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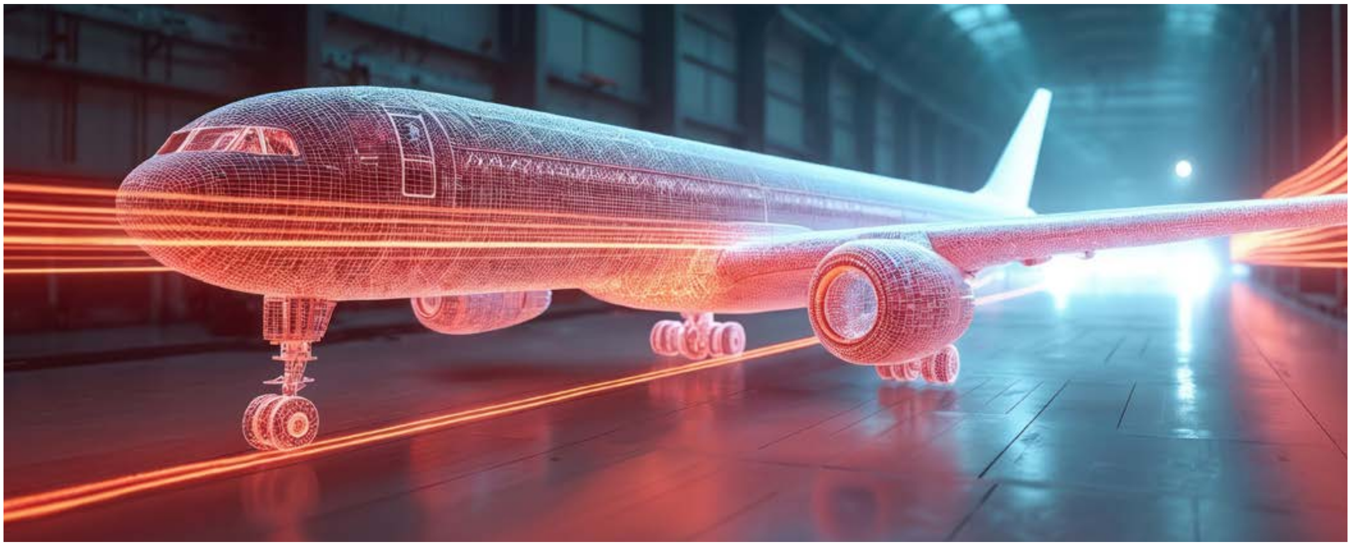

Testing Solutions for Aerodynamic & Aeroacoustic Applications

A PRODUCT GUIDE FOR ENGINEERS, RESEARCHERS, AND STUDENTS

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1. INTRODUCTION

This handbook is a practical guide for engineers, researchers, students and technicians working with aerodynamic and aeroacoustic testing. It covers both laboratory testing—especially wind tunnels—and real-world testing, with an emphasis on sensor selection.

Our goal is to help you:

- Understand the basic principles behind these disciplines.
- Select the right sensor technologies.
- Apply aerodynamic and aeroacoustic testing together to solve engineering problems efficiently.

2. FUNDAMENTALS OF AERODYNAMIC AND AEROACOUSTIC STUDIES

Aerodynamics and aeroacoustics are two tightly interwoven disciplines that together explain how air moves around and within objects—and the noise that results. By combining insights from both, engineers can design systems that are not only more efficient but also quieter and more reliable.

Aerodynamics: The Study of Airflow

Fluid dynamics is the study of how liquids and gases move and interact with solid surfaces. It is built on the assumption that fluids behave as continuous media, allowing properties such as pressure, velocity, and temperature to be defined at every point in space and time [1]. This makes it possible to analyze and measure fluid behaviors using mathematical models and physical experiments.

Aerodynamics, a specific branch of fluid dynamics, focuses on the behavior of gases, especially air, and their interaction with objects. While some aerodynamic principles apply to liquids (hydrodynamics), this handbook centers on airflows.

