 0.25° rotation) would be 2.16 kHz. This frequency of data acquisition and transmission is achieved in most of the studies reviewed in Section 2.0 and can be achieved by the hardware used to generate the cost estimates in the following subsection.

The loss of data in the onboard data acquisition system of the Tokke Power Plant studies demonstrates the risks involved in avoiding real-time data transmission. Therefore, an application of the approach used in the Porjus Hydropower Centre studies is recommended for similar in situ measurements at Ice Harbor Dam.

The location of the pressure sensors should be selected to sample the maxima and minima pressures on each side of the blade. A higher concentration of sensors over regions of rapidly changing pressure is also desirable. Such regions can be located by using numerical simulations of the turbine performance based on CFD (Cervantes et al. 2008). CFD simulations performed on the Ice Harbor Dam runner (found in units 1-3) are presented in Figure 15. The recommended arrangement of both 12 and 24 pressure sensors shared evenly across the pressure and suction side of a single blade is indicated with black circles.

As with all of the model and prototype tests reviewed in Section 2.0, the instrumentation of the runner blade or blades with pressure sensors requires some modification of the blade. Specifically, the pressure sensor must be installed in a recessed hole and the wires must be run to the hub below the surface of the blade. This is achieved by machining channels in the blades and fastening the wires inside the channels with adhesive and or epoxy resin.

Cervantes et al. (2008) note that the experimental setup must facilitate the replacement of the sensor and associated wiring in the event of instrumentation failure. As such, the pressure sensors are often mounted on a casing that can be quickly fastened to the machined recess in the blade using two screws. To increase the ease of rewiring the sensors, it is suggested that a PTFE conduit be enclosed beneath the resin to allow wiring to be removed and replaced without disrupting the surface finish over the channels.

Access to the hub is obtained by machining an access hole at the trunnion of the instrumented blade. The wires from each transducer would be fitted with a connector inside the hub. The access to such locations is limited, and the instrumentation may require to be deployed for long durations without maintenance. It is therefore important to consider the effects of cyclic loads on the instrumentation hardware and connectors. The integrity of such items may be reduced by vibration and cyclic loads over long periods, and so the longevity of the installation should be considered throughout the experimental design. This will include strain relieve systems of wire connections and vibration-dampening pads between the DAQ hardware and turbine components.

3.4 Cost Estimates

The following cost analysis represents an estimation of the cost of the key components of instrumenting a turbine for pressure measurements on the blades. The cases of 12 and 24 pressure sensors are presented for both the model and prototype turbines. Because of the smaller blade side of the model turbine, the associated pressure sensors are anticipated to be distributed over four blades in the model case, and two blades in the prototype case. The key cost components considered are

- replacement blade manufacture
- pressure sensor hardware
- pressure sensor installation
- data acquisition hardware
- data acquisition installation

- blade installation
- pressure system calibration
- data acquisition system commissioning.

A breakdown of the cost estimate for instrumenting a model-scale test setup for blade pressure measurements is presented in Table 4. The equivalent cost estimate for a prototype-scale instrumentation project is presented in Table 5. Labor costs for both of these cases are yet to be determined because they will be a function of the collaborative opportunities available.

