Making ships and offshore structures safer and more efficient

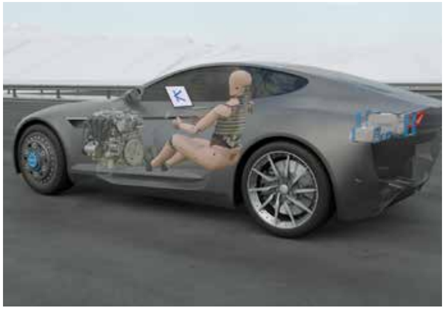
Solutions for hydrodynamic testing

Tried-and-tested measuring equipment for all naval and maritime applications

www.kistler.com

Absolute Attention for tomorrow's world

Kistler develops solutions for challenges in measurement technology with a portfolio that comprises sensors, electronics, systems and services. We push the frontiers of physics in fields such as emission reduction, quality control, mobility and vehicle safety: our products deliver top performance to meet the standards of tomorrow's world, providing the ideal basis for Industry 4.0. This is how we pave the way for innovation and growth – for our customers, and with our customers.



Kistler: the byword for advances in engine monitoring, vehicle safety and vehicle dynamics. Our products deliver data that plays a key part in developing efficient vehicles for tomorrow's world.

Measurement technology from Kistler ensures top performance in sport diagnostics, traffic data acquisition, cutting force analysis and many other applications where absolutely reliable measurements are required despite extreme conditions.

By supporting all the stages in networked, digitalized production, Kistler's systems maximize process efficiency and cost-effectiveness in the smart factories of the next generation.

Editorial

Manuel Blattner
Head of SBF Test & Measurement

Maritime transportation is a backbone of global prosperity and progress. Today's cargo vessels, tankers and bulk carriers handle about 90 percent of worldwide trade. There is constant demand for bigger ships to carry even larger cargoes, but they also have to withstand harsher weather conditions caused by climate change. To meet these challenges, marine technology is developing at a breathtaking pace – so reliable test and measurement expertise has an absolutely crucial part to play in this sector. Kistler responds to this need with hydrodynamic testing solutions for a variety of applications. Driven by the advantages of piezoelectric measurement technology, our sensors and systems deliver outstanding measurement performance for dynamic processes on board seagoing vessels and in offshore facilities. As you read this brochure, we will help you to explore the wide range of solutions we offer: not only for ships and propellers, but also for wind turbines, bridges and many other structures. Discover how you too can benefit from Kistler's long track record of excellence in measurement technology. As a leading provider of hydrodynamic testing solutions and a reliable partner for many key players in the maritime and naval sector, we offer a comprehensive portfolio of equipment backed by services and advisory support, available to our customers across the globe.

Contents

Tried-and-tested measurement technology for absolute accuracy

Hydrodynamic testing solutions from Kistler are deployed worldwide to make ships safer and more efficient. As well as optimizing overall ship integrity, our technologies improve the vessel's propulsion systems. Kistler's portfolio also includes best-in-class solutions for offshore structures such as wind turbines, oil and gas facilities, and bridges.

Today's ships combine impressive power with sophisticated technology; they come in almost all sizes, and they serve countless different purposes. Kistler, the Swiss measuring pioneer, offers an extensive range of measuring equipment that has proven its excellence over the years – backed by services and advisory support for customers across the globe.

Safer ships with high integrity and efficient drives
Hydrodynamic testing solutions from Kistler are based on the strengths of piezoelectric sensors. Developers and engineers use these systems for the complete range of hydrodynamic tests: examples include sloshing, towing, ditching and modal testing. As regards propulsion, we offer efficient solutions to counteract cavitation as well as propeller-induced noise and vibration. Quieting and silencing have also become critically important in response to growing concerns about environmental issues.

Making sure that offshore structures are robust and safe
Water exerts powerful forces on offshore and maritime facilities and installations, with the potential for massive impacts that can cause structural damage. This means that testing of hydrodynamic wave impacts (known as "slamming") is a crucial factor to ensure the integrity and safety of offshore structures. So be on the safe side – and opt for maritime solutions from Kistler!

Benefits of solutions from Kistler
- High-resolution dynamic measurements thanks to piezoelectric (PE) technology
- PE sensors based on ultra-precise Piezostar crystals
- Waterproof solutions for underwater measurements of vibration, pressure and force
- Professional and customized dynamometer design and production
- Innovative DAQ solutions
- Global service network for outstanding support

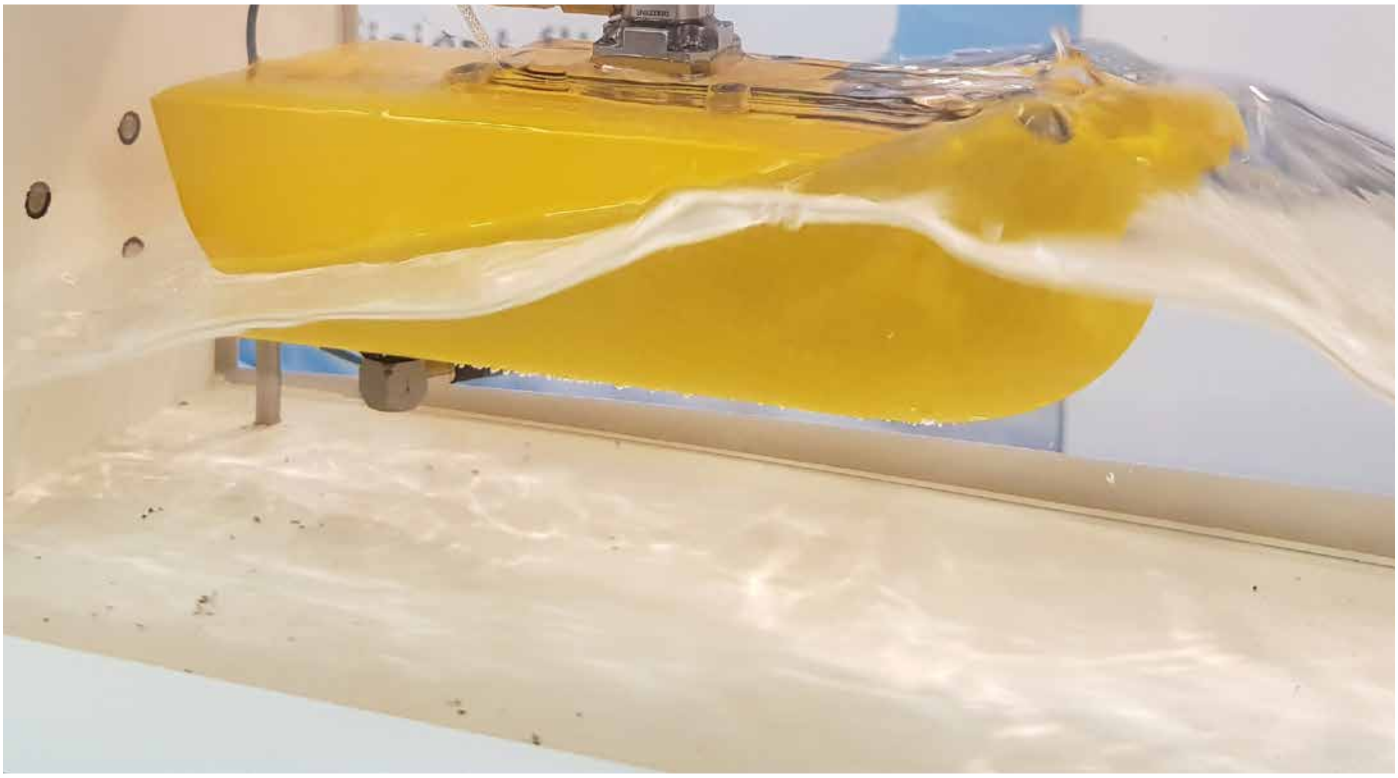
Waterproof sensor solutions for underwater vibration measurements

For hydrodynamic test procedures such as slamming, ditching, operational modal analysis and flow-induced vibration testing, accelerometers may have to be used underwater or could be exposed to watersplash. In these cases, sensors should be proven to withstand pressures of up to 10 bar (150 psi) for exposure periods of at least 3 days.

Kistler has extensive experience of providing lightweight integral cable vibration solutions that meet these requirements. We offer an IEPE portfolio of uniaxial and triaxial sensors for dynamic applications as well as MEMS capacitive sensors for lower-frequency applications.

Every sensor manufactured by Kistler is tested under water at 10 or 14 bar (150 or 220 psi) for 48 hours and is delivered with a device-specific test certificate.

Product highlights	
	**Uniaxial IEPE family 8774B/8776B…sp** • Lightweight, modular, 50 g … 500 g ranges available
	**Triaxial IEPE family 8763B…CBsp** • Lightweight, miniature, modular, 50 … 2,000 g ranges available
	**Triaxial MEMS capacitive sensor 8396M0x…** • From DC up to 1,000 Hz measurement capability for very low-frequency events and displacement/tilt computing.



Every sensor produced by Kistler is tested in a pressurized water vessel at 10 to 14 bar (150 or 220 psi) for 48 hours.