Aerodynamic forces are commonly classified as:

- **Lift**: The upward force enabling flight.
- **Drag**: The resistance force opposing motion.
- **Thrust**: The forward force propelling an object.

Internal Aerodynamics is not concerned with external flows around an object, but instead focuses on airflow within systems, such as engine intake and exhaust flows, turbomachinery components, and ducted ventilation systems. Although the measured quantities—such as pressure and force—are similar to external tests, internal aerodynamics often involves more extreme environmental conditions, particularly in terms of temperature.

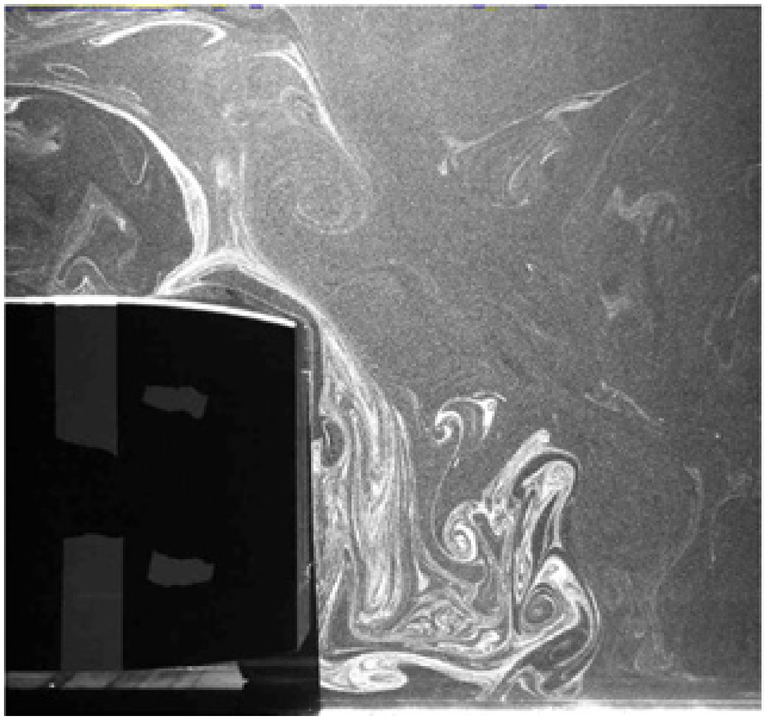


Figure 1: Flow patterns around a squareback Ahmed body [2].

Aeroacoustics: The Study of Flow-Induced Noise

Aeroacoustics is a specialized branch of acoustics focused on the noise generated by fluid flow, particularly from turbulence or interactions with solid surfaces. It blends the disciplines of aerodynamics and acoustics, making it inherently multidisciplinary.

Once the primary aerodynamic behavior of an object is understood—typically through measuring mean pressures and forces—the focus often shifts to fluctuating, unsteady flow features. These include turbulence within the airflow, vortex shedding, and similar flow instabilities.

These unsteady phenomena are key sources of flow-generated noise, making them essential targets for aeroacoustic analysis.

A Brief Look Back: Key Equations & History

Understanding today's methods starts with a brief look at the evolution of fluid mechanics and aeroacoustics:

- Building on ideas from ancient Greece about drag and pressure, 17th-century scientists formalized the concept of air resistance, marking the first comprehensive framework for aerodynamic behavior [3].
- In the 18th century, **Bernoulli's Equation** [4] provided a simple relationship between pressure, density, and flow velocity for incompressible flow. By 1809, Cayley defined the four aerodynamic forces involved in flight—lift, drag, thrust, and weight—and described their interrelationships through equations involving velocity, pressure, and viscosity [5].
- The development of the **Euler equations** [6] and **Navier–Stokes equations** [7,8] enabled analysis of compressible and viscous flows, laying the foundation for modern computational methods. While they allow numerical solutions, a full analytical solution to the Navier–Stokes equations remains one of the seven Millennium Prize Problems in mathematics.

Aeroacoustics emerged much later:

- In the 1950s, Sir James Lighthill reformulated the Navier–Stokes equations into an inhomogeneous wave equation, now known as **Lighthill equations** [9], to describe how turbulence generates sound.
- Later, the **Landau and Lifshitz equations** [10] offered additional tools to analyze sound in fluid systems, especially in complex or nonlinear conditions.