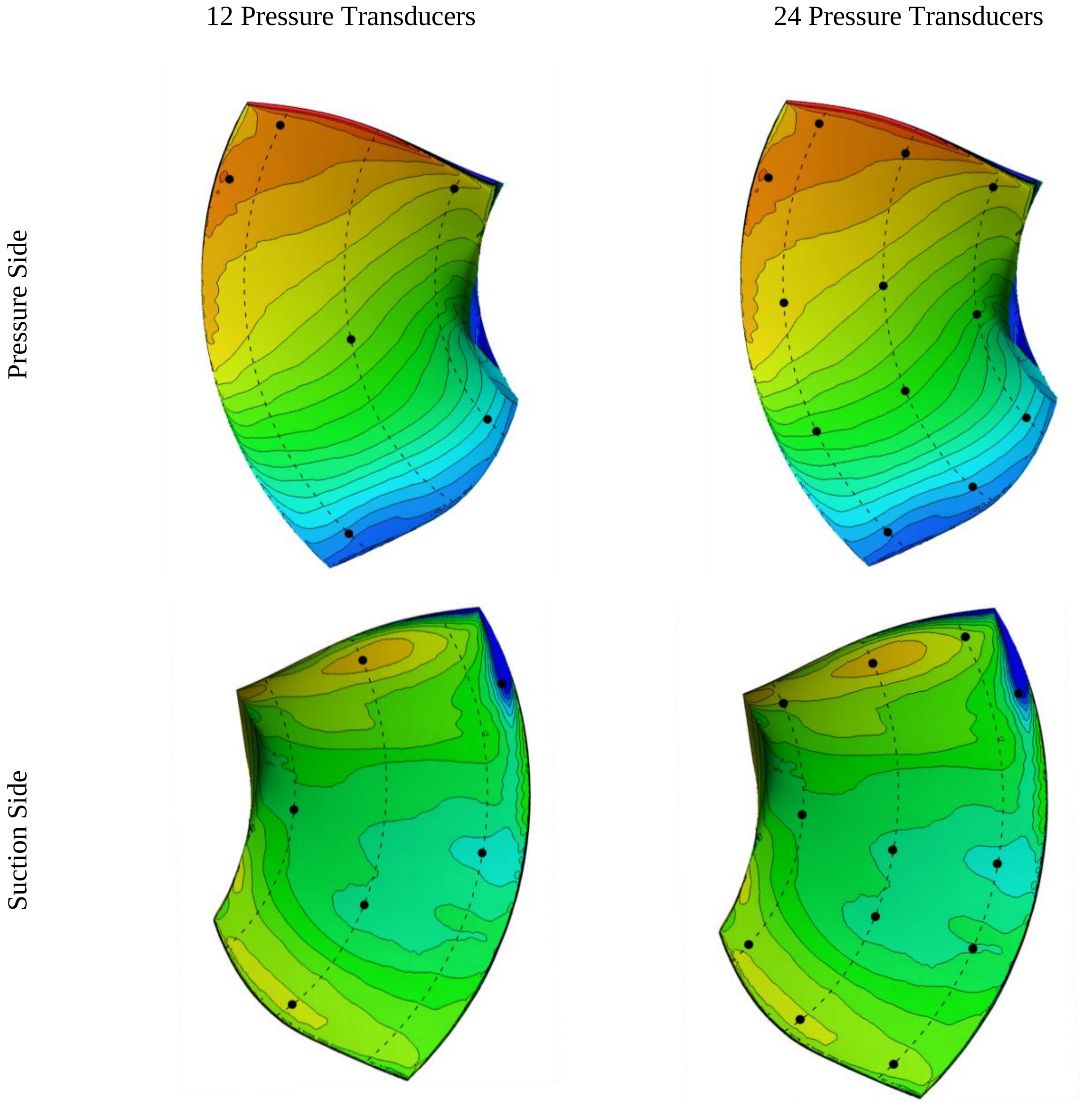

Figure 15. Suggested locations of 12 (left column) and 24 (right column) pressure transducers, indicated using black circles, on the pressure (top row) and suction (bottom row) side of a runner blade at Ice Harbor Dam.

Table 4. Breakdown of cost estimates for instrumentation of hydropower turbine model for pressure measurement

			Number Required		Configuration Cost	
Cost Component	Reference Make / Model	Unit cost (USD)	Option 1: 12 Pressure Sensors	Option 2: 24 Pressure Sensors	Option 1: 12 Pressure Sensors	Option 2: 24 Pressure Sensors
Replacement blade manufacture	NA	$3,000	2	4	$6,000	$12,000
Pressure sensor hardware	Kulite LL-080	$900	12	24	$10,800	$21,600
Pressure sensor installation	Kulite Custom Installation	$500	12	24	$6,000	$12,000
Telemetry system hardware:	LORD V-Link 200M Transmitter	$800	1	1	$800	$800
	LORD WSDA-BASE-104 Receiver	$1,000	1	1	$1,000	$1,000
DAQ system hardware:	NI PXI Chassis	$3,800	1	1	$3,800	$3,800
	NI PXI-PC Interface	$2,250	1	1	$2,250	$2,250
	NI Service Pack	$5,100	1	1	$5,100	$5,100
Data acquisition installation	NA	$5,000	1	1	$5,000	$5,000
Blade installation	NA	$5,000	2	4	$10,000	$20,000
Pressure sensor calibration	NA	$2,000	2	4	$4,000	$8,000
Data acquisition commissioning	NA	$5,000	1	1	$5,000	$5,000
TOTAL					$59,750	$96,550