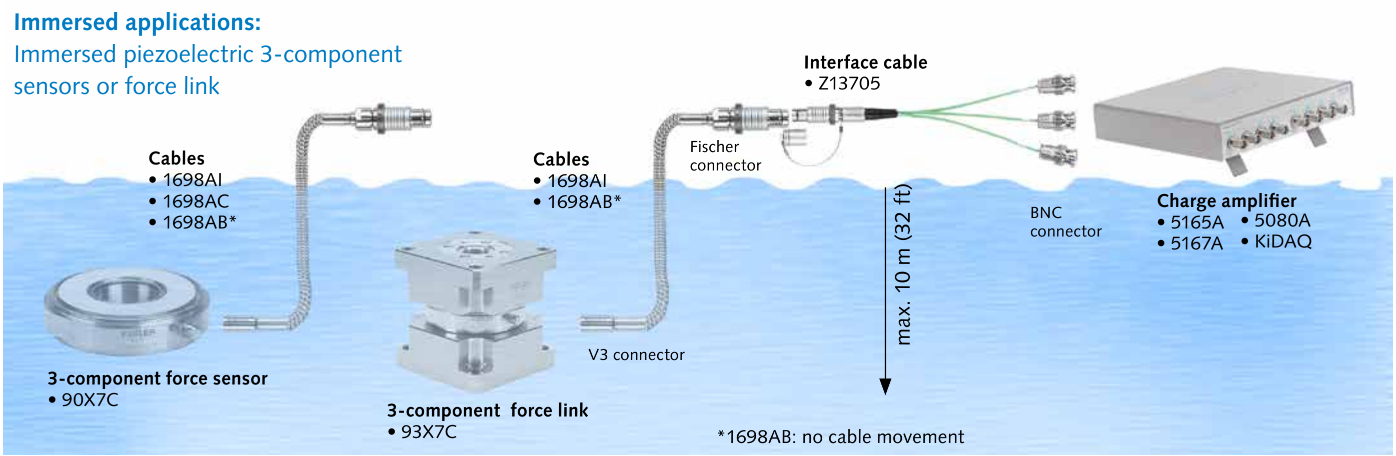
Waterproof sensor solutions for underwater force measurements

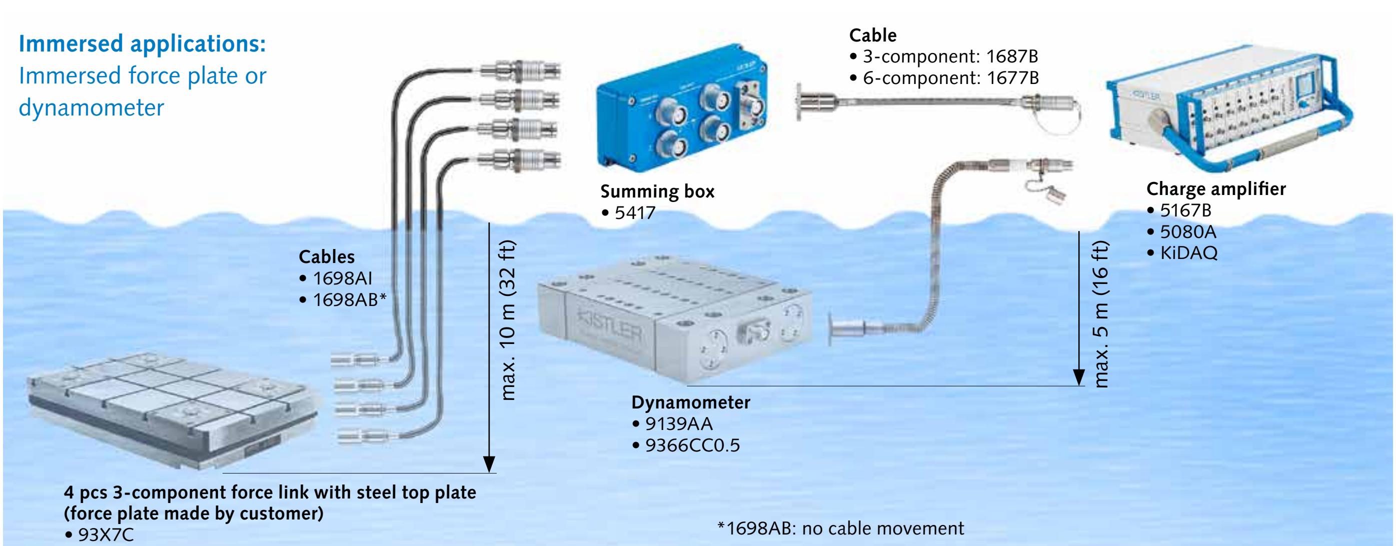
Underwater force sensors are often used in towing tanks and for slamming or propulsion investigations. Piezoelectric force sensors have the key advantage of a very wide measuring range. This enables them to measure small force variations with a static preload – for example, variations in drag force caused by small eddies with a heavy ship model in a towing tank. Force sensors from Kistler are hermetically sealed with a welded design to ensure that they are watertight. Cables are fitted with seals specifically designed for underwater use.

At Kistler, we test sensors and cables in our own pressure tank to guarantee reliable measurements in underwater applications. We also offer tested cable feedthroughs, so customers benefit from a fully qualified measuring chain for underwater applications.

Sensor and cable are immersed in water, maximum depth 10 m (32 ft), with the charge amplifier out of the water. Typical applications: towing tanks and slamming.

Product highlights	
	**3-component force sensor 90x7C with sealed cable 1698AI, 1698AC or 1698AB**
	**1-component force sensor 90x1A with vulcanized cable 1983AC**





Immersed underwater force measurements

Pressure sensors used in hydrodynamic testing may be exposed to watersplash and can also be used under water.

Waterproof sensor solutions for underwater pressure measurements

Pressure sensors used in hydrodynamic testing may be exposed to watersplash and can also be used under water. Kistler has extensive experience of providing sensors as well as cable solutions for challenging environments such as these.

Kistler offers both screwed and welded waterproof and moisture-proof cable solutions made of FKM rubber (including vulcanized connectors). Screwed connector solutions are preferred for watersplash and non-pressurized underwater environments. Welded sensor cables are the solution of choice for pressurized water environments, and in situations where it is essential to prevent unscrewing of the connector due to strong vibrations.

Each solution is qualified for up to 16 bar (230 psi) of pressurized water.

Product highlights	
	**Series 601C and 603C with screwed or welded cable solution**

Our engineering team will work closely with you to analyze your specific setup in depth and develop the right sensing solution.

Customized dynamometer solutions

Kistler offers an extensive portfolio of standard single and multi-component force sensors. They can be used as standalone devices, combined sets or within standard off-the-shelf dynamometers that meet a vast range of size and accuracy requirements for test objects. However, there are some cases where no standard sensor or dynamometer is suitable. It is our passion to provide you with exactly the measuring tool that will best meet your requirements. To achieve this, our engineering team will work closely with you to analyze your specific setup in depth and develop the right sensing solution.

We know the right questions to ask, thanks to the expertise we have gained in designing and manufacturing custom dynamometers for aerospace applications over many years. Our aim: to take the correct action at every stage of the process, right from the start.

Professional design and manufacturing services by Kistler – your benefits:

- In-depth analysis of your requirements
- Control drawing, including dynamometer design and main specifications
- Approval by customer
- Detailed design, manufacturing of all parts and assembly of the dynamometer
- In-house calibration on our unique 3-component reference force press
- Delivery of the finished dynamometer, including the calibration certificate and Bode natural frequency diagram

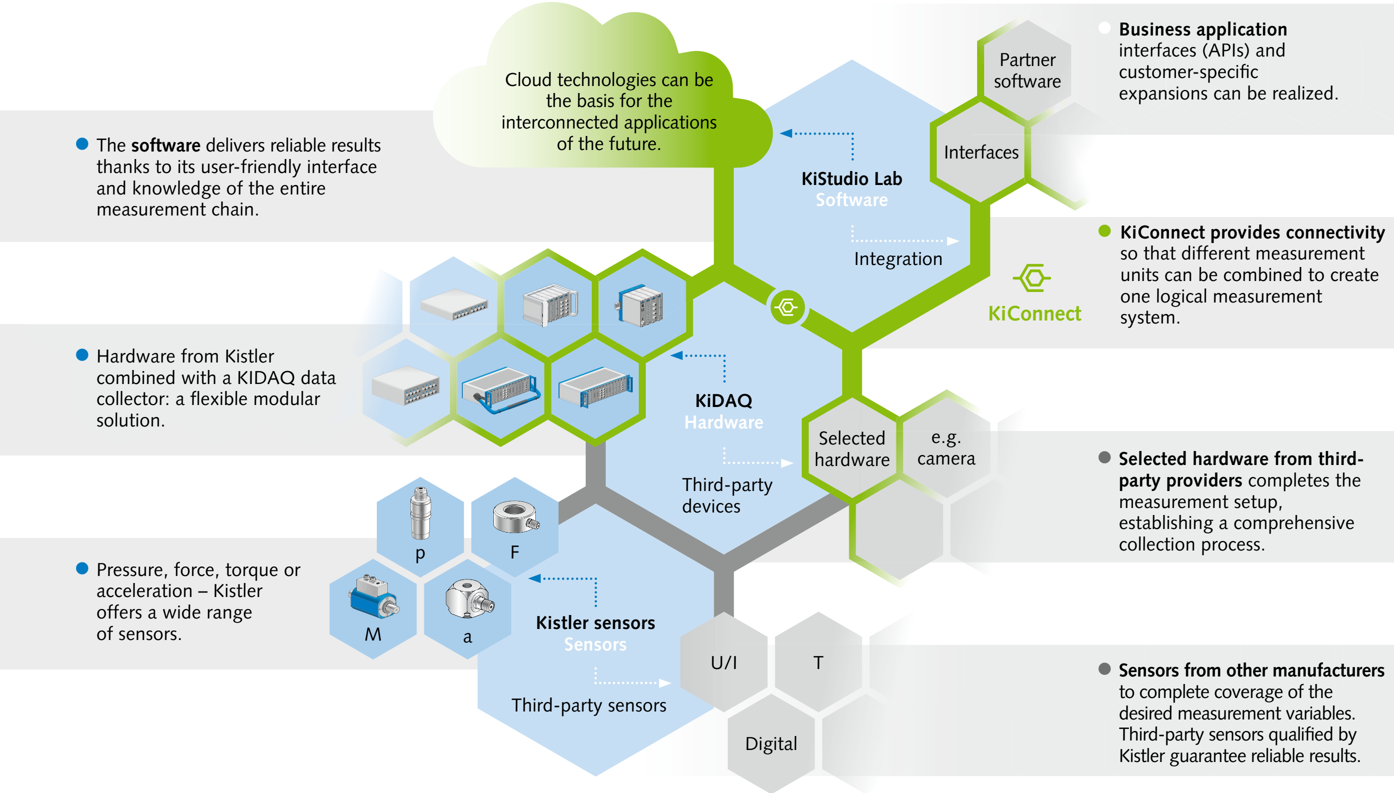
In-house calibration on Kistler's unique 3-component reference force press

6-component dynamometer consisting of four 9047C force sensors. The top and base plate were specifically designed to meet the customer's requirements. Special calibration with a specific adapter reproduces the same situation as in the real application.