These equations demonstrate how sound generation is fundamentally linked to fluid motion.

Approaches to Aerodynamic and Aeroacoustic Testing

Modern aerodynamic and aeroacoustic investigations rely on a combination of experimental methods, precision instrumentation, and simulation tools. This catalog highlights the role of experimental testing, such as wind tunnel campaigns, flight trials, and on-road testing, alongside the sensors and instrumentation that enable accurate measurement—ranging from pressure sensors and microphones to multi-axis force and vibration sensors.

These physical tests are often complemented by computational methods, including computational fluid dynamics (CFD), to simulate complex flow patterns and acoustic behavior. Together, these approaches provide a complete picture of how airflows behave and how noise is generated or mitigated in real-world conditions.

KEY INSIGHT

Despite differences in mathematical formulations, the measurement principles and testing approaches for aerodynamics and aeroacoustics are often the same. A combined testing strategy provides a fuller picture of performance and noise behavior.

Real-World Applications of Aerodynamic and Aeroacoustic Testing

Aerodynamic and aeroacoustic principles shape the design and performance of everything from aircraft and automobiles to buildings and bridges. The following sections outline how these principles are applied across industries to improve safety, efficiency, and environmental performance.

Aerospace and Automotive Testing

In both aerospace and automotive applications, controlling airflow is key to achieving performance goals.

In aerospace applications, air vehicles such as aircraft, rockets, missiles, and drones are typically designed to maximize lift while minimizing drag, improving fuel efficiency and flight stability. Ground vehicles—including cars, motorcycles, and trains—also focus on reducing drag, reducing drag and lift to enhance traction and control, particularly at high speeds.

Aerodynamic studies also support:

- Flight safety, such as managing aircraft separation during takeoff and landing.
- Marine operations, including helicopter landings on ship decks and aerodynamic effects on vessels.
- Mechanical and structural engineering, by ensuring components can withstand flow-induced forces.
- Heating, ventilation and air conditioning (HVAC) and interior systems, through improved air circulation and flow control.

Architecture and Civil Infrastructure Testing

Aerodynamic testing in civil engineering supports a wide range of goals: buildings are evaluated for wind stability and resilience under extreme weather conditions; airflow patterns around streets and open spaces are analyzed to improve pedestrian safety and comfort; and indoor ventilation systems are modeled to enhance energy efficiency and pollutant dispersion. Critical infrastructure, including bridges and cable-supported structures, is also tested to ensure durability against wind-induced vibrations.

These evaluations are essential for maintaining structural integrity and occupant well-being across a range of environmental scenarios.

KEY INSIGHT

Even small design choices are guided by aerodynamic principles. The Magnus Effect [11], which explains how a spinning baseball curves midair, also applies to rotating cylinders used in marine propulsion and certain architectural designs.

Noise, Vibration, and Harshness (NVH) Considerations

Unsteady aerodynamic forces—such as those caused by turbulence or vortex shedding—can generate unwanted noise and vibration. Many industries address these issues through **noise, vibration, and harshness (NVH) testing**, which captures pressure, sound, and motion simultaneously. This integrated testing strategy helps engineers design for passenger comfort, product durability, and acoustic performance all at once.

Design Trade-offs and Constraints

In practice, aerodynamic and acoustic optimization must coexist with other real-world design considerations:

- Aesthetic appeal, especially for consumer-facing products like automobiles.
- Functional constraints, such as cargo capacity, internal layout, or system packaging.
- Regulatory requirements, which may limit design freedom or shape performance goals.

For example, a teardrop shape may offer the lowest drag coefficient—but few vehicles adopt this ideal form due to practical limitations [12]. Ultimately, aerodynamic performance is just one factor in a broader system of trade-offs.