Table 5. Breakdown of cost estimates for instrumentation of hydropower turbine prototype for pressure measurement

Cost Component	Reference Make/Model	Unit cost (USD)	Number Required		Configuration Cost	
			Option 1: 12 Pressure Sensors	Option 2: 24 Pressure Sensors	Option 1: 12 Pressure Sensors	Option 2: 24 Pressure Sensors
Blade preparation	NA	$10,000	2	4	$20,000	$40,000
Pressure sensor hardware	Custom	$2,000	12	24	$24,000	$48,000
Pressure sensor installation	NA	$10,000	12	24	$120,000	$240,000
Telemetry system hardware:	WLAN	$2,000	1	1	$2,000	$2,000
DAQ system hardware:	NI PXI Chassis	$3,800	1	1	$3,800	$3,800
	NI PXI-PC Interface	$2,250	1	1	$2,250	$2,250
	NI Service Pack	$5,100	1	1	$5,100	$5,100
Data acquisition installation	NA	$50,000	1	1	$50,000	$50,000
Blade installation	NA	$50,000	2	4	$100,000	$200,000
Pressure sensor calibration	NA	$10,000	2	4	$20,000	$40,000
Data acquisition commissioning	NA	$10,000	1	1	$10,000	$10,000
TOTAL					$357,150	$641,150

4.0 Conclusions and Recommendations

In summary, the instrumentation of hydropower turbine blades at both model and prototype scales has successfully been achieved by a number of researchers during the past 15 years. Such projects have been based on identifying the source of several constituents of unsteady loads, which were previously only detected by force measurements as well as pressure measurements in stationary components of the hydropower turbine flow passage.

In situ measurements of blade pressures will benefit the BioPA through the validation of CFD models that have been developed to assess the biological impact of turbine passage for fish. Experimental pressure data are an important metric in the assessment of flow quality, mechanical performance, and fish survival, and so experimental pressure data are a valuable tool in the validation of the BioPA.

Few prototype-scale studies have been completed owing to the increased cost of the operation as well as the reduced access to full scale facilities available to engage in research that may cause disruptions to normal plant operation. The two studies presented in this review are the Tokke Power Plant in Norway and Porjus U9 turbine of the Porjus Hydro Power Centre in Sweden. Both of these studies required significant collaborative efforts with the plant owner and turbine developers.

The key conclusions and recommendations from the review of existing in situ pressure instrumentation are as follows:

1. Pressure measurement locations are most useful for CFD validation at the locations of local pressure maxima and minima as well as in regions of peak pressure gradients.
2. Restrictions in available surface area on model-scale experiments require a grid of pressure taps to be distributed over multiple blades in order to achieve the desired resolution of pressure mapping. The measurements taken on multiple blades are then overlaid in post-processing by accurately measuring the location of the blades at each pressure measurement and synchronizing the results.
3. Real-time data transmission and offload of pressure measurements alleviates the risk of completing an experimental campaign with no recorded results. Onboard data acquisition is prone to such risks.
4. Real-time data offload is achieved using wireless telemetry at the model scale and WLAN at the prototype scale.
5. For Ice Harbor Dam, the data acquisition rate to achieve a minimum resolution of 1440 samples per revolution (one sample for every 0.25° rotation) would be 2.16 kHz. This frequency of data acquisition and transmission was achieved in most of the studies reviewed and can be readily achieved by the hardware identified in the cost estimates.

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Appendix A

Quotes Used in Cost Estimates

LORD Corporation
459 Hurricane Lane, Suite 102
Williston, Vermont 05495
U.S.A.