Our absolute commitment to quality is your guarantee that every Kistler dynamometer will meet your specifications. Starting on day one, your dynamometer will function correctly throughout a long service lifetime.

- **Multi-component**
  Our 3-component force sensors are at the core of all our custom-built dynamometers.
- **One single source**
  Kistler grows its own crystals for sensors that operate under extreme conditions. Precision measuring equipment from Kistler is subject to 100% quality control; all manufacturing steps are performed in-house.
- **Highly specialized**
  Our customized high-performance dynamometers will meet your specifications – which is not always the case with self-built dynamometers.
- **Professional**
  Many years of experience and expertise in designing and manufacturing dynamometers for highly demanding industries such as aerospace make us your ideal partner.

Product highlights	
	**Customized force measurement** with integrated charge amplifier for immersion depth >10 m (32 ft)
	**Customized 6-component dynamometer** for thrust measurement



KiDAQ measurement architecture at a glance

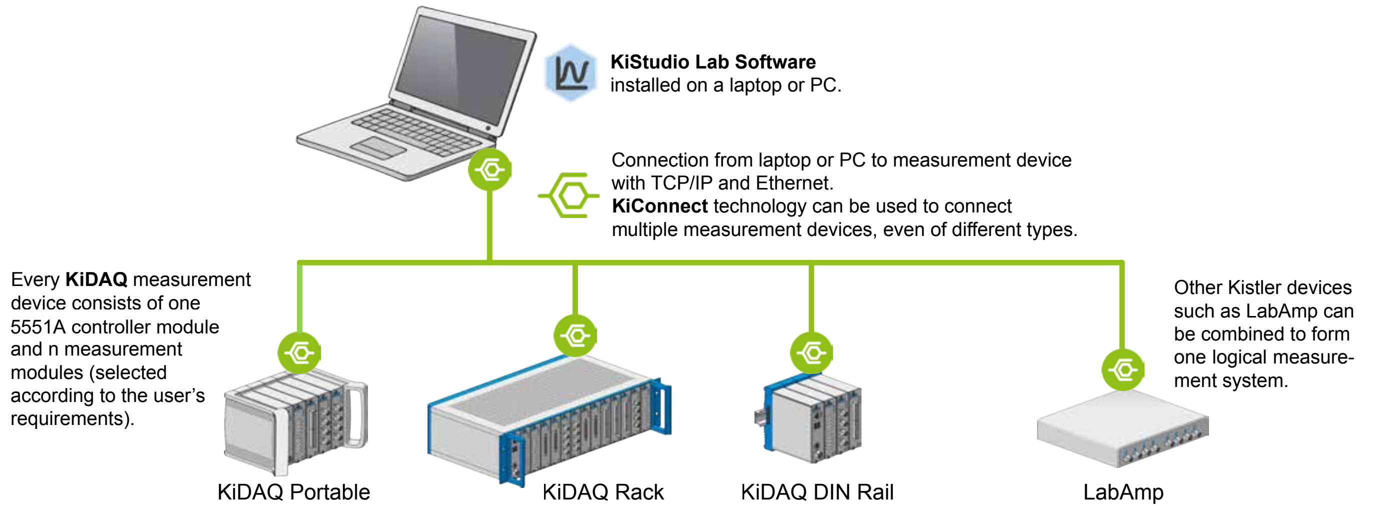
Innovative modular DAQ solutions for transparent and reliable measuring chains

Most measurement tasks in maritime research and development start with a complex and lengthy test setup. This is because measurement technicians or engineers have to connect measurement elements from different sources before they can assemble the system. To solve this problem, the measurement technology experts at Kistler developed KiDAQ: an innovative, integrated data acquisition system that offers all the components you need for your measurement task – all from one single source.

Intelligent KiConnect technology is the connecting element inside the KiDAQ data acquisition system. Thanks to KiConnect, users can easily connect Kistler products and selected devices from other suppliers to assemble a logical measurement setup, enabling time-synchronized measurements with the Precision Time Protocol (PTP).

As the leading manufacturer of piezoelectric measurement equipment, Kistler offers extensive measurement technology and application know-how backed by decades of experience. Our measurement specialists can draw on this expertise to obtain reliable information about the measurement uncertainty of the entire measuring chain. To share this know-how with our users, we offer automatic calculation of the measurement uncertainty based on our KiXact technology. Once users know the measurement uncertainty percentages and magnitudes for each individual component, they can reduce the percentages by changing the operating conditions or optimizing device selection – so they benefit from maximum transparency and know-how. Kistler has filed a patent for its KiXact technology.

Product highlights



Each KiDAQ measurement module supports one or more different measurands:

- Voltage
- Current
- Resistance
- Potentiometer
- Pt100/Pt1000 (RTD)
- Thermocouple
- Strain gage
- Inductive bridge
- LVDT
- Piezoelectric (charge)
- IEPE (Piezotron)
- Frequency
- Pulse width
- Counter signal
- Time
- Status

LabAmp measurands:

- Piezoelectric (charge)
- IEPE (Piezotron)
- Voltage

KiConnect technology offers the benefits of a highly modular interconnected hardware portfolio.

Sloshing simulation system using an LNG tank model mounted on top of a hexapod (Source: Symétrie)

Sloshing

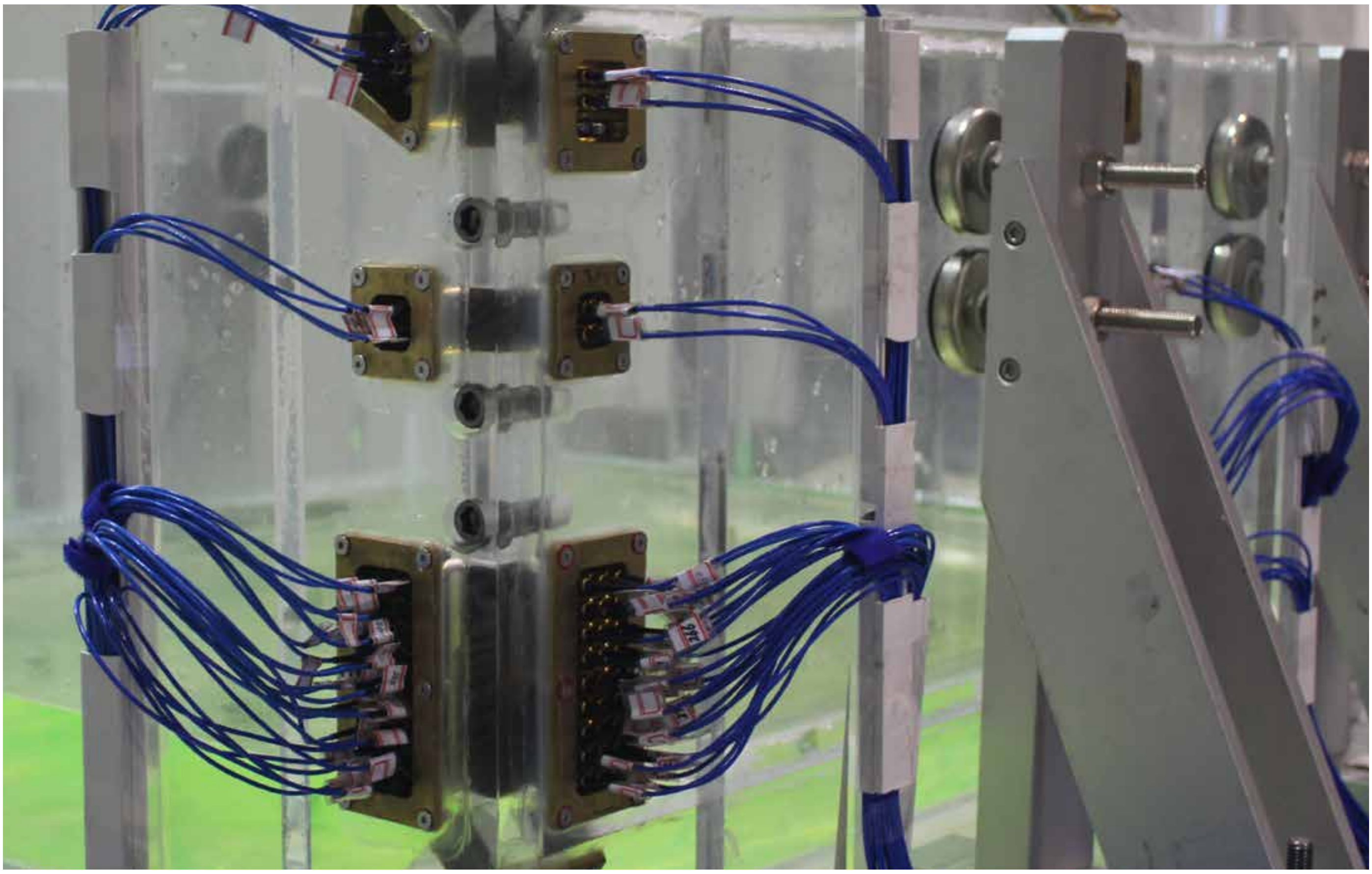
Natural gas is gaining importance as an energy source. As compared to crude oil – and especially coal – its carbon footprint is smaller, and it contributes less to global warming. When distances of several thousand kilometers have to be covered, large tankers offer the only cost-efficient way of transporting this fuel.