3. TYPES OF AERODYNAMIC & AEROACOUSTIC TESTS

Despite the widespread use of CFD experimental testing remains essential in aerodynamic and aeroacoustic studies for practical validation. Certain phenomena, such as fine-scale turbulence and large-scale unsteady flows, are still difficult to predict with high accuracy using numerical methods alone. Experimental testing complements simulations by capturing complex flow behaviors that are challenging to model computationally.

KEY INSIGHT

Combining computational models with experimental testing provides the most reliable path to safe, efficient, and quiet designs.

Experimental approaches can be broadly divided into two categories: laboratory-based testing and real-world testing. Laboratory tests provide tightly controlled environments for evaluating airflow, pressures, aerodynamic forces, and noise generation with high repeatability. Real-world tests, by contrast, capture performance under true operating conditions—on the road, rail, or in flight—where environmental influences such as weather, terrain, and dynamic loads play a significant role. While this handbook focuses primarily on laboratory methods, particularly wind tunnels, real-world testing is equally important and is discussed in greater detail in section 7 of this handbook.

External Aerodynamics

This category focuses on assessing the impact of airflow on a test object, as well as the object's influence on the surrounding flow. These tests are essential for validating computational models and optimizing designs before full-scale implementation.

Key measurements include:

- Surface pressures on the object.
- Flow-field pressures at points around the object.
- Aerodynamic forces, such as drag and lift, acting on the object.

Wind tunnels are the most widely used laboratory tools for this type of testing. They allow engineers to simulate airflow around stationary models, supporting analyses such as lift and drag force evaluations; surface pressure distribution mapping; and flow visualization studies including separation, reattachment, and vortex shedding. Advanced testing may also incorporate aeroacoustic analysis to identify noise sources generated by airflow over the object.

The importance of this type of testing is underscored by real-world incidents where improper aerodynamic balance led to severe consequences. For example, the first-generation Audi TT experienced high-speed instability due to uncontrolled rear lift [13], while the infamous Mercedes crash on the Les Hunaudières straight at Le Mans highlighted the dangers of inadequate aerodynamic validation. Ground testing helps identify and correct such risks early in the design process, before they can cause catastrophic failures.

Refer to section 5 of this handbook for comprehensive information about tunnel classifications, flow regimes, instrumentation, and specialized techniques.

Aeroacoustics

This category encompasses two subtypes of testing, depending on whether external airflow is present:

With external flow: Tests are conducted in a wind tunnel with airflow over the object, similar to aerodynamic tests. Microphones, high-sensitivity pressure sensors, and sometimes accelerometers are installed both inside the test object and in its surroundings. Acoustic and vibration data are collected during the test to evaluate sound generation and transmission.

Transfer path testing (without flow): These tests are typically conducted in anechoic chambers or quiet facilities without airflow. Sound and vibration—both internal and external—are measured using controlled sound sources and microphone arrays to measure noise transmission through the test structure. This approach helps engineers identify how noise generated during operation would be transmitted to users, even though no airflow is present during the test itself.

Internal Aerodynamics

Internal aerodynamic testing is focused on the flow of air or gases within ducts, nozzles, or engine components. These tests are especially critical in the design and optimization of ventilation systems, jet engines, intake systems and exhaust systems.

Objectives include evaluating:

- Pressure losses through internal components.
- Flow uniformity at inlets, outlets, and within flow passages.
- Levels of turbulence throughout the internal flow path.

In typical internal flow tests, air is supplied to the system under study, either at real operating temperature or at a reduced temperature, depending on the objectives of the test and facility capabilities. Internal pressures are carefully measured at various locations to characterize flow behavior throughout the system. These tests are often conducted in quiet facilities, allowing engineers to also estimate acoustic phenomena such as jet noise at the exhaust.

KEY INSIGHT

Laboratory testing methods remain indispensable for identifying and correcting aerodynamic or acoustic issues before they lead to dangerous instabilities in real-world operation.

The most common measurements collected during internal flow tests include static and dynamic pressure, velocity profiles, and, in some cases, temperature. Engineers may also use specialized probes or flow visualization techniques to capture these variables, providing a comprehensive picture of system performance and efficiency under various simulated operating conditions.