Tel: (802) 862-6629
Fax: (802) 863-4093
Web: www.lord.com

Quotation

Ship-to Party Address	Information			
PACIFIC NORTHWEST NATIONAL LABORATORY 902 BATTELLE RICHLAND WA 99354	**Quotation No.** 196710 **Document Date** 09/26/2016 **Customer No.** 38170		**Valid From** 09/26/2016 **Valid To** 12/26/2016	

Sold-to Party Address

PACIFIC NORTHWEST NATIONAL LABORATORY
902 BATTELLE
RICHLAND WA 99354

Customer Ref. No.	SAM HARDING	**Incoterms**	FCA SHIPPERS DOCK
Payment Terms	Credit Card	**Currency**	USD
Gross weight	2 LB	**Net weight**	2 LB

Quotation Details

Item	Material Description	Quantity	Unit Price	Amount
	ORDER LEAD TIME: 1-2 WEEKS ARO *LORD CORP IS REQUIRED TO COLLECT SALES TAX ON BEHALF OF THE STATE OF WASHINGTON. IF TAX EXEMPT, PLEASE PROVIDE A SALES TAX EXEMPTION CERTIFICATE.* *SHIPPING IS FEDEX PRE-PAY AND ADD UNLESS OTHERWISE NOTED AND INCLUDES FULL INSURANCE. IF SHIPPING COLLECT, PLEASE PROVIDE A FEDEX OR UPS ACCT NUMBER.* *PLEASE PROVIDE CURRENT SHIPPING/INVOICING INSTRUCTIONS WHEN PLACING ORDER.*			
0010	6312-2000 V-LINK_200-M Country of Origin: US	1	795.0000 per 1 EA	795.00
0020	6307-1041 WSDA-BASE-104-SK Additional Description: WSDA-BASE-104-SK, Wireless USB starter kit, includes USB base station, USB cable, Node Commander software and node charger. Country of Origin: US *Wireless USB starter kit, includes USB base station,* *USB cable, Node Commander software and node charger*	1	995.0000 per 1 EA	995.00
			Freight	30.00
			Tax Amount	118.30
			Total Amount	**$ 1,938.30**

Samuel Harding
Pacific Northwest National Laboratory
902 Battelle Blvd
RICHLAND, WA 99352
UNITED STATES

Quotation Date: 26-SEP-2016
Quote Valid Until: 26-OCT-2016
Phone: +1 (509) 375 3799
Fax:
Contact No: 8558325

Quotation No. 2360243

To ensure order accuracy and pricing, please reference the above quote number when placing your order. For faster order processing, check out online with a purchase order (PO) or credit card.

Line No.	Part Number	Description	Qty.	Unit Price	Discount	Amount
		NI PXI SYSTEM Configuration ID: PX5134203 				
1.1	780321-01	PXIe-1082, 8-Slot 3U PXI Express Chassis Standard Delivery time: 10 - 15 business days ARO. *Country of Origin: Malaysia* Service details for this product: Standard Repair Coverage Duration: 3 Year(s) 15% multiyear discount applied.	1	3,799.00		3,799.00
1.2	763000-01	Power Cord, AC, U.S., 120 VAC, 2.3 meters Standard Delivery time: 10 - 15 business days ARO. *Country of Origin: China*	1	9.00		9.00
1.3	782522-01	NI PXIe-PCIe8381, x8 Gen2 MXI-Express for PXI Express Interface, 3m Cable Standard Delivery time: 10 - 15 business days ARO. *Country of Origin: Hungary* Service details for this product: Standard Repair Coverage Duration: 3 Year(s) 15% multiyear discount applied.	1	2,249.00		2,249.00
1.4	SRV-PX5134203	Standard Service Program for PXI Systems Standard Delivery time: 10 - 15 business days ARO. *Country of Origin: Hungary* Note: Service applied to eligible items. See Service Details for more information.				5,071.42

Quotation No.: 2360243

Line No.	Part Number	Description	Qty.	Unit Price	Discount	Amount
1.5	781490-01	PXIe-4492, 24-Bit, 204.8 KS/S, 8 Input 2 Gain, TEDS, AC/DC Coupled, IEPE Standard Delivery time: 10 - 15 business days ARO. *Country of Origin: Hungary* Service details for this product: Standard Repair and Traceable Calibration Coverage Duration: 3 Year(s) 15% multiyear discount applied.	4	4,568.00		18,272.00
1.6	780040-01	2 Pack InfiniBand to BNC Cables, AI0-7 and AI8-15, 0.2m, for 449x Standard Delivery time: 10 - 15 business days ARO. *Country of Origin: China* Service details for this product: Standard Repair Coverage Duration: 3 Year(s) 15% multiyear discount applied.	4	463.00		1,852.00
		Sub-Total:		**$ 32,147.37**	**2.78%**	**$ 31,252.42**
		Shipping and Handling:				**$ 120.11**
		Total:				**$ 31,372.53**

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To: Samuel Harding, PhD	**From:** Andrea Cabral
Company: Pacific Northwest National Laboratory	Kulite Semiconductor Products, Inc.
Phone: 509-375-3799	1 Willow Tree Road
Email: Samuel.Harding@pnnl.gov	Leonia, NJ 07605
Quote #: KQ0916-35166AC	201-461-0900x373, andrea.cabral@kulite.com
Customer reference: Request for Quote	**Date:** September 27, 2016

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Dear Samuel,

Thank you for your inquiry. I forward herewith our formal quotation in response.