Natural gas can only be transported efficiently in liquefied form. Cooling the gas to –162°C (–260°F) makes its volume 600 times smaller, so it can be transported by special liquefied natural gas (LNG) tankers. Wind and waves can cause movements of the LNG in partially filled ship tanks. These movements – known as sloshing – can affect ship stability and may expose the internal tank membranes to heavy loads. Potential consequences include structural damage to tank membranes and insulation, leakage and even tank rupture. The tank structures of LNG vessels must therefore be able to withstand LNG sloshing, even in heavy swells.

Many research laboratories throughout the world study the sloshing-induced dynamic loads on the tank structures of LNG tankers. Tests with water or other fluids are carried out in small-scale tanks, and the data is scaled up to partial size in order to predict tank loadings under different assumed wave conditions and fill levels. The test results are then compared with computational models for validation. Computational models ensure fast turnaround times on investigations of different tank geometries, wave conditions and fill levels. Tests and computational models therefore play a key part in the development of larger and safer tank structures.

A sloshing test set usually involves a rectangular 2D model of an LNG tank on a hexapod; small-scale 3D models are also used. The scale of the small LNG tank models is generally between 1:20 and 1:70. The pressure sensors are usually deployed in cluster configurations on the tank model wall, at various locations where severe impacts are most likely. A cluster consists of a sensor array that is flush-mounted onto a metallic block (direct mounting with no adapters). Thanks to this configuration, the sensors can be installed as close to one another as possible so as to optimize spatial resolution.

The pressure measurement may also be correlated with the measurement of the reaction forces; in this case, purpose-designed triaxial piezoelectric force plates are mounted on the interface between the LNG tank model and the hexapod.



601C IEPE pressure sensor matrix by Kistler used to map water pressure behavior during a sloshing test

Key technologies for the application

- **Pressure sensors with small dimensions**
  A small front diameter is one of the key requirements for the sensors in this application. Thanks to this configuration, the sensors can be installed as close to one another as possible so as to optimize spatial resolution.

- **Pressure sensors with fast rise times and high natural frequencies**
  Impact pressures are largely dependent on induced motion. They can range from 50 mbar to 7 bar (0.7 to 100 psi), with fast rise times of between 1 and 10 ms. These conditions require pressure sensors with fast rise times and/or high natural frequencies.

- **IEPE (voltage) pressure sensors for cost-effective solutions**
  This application requires a considerable number of sensors, so a cost-effective measuring chain solution is essential. Thanks to IEPE technology, the pressure sensors can be connected directly to the DAQ system with no need for costly charge amplifiers.

- **Pressure sensors with low thermal shock sensitivity**
  Measured impact pressures may be affected by a pressure sensor's thermal shock behavior. The design of Kistler's 601C series features very low sensitivity to thermal shock, so these sensors are highly suitable for measuring impact pressures due to sloshing.

Product highlights	
	**PiezoStar IEPE pressure sensor family** 601C
	**3-component load cell family** 9017C … 9077C.
	**Dynamic 4-channel charge amplifier and data acquisition unit** 5165A

Slamming test in progress on an oil and gas platform model (Source: HSVA)

Ocean engineering tanks and wave basins – slamming

Ocean engineering tanks – also known as wave pools or wave basins – are usually equipped with a segmented wave maker consisting of hinged flaps that generate directional waves (which may be either regular or irregular). A tank of this sort can be used as a seakeeping and maneuvering basin to verify the performance and safety of a ship and its ride control elements in relevant wave conditions.

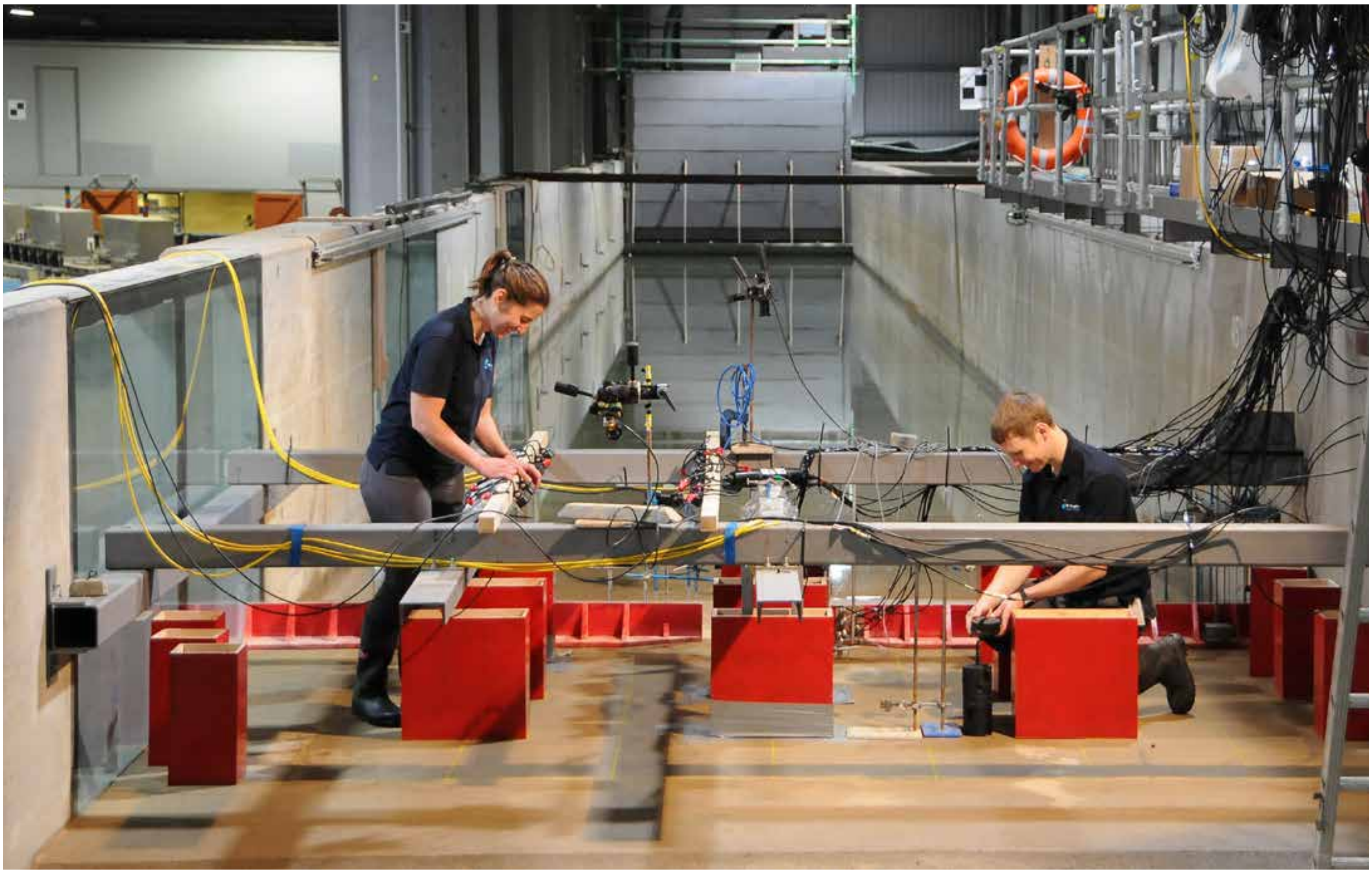
Examples of tests:
- Seakeeping tests in waves and wind from arbitrary directions
- Resistance and self-propulsion tests in calm water and waves
- Oscillation (PMM) and rotating arm tests in calm water and waves with a restrained model to determine hydrodynamic coefficients
- Captive or free sailing maneuvering tests in calm water and waves

Installation and sea transport tests for offshore structures
Selecting the most economical platform with minimized motions presents a major technical challenge. Thorough tests play a critical part in developing oil and gas platforms or floating wind turbines that can successfully meet the challenges of the future.

Applications for the wave basins described here include testing of moored or fixed objects (such as oil and gas platforms or offshore wind turbines) to determine motions and loads caused by waves and wind.

For offshore wind turbine testing, the wind and waves that act simultaneously on the turbine can be measured by a set of 3-component dynamometers positioned at the base of the mast between the anchorage and the unit under test. These tests provide high-quality benchmark data to validate methods of simulating the coupling between aerodynamic and hydrodynamic behaviors.

Test measurements for oil and gas platforms (or even ships) typically require the pressure sensors to be flush-mounted on the wall of the structure or the ship's hull.



The English town of Wallingford is home to one of Europe's largest wave flumes, the Fast Flow Facility, where tsunamis can be simulated on a scale of 1:50. (Source: HR Wallingford)

Key technologies for the application

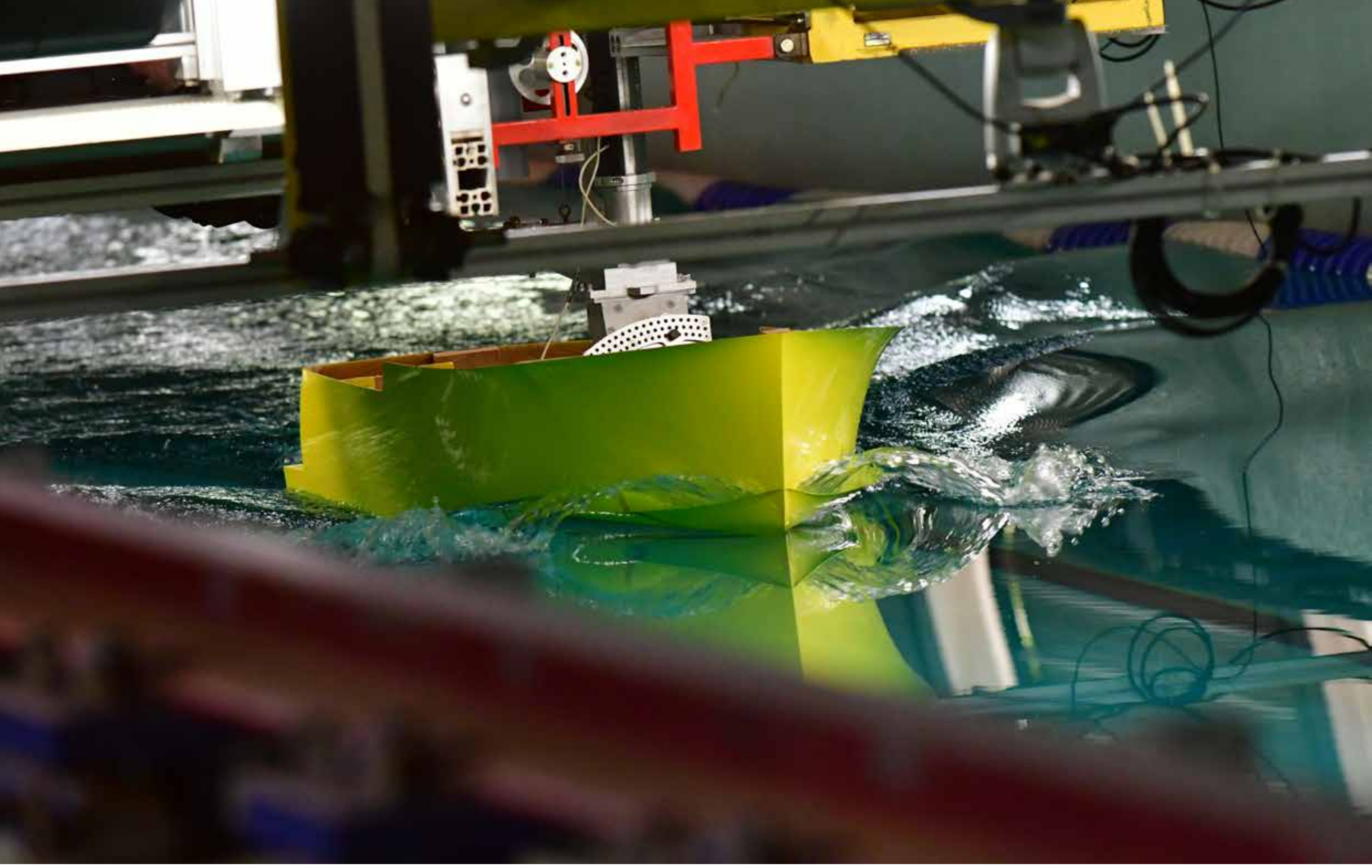
- **High-sensitivity IEPE (voltage) pressure sensors**
  Expected pressure of less than 1 bar (15 psi) should be measured with the correct accuracy; thanks to IEPE technology, the pressure sensors can be connected directly to the DAQ system with no need for costly charge amplifiers.

- **Pressure sensors with fast rise times and high natural frequencies**
  Common impact pressures are below 1 bar (15 psi) with fast rise times of roughly 1 ms. These conditions require pressure sensors with fast rise times and/or high natural frequencies.

- **Pressure sensors with low thermal shock sensitivity**
  Measured impact pressures may be affected by a pressure sensor's thermal shock behavior. The design of Kistler's 601C series features very low sensitivity to thermal shock, so these sensors are highly suitable for measuring impact pressures due to slamming.

- **Waterproof multicomponent force sensor solutions with wide measuring range**
  Piezoelectric technology can handle heavy structures while focusing on the smallest dynamic variations thanks to the right choice of charge amplifier settings.

Product highlights	
	**Piezostar IEPE pressure sensor family** 601C
	**3-component load cell family** 9017C … 9077C with waterproof capability
	**Dynamic 4-channel charge amplifier and data acquisition unit** 5165A
	**Quasi-static 8-channel charge amplifier and data acquisition unit** 5167A



Towing tank carriage setup (Source: École Centrale de Nantes)

Towing tanks, ship model test and ditching

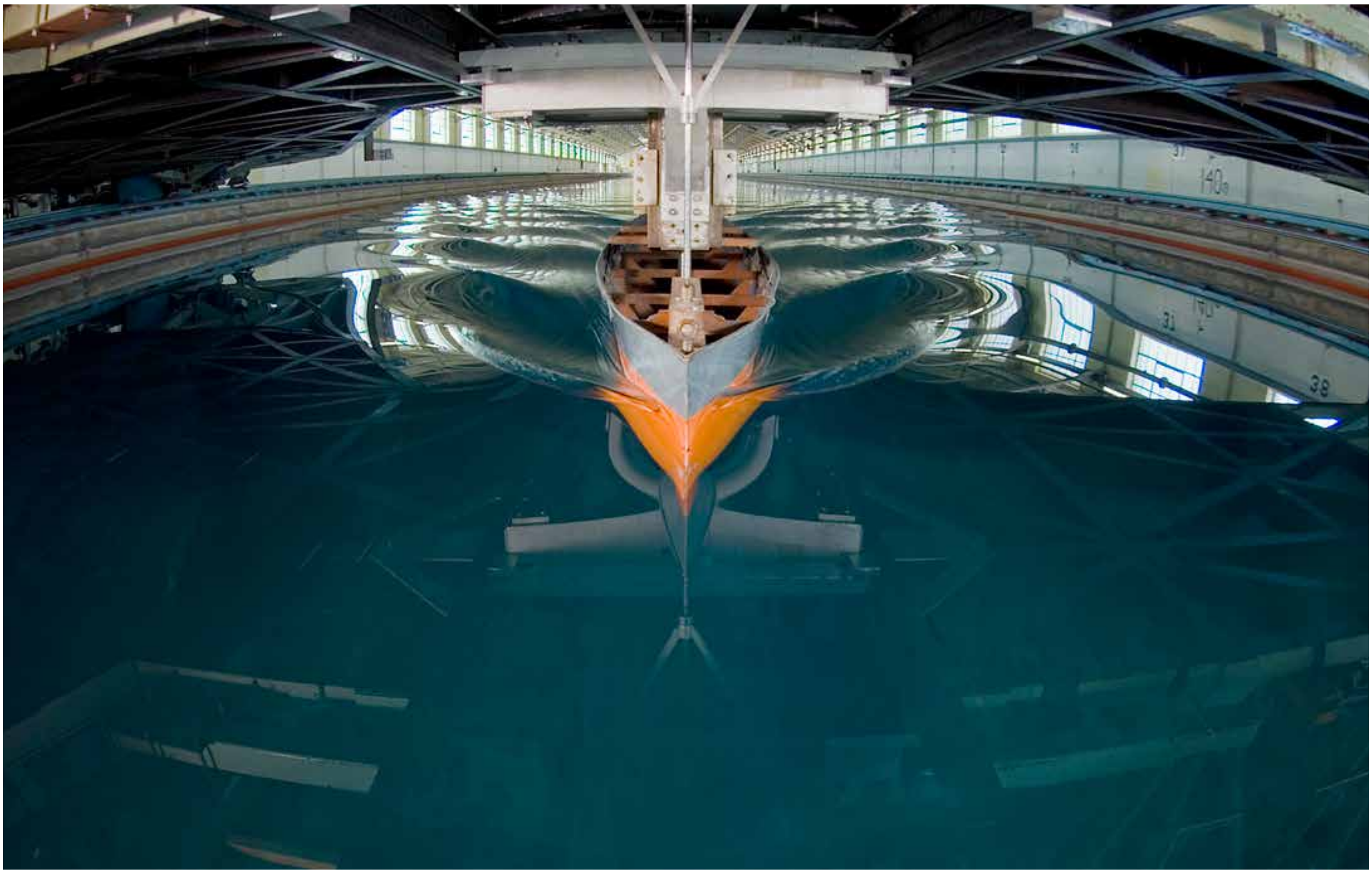
A towing tank is a huge basin equipped with a towing carriage that runs on two rails installed on either side of the tank. Towing tanks can be several meters wide and many hundreds of meters in length. The towing carriage is used in two ways: it can tow the model or, if the model is self-propelled, the carriage follows it. Computers and instruments on board the carriage record and control a range of variables such as speed, rudder angle, or propeller thrust and torque.

Towing tanks play a key part in many different tests on ship models. Examples include resistance and propulsion tests that are performed with both towed and self-propelled models: the aim here is to determine how much power the engine must generate to achieve the speeds specified in the contract between the shipyard and the shipowner. Towing tanks are also used in scaled-down tests to determine a vessel's maneuvering behavior. In this case, the self-propelled model performs a series of zig-zag maneuvers at varying rudder angle amplitudes.

To extend their application scope, towing tanks can be fitted with additional equipment such as a planar motion mechanism (PMM) or a computerized planar motion carriage (CPMC). These devices measure the hydrodynamic forces and moments acting on ships or submerged objects due to the influence of oblique inflow and enforced motions. Another possibility is to equip the towing tank with a wave generator to carry out seakeeping tests. The generator can simulate natural (irregular) waves, or can expose the model to a wave packet: the statistics obtained with this method predict the ship's likely seagoing behavior when it has to negotiate real waves of varying amplitudes and frequencies.

However, the applications are not limited to ships. Several specialized test centers also use their towing tanks to investigate how helicopters or airplanes will behave during an emergency landing on water. These ditching simulations involve a model aircraft with its fuselage fixed below an overhead rail. As the model moves forward, two vertical actuators lower it into the water at an adjustable immersion angle. This method is used to test multiple configurations with different immersion profiles.