Please note that in addition to the formal quotation on Kulite products, this message also includes an "End User Certificate". Kulite has instituted an Export control Policy to ensure that we do not inadvertently support the activities of individuals, groups or countries, which sponsor or engage in acts of terror or in activities, which promote political and military instability around the world. A completed certificate must accompany any new purchase order before Kulite may accept it. Should you issue a purchase order in response to this offer, please be sure to forward a completed end use certificate with it.

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To: Samuel Harding, PhD	**From:** Andrea Cabral
Company: Pacific Northwest National Laboratory	Kulite Semiconductor Products, Inc.
Phone: 509-375-3799	1 Willow Tree Road
Email: Samuel.Harding@pnnl.gov	Leonia, NJ 07605
Quote #: KQ0916-35166AC	201-461-0900x373, andrea.cabral@kulite.com
Customer reference: Request for Quote	**Date:** September 27, 2016

Item No.	**Type, Cat. or Part #**	**Description**	**Qty.**	**Unit Price**	**Total Price** (extended)	**Delivery**
1	**LL-080-7BarA**	**THIN LINE PRESSURE TRANSDUCER** Standard specifications per data sheet (12 pcs + 2 spares) (24 pcs + 4 spares)	14* 28*	$881.02	$12,334.28 $24,668.56	24-28 weeks ARO
2	**INSTALLATION**	**CUSTOM INSTALLATION FEE** Sensor mount configuration and pre-machined work piece(s) to be supplied by customer. ROM pricing only, subject to change upon evaluation of customer's finalized configuration	12 24	$500.00 (per sensor)	$6,000.00 $12,000.00	
Notes: *Minimum order quantity is 5pcs. Parts are not designed for use in water.						

QUOTATION TERMS:

- **Validity**: This quotation is valid for thirty (30) days only unless otherwise agreed.
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- Kulite is a Woman-Owned Small Business as defined by the Small Business Administration.

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Kulite Semiconductor Products, Inc.
Confidential

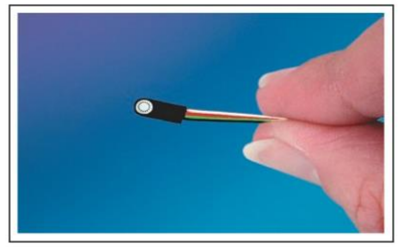
kulite®

THIN LINE PRESSURE TRANSDUCER

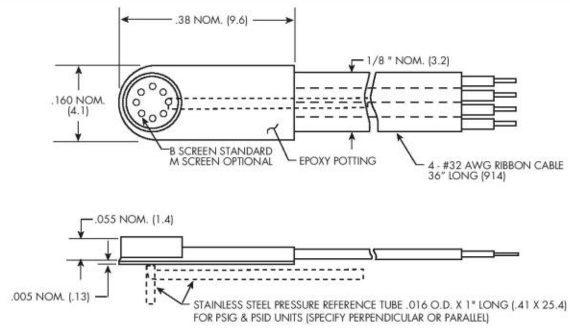
LL-080 SERIES   LL-125 SERIES

- Patented Leadless Technology **VIS**®
- High Natural Frequency
- Ideal For Flight Test & Wind Tunnel Applications
- Excellent Stability

The LL Series features Kulite's Patented Leadless Technology and demonstrates Kulite's ability to provide pressure transducers suited for adaptation into custom packages. These devices can be integrated into various test articles such as fan blades, engine nozzles of various types, etc. The features of these transducers include small foot print, high natural frequency, extreme resistance to vibration and shock, and wide temperature range.



Kulite recommends the KSC-2 signal conditioner to maximize the measurement capability of the LL-080 and LL-125 transducers.