Piezoelectric six-component force sensors or dynamometers that include triaxial piezoelectric sensors play a critical part in all these applications: they measure the induced forces and moments. Waterproof solutions are usually essential for these tests. In some cases, acceleration is measured at the same time as force and moment, so tilt can be calculated on the basis of signals from a MEMS capacitive accelerometer.



Towing tank carriage setup (Source: QinetiQ)

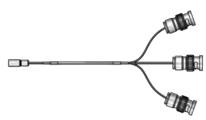
Key technologies for the application

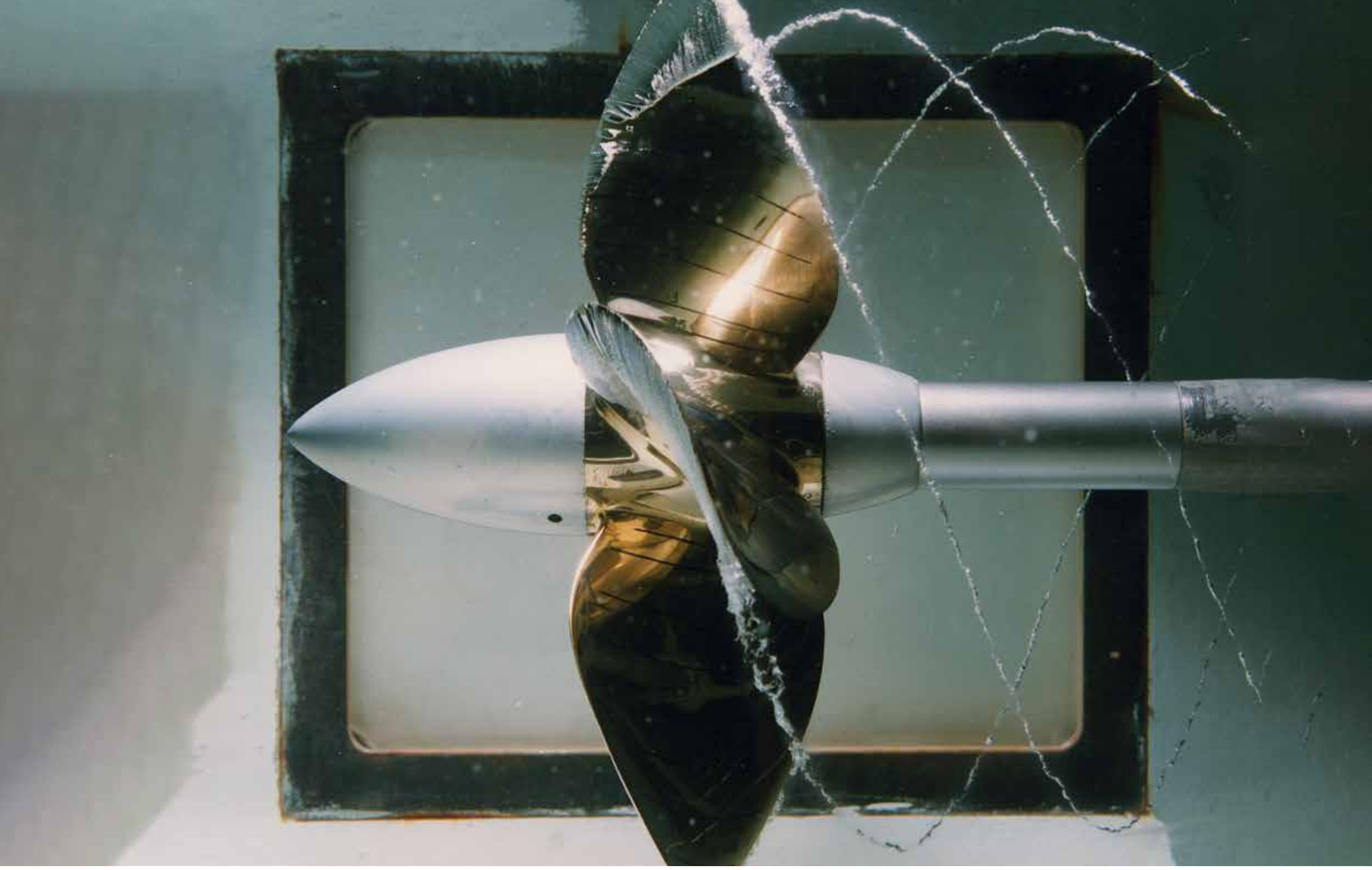
- **High force measuring range and high moment handling capability**
  Piezoelectric technology can work under very high loads while focusing on measurements of very small variations, thanks to the right choice of charge amplifier settings. Benefits: very high versatility, smaller sensors and easy installation.

- **High- and low-frequency response capability**
  The stiffness of piezoelectric technology allows high resonance frequencies for the mechanical assembly, so high-frequency measurements can be performed. Quasi-static measurements are also possible thanks to a charge output solution combined with high-insulation.

- **High measurement accuracy**
  Achieved thanks to high linearity and low crosstalk.

- **Waterproof capability**
  Implemented with 1698A cable that can be welded onto the sensors.

Product highlights	
	**3-component load cell family** 9017C…9077C
	**6-component force link** 9306A
	**High-insulation cable, water-resistant, with welded connector** 1698ACsp
	**Quasi-static 8-channel charge amplifier and data acquisition unit** 5167A



Cavitation phenomena on propellers or appendages mainly lead to significantly increased vibration amplitudes. (Source: Qinetiq)

Cavitation and propeller-induced noise and vibration

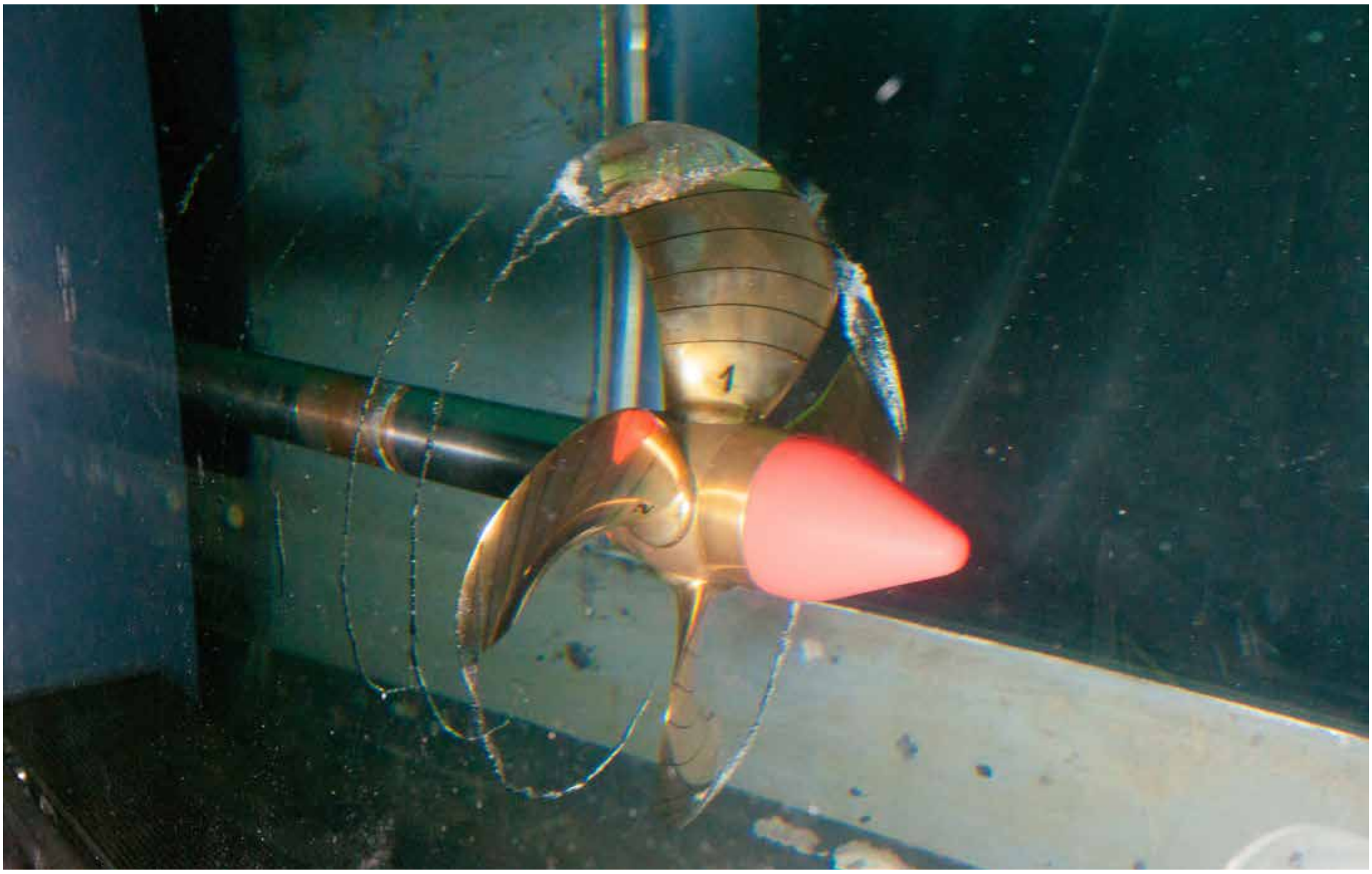
Onboard noise and vibration can cause discomfort to ships' passengers and crews. But these phenomena can also have other negative effects: the crew may not be able to perform their duties efficiently, damage could be caused not only to sensitive equipment but also to structural components of the ship and its cargo – and the vessel's safety might even be compromised. Today's passengers and crew members are less willing to accept onboard discomfort due to noise and vibrations, so ship designers now treat both phenomena as key factors that must meet increasingly strict requirements.