WIRING	
COLOR	DESIGNATION
RED	+ INPUT
BLACK	− INPUT
GREEN	+ OUTPUT
WHITE	− OUTPUT

INPUT	Pressure Range	0.35 5	0.7 10	1.7 25	3.5 50	7 100	17 250	35 BAR 500 PSI
	Operational Mode	Absolute, Gage, Differential		Absolute, Gage, Sealed Gage, Differential			Absolute, Sealed Gage	
	Over Pressure	2 Times Rated Pressure						
	Burst Pressure	3 Times Rated Pressure						
	Pressure Media	Most Conductive Liquids and Gases (Please Consult Factory)						
	Rated Electrical Excitation	10 VDC						
	Maximum Electrical Excitation	12 VDC						
	Input Impedance	1000 Ohms (Min.)						
OUTPUT	Output Impedance	1000 Ohms (Nom.)						
	Full Scale Output (FSO)	100 mV (Nom.)						
	Residual Unbalance	± 5 mV (Typ.)						
	Combined Non-Linearity, Hysteresis and Repeatability	± 0.1% FSO BFSL (Typ.), ± 0.5% FSO (Max.)						
	Resolution	Infinitesimal						
	Natural Frequency of Sensor Without Screen (KHz) (Typ.)	150	175	240	300	380	550	700
	Acceleration Sensitivity % FS/g Perpendicular	1.5×10^{-3}	1.0×10^{-3}	5.0×10^{-4}	3.0×10^{-4}	1.5×10^{-4}	1.0×10^{-4}	6.0×10^{-5}
	Insulation Resistance	100 Megohm Min. @ 50 VDC						
ENVIRONMENTAL	Operating Temperature Range	-65°F to +250°F (-55°C to +120°C)						
	Compensated Temperature Range	+80°F to +180°F (+25°C to +80°C) Any 100°F Range Within The Operating Range on Request						
	Thermal Zero Shift	± 1% FS/100°F (Typ.)						
	Thermal Sensitivity Shift	± 1% /100°F (Typ.)						
	Linear Vibration	10-2,000 Hz Sine, 100g. (Max.)						
	Mechanical Shock	20g half Sine Wave 11 msec. Duration						
PHYSICAL	Electrical Connection	4 Conductor 32 AWG Ribbon Cable 36" Long						
	Weight	.2 Gram (Nom.) Excluding Module and Leads						
	Pressure Sensing Principle	Fully Active Four Arm Wheatstone Bridge Dielectrically Isolated Silicon on Silicon Patented Leadless Technology						

Note: Custom pressure ranges, accuracies and mechanical configurations available. Dimensions are in inches. Dimensions in parenthesis are in millimeters. All dimensions nominal. (G)
Continuous development and refinement of our products may result in specification changes without notice.
Kulite miniature pressure transducers are intended for use in test and research and development programs and are not necessarily designed to be used in production applications. For products designed to be used in production programs, please consult the factory.

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ProtoCAM

Excellence in Rapid Prototyping

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QUOTATION

October 4, 2016

To:	Pacific Northwest National Laboratory	Preparer:	Jeremy Belknap
Attention:	Samuel Harding Pacific Northwest National Laboratory 902 Battelle Blvd Richland, WA 99352 Phone: (509)375-3799	Email:	jbelknap@protocam.com
Proposal For:	**1 file**	Quote:	161004-05J

Quantity	Deliverable	Timing*	Cost
1	Investment Metal Prototype of part: **RunnerBlade.stl** Material Brass	2.5 weeks ARO	$1,425.00

Notes: ProtoCAM is pleased to provide this quote for Pacific Northwest National Laboratory and looks forward to your valued order. For any technical questions, please contact the preparer listed above.

Materials: A full list of stereolithography resins, including our new *Accura 25* and *Accura 60* materials, is available at www.protocam.com.

Terms: Net 30 days for clients with established credit with ProtoCAM. For all other clients American Express, MasterCard and Visa credit cards or COD are accepted. Unpaid balances will accrue at 1.5% per month.

***Timing:** Delivery date subject to available capacity at time of order placement.

Shipping: Shipping and handling not included. Freight collect when account number is provided. Packages will be shipped to arrive the next day unless otherwise requested. FOB Allentown, PA.

Pacific Northwest
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY

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