Other than the main engine, the propeller is the principal exciter of ship vibrations. This is why design specifications generally include limits for the pressure fluctuations induced by the propeller. To reduce noise emissions, acoustic limits are also specified for certain special-purpose vessels such as naval or research ships and yachts.

Propellers generate periodic pulsating pressure forces on the vessel's hull; occasional cavitation that occurs on the propeller blade can significantly intensify these forces. To take account of these issues, propeller tests generally include measurements of pressure fluctuation, vibration and sound. Most of these tests are performed on ship models in cavitation tunnels, but testing is also carried out on real vessels in some cases.

Piezoelectric pressure sensors are the solution of choice for measuring very small pressure pulsations (down to a few microbars/1E^{-5} psi), and they can also cope with high static pressure levels. These sensors can be used to obtain long-term measurements of very small pressure pulsations with high resolution and an excellent signal-to-noise ratio in the frequency range above 100 kHz.

Vibrations are measured directly on the propeller in order to analyze and compare acoustically optimized propellers. High-frequency acoustic emission sensors can be combined with a pre-amplifier and transmitter in a special hub cap to measure the acoustic waves propagating on the surface of the structure at frequencies above 50 kHz.



In the cavitation tunnel, pressure sensors are placed in the stern area above the propeller or at positions of interest on the hull. (Source: SVA Vienna)

Key technologies for the application

- **Flush-mounted pressure pulsation sensors**
  Highly sensitive flush-mounted piezoelectric pressure sensors (such as the 601C series) are the key to measuring pressure pulsations down to a few microbars/1E^{-5} psi. When needed, the option of using IP68 cable solutions must also be available for this application.

- **Accelerometers with waterproof capability**
  Accelerometers sometimes need to be mounted inside the tunnel, in direct contact with water. These situations require very small sensors with waterproof capability up to IP68 (qualified to 10 bar/150 psi). Pressurized water tests are carried out on all waterproof accelerometers from Kistler before they leave our factory.

- **Acoustic emission measurement capabilities**
  Frequencies above 20 kHz can be encountered when taking surface acoustic wave measurements during cavitation. Acoustic emission sensors with a frequency range capability of up to 1 MHz are required in these situations.

Product highlights	
	**PiezoStar IEPE pressure sensor family** 601C
	**Miniature uniaxial IEPE waterproof accelerometer families** 8774B…sp and 8776Bsp
	**Miniature IEPE triaxial waterproof accelerometer family** 8763B...CBsp
	**Acoustic emission sensor** 8152C

The main producers of mechanical noise and vibration are the power and propulsion systems. But there are also other sources such as piping, air conditioning, compressors, the drivetrain, electric motors and mooring machinery as well as cargo handling and control equipment.

Noise reduction – flow-induced and structure-borne noise and vibration

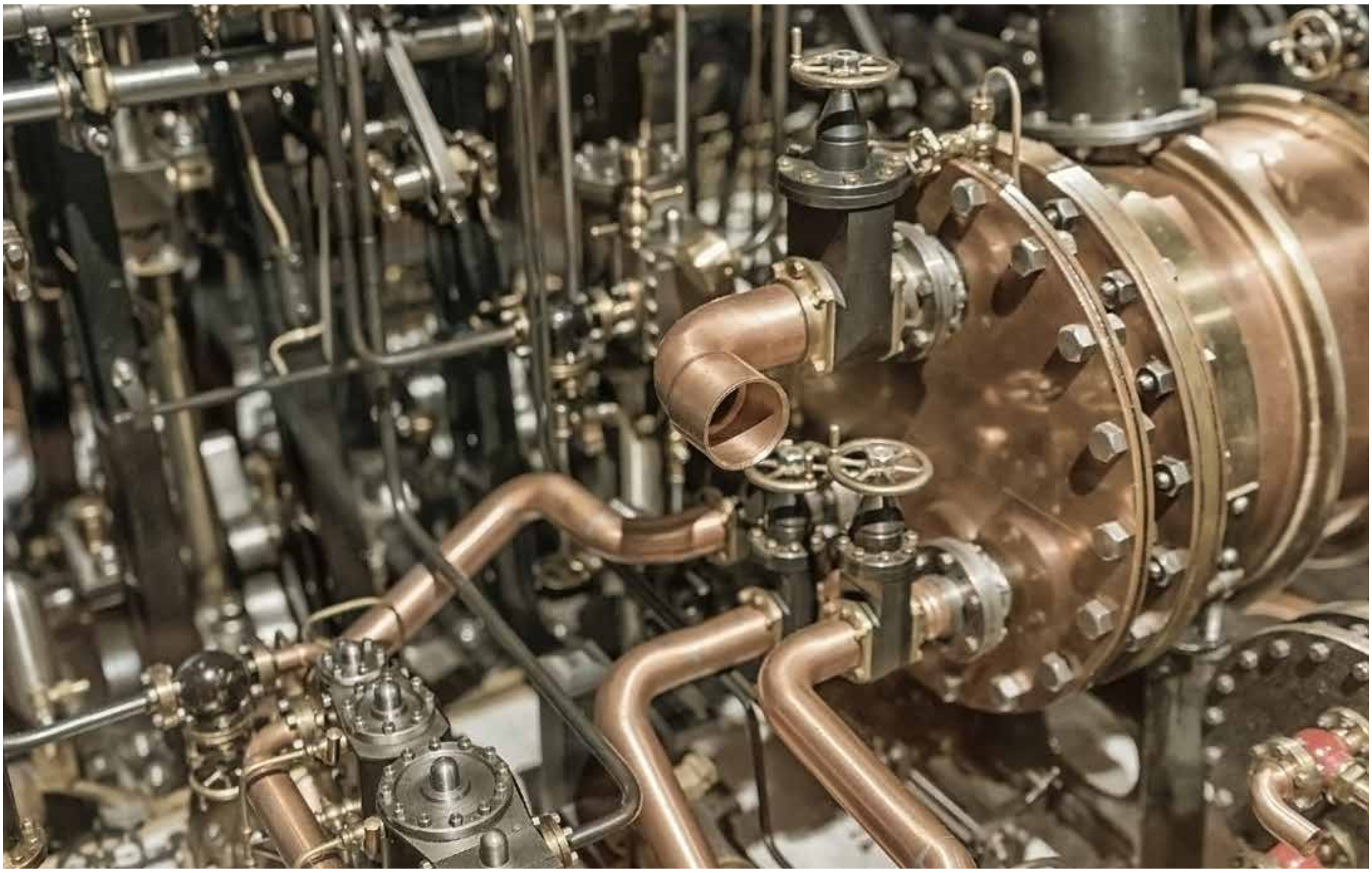
Mechanical noise and vibrations are investigated with the aim of improving passenger ride comfort, reliability, durability and silencing. Structural behavior and the many sources of noise and vibration are characterized in order to understand and optimize performance.

In vessels with power and propulsion based on a diesel engine, operational vibrations can travel from the engine foundation and spread throughout the ship. Vibrations of this sort usually manifest as audible noise or are perceived as vibrations transmitted through the ship's structure; acoustic signatures can also excite mechanical vibration.

Ships can also use motors for electrical propulsion: in this case, electrical power is developed by the diesel motor/generator. Noise and vibrations due to electric motors can originate from mechanical and aerodynamic sources; there may also be electromagnetic characteristics that can be represented by the "whining noise" of the motor.

Ships that use steam and gas turbines are also subject to noise and vibrations. Even if preventive maintenance is undertaken at appropriate intervals or according to usage, vibration levels may increase because of wear on bearings and turbine blades. For example, turbine blades normally rotate in a smooth gas flow – but increased use and aging can gradually give rise to defects that cause surface pitting of the intake and blades. This, in turn, creates gas flow eddies that lead to loss of performance and vibrations. Vibration levels are affected by operational factors such as increased demand or loading, weather or sea conditions, and maneuvers.

Low-noise uniaxial and triaxial accelerometers are used to investigate these phenomena, and waterproof capabilities may also be required to support submersible installations.



Steam and gas turbines generate vibrations due to bearing and blade imbalance which degrades gradually as the turbine components age, eventually leading to higher vibration levels.

Key technologies for the application

- **Wide bandwidth/high resolution**
  Accelerometers offering various g-ranges, frequency ranges and resolutions are useful, depending on the source of vibration. Uniaxial and triaxial ceramic accelerometers meet these requirements, with g-ranges from 50 g to 2,000 g, broadband noise down to 0.0004 grams and 10% frequency up to 20 kHz.

- **Flexible/easy mounting**
  Tapped holes in a test article may not be possible to mount accelerometers. Alternate options include adhesive and magnetic mounting which are performed with direct mounting of the accelerometer or using mounting accessories.

- **Ground isolation**
  Best practice is to have one grounding point in the measuring chain to avoid ground loops that can degrade the signal-to-noise ratio. Accelerometers are available with integral ground isolation for direct mounting, or with a ground-isolated base accessory.

- **Waterproof accelerometers**
  Accelerometers sometimes have to be submerged in water. Such cases often require miniature uniaxial and triaxial accelerometers with an IP68 waterproof rating (qualified to 10 bar/145 psi). Pressurized water tests are carried out on all waterproof accelerometers from Kistler before they leave our factory.

Product highlights	
	**Low-noise miniature uniaxial IEPE accelerometers** 8774B050A and 8776B050A
	**Low-noise miniature IEPE triaxial accelerometer** 8763B050BB
	**Miniature uniaxial IEPE waterproof accelerometers** 8774B050sp and 8776B050sp
	**Miniature IEPE triaxial waterproof accelerometer** 8763B050CBsp

Structural vibrations and related damage on ships affect the safety of the structure as well as crew comfort and normal equipment lifetimes. Vibration levels therefore play an important part in engineering practice.

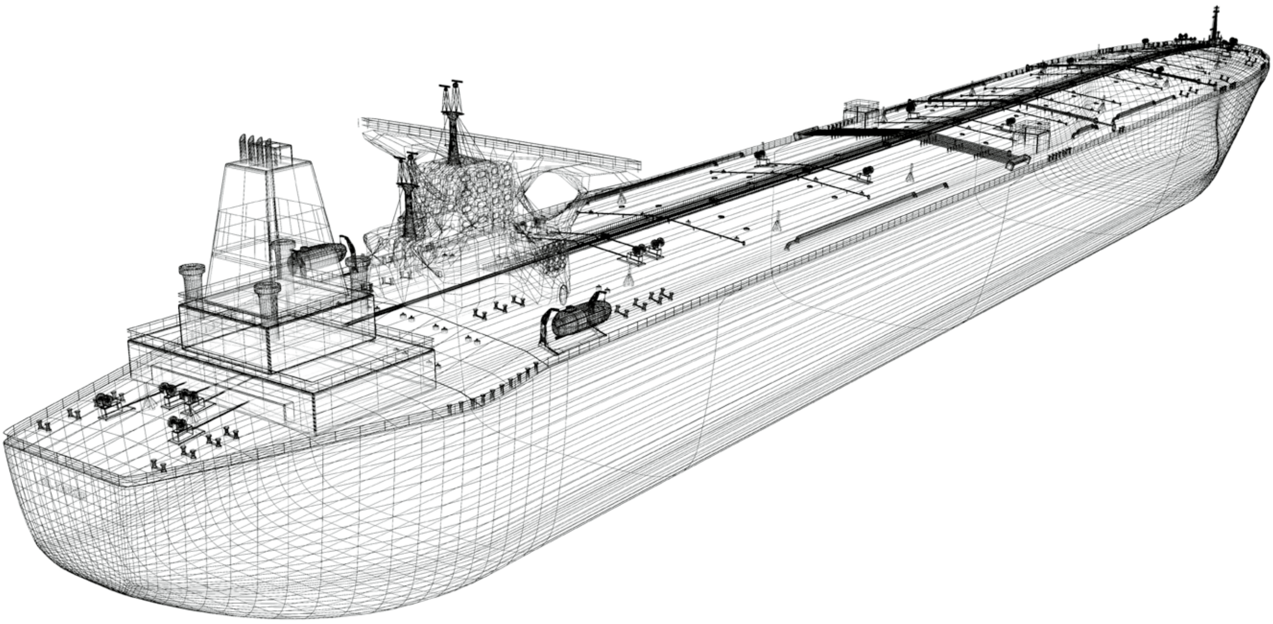
Modal and structural analysis

Structural vibrations and related damage can affect the safety of a ship's structure, the comfort of the crew and the normal lifetime of the vessel's equipment. This is why vibration levels are the focus of much attention in engineering practice. Modal analysis of the data obtained from structural testing provides a definitive description of the structure's response, which can then be evaluated against design specifications.

While ships are at sea, they are continuously exposed to varying loads from waves that subject the vessel to rigid body motions and deformations. A distinction is made between two types of deformation: the quasi-static response and the dynamic response. A quasi-static response depends solely on the structure's stiffness distribution, whereas the dynamic response is also dependent on mass distribution. A vessel's dynamic response can be characterized by its modal parameters.

Springing and whipping are two of the relevant dynamic responses for ships. Springing is the steady-state resonant vibration of the two-node flexural mode in response to continuous wave loading. Whipping is the transient elastic vibration of the ship's hull girder caused by phenomena such as slamming. Whipping vibrations typically result in higher accelerations that can, in turn, cause loss of cargo; they may also produce higher stresses that lead to increased fatigue accumulation or even exceedance of ultimate strength. Design procedures need to take adequate account of these dynamic effects.

Traditional methods of identifying modal parameters depend on accurate knowledge of the loads as well as the structure's response to them. A ship's excitation signals are hard to measure, and this creates problems when applying traditional methods to identify the modal parameters (i.e. modal frequency, modal damping and modal shape). Also, given that a ship is such a huge structure, artificial generation of sufficient energy to excite its global vibration is difficult without causing local plastic deformation. To overcome these challenges, operational modal analysis (OMA) methods are often chosen when the only requirement is to measure the dynamic response signal while the ship is navigating: accelerometers are the solution of choice in situations such as these. Standard and IP68 waterproof accelerometers are generally chosen. They must meet several key technical requirements to ensure successful measurements: watertightness (sometimes up to 10 bar/150 psi)), small size and lightweight design (to avoid mass loading effects), wide frequency range, and very low noise specifications (so that signals of very small amplitude can be measured).



Identification of the modal parameters traditionally requires accurate knowledge of loads and structural load response – these are key factors in stable operation.

Key technologies for the application

- **Low noise**
  The low-noise performance of ceramic-based acceleration sensor families allows measurement of the very small signals often encountered during modal analysis investigations.

- **Flat frequency response**
  IEPE Modal sensors from Kistler are characterized by a flat and repeatable frequency response, especially towards low frequencies. We also provide specific low-frequency calibration certificates and phase response characterizations on request. Kistler offers MEMS capacitive accelerometers for investigations of modal parameters toward the lowest frequencies.

- **Easy handling for fast and simple installation**
  Special clips or housings allow flexible orientation of the sensitive axis.

- **Waterproof accelerometer capability**
  Accelerometers used for operational modal analysis must be mounted on the ship's hull. Very small sensors with waterproof capabilities up to IP68 (qualified to 10 bar/150 psi) are required for this purpose. Pressurized water tests are carried out on all waterproof accelerometers from Kistler before they leave our factory.

Product highlights	
	**Orientable uniaxial modal sensor with TEDS capability** 8775A
	**Miniature uniaxial IEPE waterproof accelerometers** 8774B050sp and 8776B050sp
	**Miniature IEPE triaxial waterproof accelerometer** 8763B050CBsp
	**Triaxial DC MEMS capacitive sensor family** 8396M0x

Increasing attention has been focused on propeller investigations in recent years, not only to optimize consumption efficiency but also to reduce noise.

Propulsion investigations and optimization

Ship propeller investigations focus on various aspects: operational efficiency (the conversion of power delivered by a rotating shaft into thrust), propeller design (including blade design, number of blades and propeller pitch) as well as quieting. Propulsion systems with rotational propeller dynamics can induce vibration (torsional, axial/longitudinal and/or lateral) as well as radiated underwater acoustics.

The propeller operates in a spatially non-uniform wake, so there are fluctuations in parameters such as the propeller thrust and boundary pressure of a submarine hull which, in turn, can generate significant acoustic signature.

Alongside the cavitation analysis already described in this brochure, options for investigating the forces and torques acting on the propeller shaft include static test benches, cavitation tunnels and propelled model testing in towing tanks or wave pools.

Static test benches, cavitation tunnels and propelled model testing are among the options for investigating forces and torques on the propeller shaft. (Source: HSVA)

Key technologies for the application

- **High natural frequency**
  Rotating equipment often requires higher-frequency force and moment measurement to characterize test articles and conditions as a function of harmonics (e.g. multiples of rotational speed). For example, a 3,000 Hz natural frequency would result in a 10% frequency of 1,000 Hz. Piezoelectric (PE) pressure measurement provides a much wider frequency range (>300 kHz) to characterize cavitation effects.

- **Rangeability**
  PE measurement technology provides both high-resolution quasi-static and dynamic measurement and is rangeable with an external charge amplifier. For example, force and moment instabilities can manifest as low-level dynamic events under high hydrostatic conditions that can easily be measured with high fidelity. PE pressure measurements have the same advantages as PE force measurements; however, using IEPE to measure pressure would result in a fixed measuring range.

- **Application flexibility**
  Single and multicomponent force sensors from Kistler can be configured to create dynamometers that meet specific application requirements; they are flexible enough to allow adaption to different dynamometer designs as requirements evolve. With their small diaphragm diameters, PE pressure sensors can be mounted either singly or in a closely spaced array of several sensors.

Product highlights	
	**Waterproof PE and IEPE pressure sensor family** 601C, waterproof IP68 options
	**3-component force sensors and force links with welded cables** Waterproof IP68 options
	**Laboratory charge amplifier for quasi-static and dynamic measurement** 5080A high resolution, 5167A integral DAQ
	**Customized 6-component dynamometer for thrust measurement** Waterproof IP68 options

Kistler services: increasing success you can measure

Good service is the cornerstone of daily interactions with customers. But at Kistler, we believe that “good” is simply not good enough. And to prove the point, we make sure that our extensive service program is precisely tailored to your specific needs.

Kistler services do not end when you purchase our sensors or electronic measuring equipment. We are happy to advise you on your measuring problem and help you select the right components. Our experienced service technicians offer on-site support to ensure that your new Kistler system is optimally integrated, connected and configured into your system. The benefit: after just a brief introduction, you can start work on your measurement task immediately.

Calibration with continuous documentation
Thanks to our calibration service, you can rest assured that your Kistler sensors and systems will remain fully functional throughout their service lifetime – the basis for precise and reliable measurement results. Each calibration is documented, without exception. On request, our measurement technology experts can also perform the calibration directly at your location. Our calibration laboratories in China, the US, Japan and Germany can also perform fast and efficient on-site recalibrations.

Custom solutions
As a system provider, Kistler supplies you with complete solutions that optimally meet your measurement needs. Our specialists are happy to design a new, tailor-made solution together with you – for even better performance in your field of application.

Kistler services
- Guidance on how to define your measurement task and select the components
- Startup
- Device calibration
- Repair
- Training
- Customized solutions

At our customers' service across the globe

Thanks to Kistler's global sales and service network, we are always close to our customers. Some 2,200 employees at more than 60 locations are dedicated to the development of new measurement solutions, and they offer customized on-site support for individual applications.

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Find out more about our applications:
www.kistler.com/applications

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