4. SENSOR TECHNOLOGIES

Structures subjected to aerodynamic and aeroacoustic forces undergo rigorous testing throughout the design and validation process. These tests are essential to ensure that vehicles, aircraft, and infrastructure can withstand operational environments while meeting safety and performance targets.

Why Sensors Matter

At the heart of these tests are measurements of key physical quantities: pressure, force, vibration, and sound. Sensors convert these physical phenomena into electrical signals that engineers can analyze to understand how a design performs under realistic conditions.

Pressure sensors are the most common starting point, as they provide essential data for assessing flow behavior, calculating aerodynamic forces, and evaluating sound generation. In many cases, velocity measurements are also needed—but rather than measuring it directly, engineers often derive velocity from pressure data, which is easier to obtain in many setups.

No single sensor provides a complete picture of aerodynamic behavior. Microphones, accelerometers, and force sensors are critical for capturing acoustic signals, vibrations, and dynamic loads. Strain sensors, though more specialized, help measure structural deformation under aerodynamic and aeroacoustic loads.

Selecting the right combination of sensors—and knowing which measurements are most important for each test—is fundamental to gathering accurate, meaningful data in aerodynamic and aeroacoustic research.

Common Sensor Types and Applications

Sensor Type	Key Function & Technical Features
ICP® Acoustic Pressure Sensors	Similar to piezoelectric microphones but powered by constant current sources. Provide low-noise performance for dynamic acoustic measurements, commonly used in wind tunnels and in-flight tests of rockets and reentry vehicles.
Miniature ICP® Accelerometers	Capture vibration and solid-borne sound transmission with high frequency response, small size, and low mass. Widely used for vibration testing in flight vehicles, aerodynamic models, and structural studies.
Miniature ICP® Pressure Sensors	Designed for short-wavelength, high-frequency pressure phenomena such as turbulence, pulsations, and noise in both laboratory and harsh operational environments.
Piezoelectric Microphones	Measure high-intensity acoustic noise and low-pressure fluctuations, even in harsh environments, making them ideal for the extreme acoustic conditions of a rocket launch.
Piezoresistive Pressure Sensors	Suitable for both static and dynamic pressure measurements. Known for high sensitivity and fast response, making them effective for airflow studies and high-intensity sound tests.
Piezoelectric Force Sensors	Measure dynamic forces, including oscillating loads, impacts, and transient aerodynamic forces. Provide rapid response and high stiffness for accurate force measurements in wind tunnels and structural tests.
Piezoelectric Strain Sensors	Used to measure dynamic structural strain. Offer high signal-to-noise ratio, reusability, and minimal thermal sensitivity, making them ideal for dynamic testing of structural components under aerodynamic loads.
Variable Capacitance (VC) MEMS Accelerometers	Capture low-frequency vibration and motion with rugged, gas-damped MEMS technology. Used in aerodynamic model testing, flutter and buffeting studies, and simulated environmental testing with shakers and centrifuges.

Integrated Testing Approaches

In modern testing programs, multiple sensors are often used together. This enables a comprehensive view of system behavior by capturing aerodynamic loads, acoustic behavior, and structural response in parallel during a single test campaign.

Integrated sensing solutions support a wide range of ground and flight test applications, including ground vibration (modal) testing, propulsion and motor vibration monitoring, flutter and structural response studies, and crash testing for passenger safety and structural integrity. Engineers may also assess cabin vibration and noise exposure for passenger comfort, monitor environmental flyover noise, or conduct HALT/HASS and reliability testing of subcomponents such as batteries. From early-stage wind tunnel development to final flight certification, these coordinated approaches play a vital role across industries including aerospace, automotive, civil infrastructure, and urban air mobility (UAM).

To achieve this level of insight, a variety of specialized sensors are used throughout the testing process. Among these, accelerometers play a central role in capturing vibration data.

4.1 ACCELEROMETERS

When airflow moves over a structure, it generates forces that can cause vibrations. Measuring these vibrations is critical for understanding both aerodynamic behavior and solid-borne acoustic transmission—that is, the transmission of sound through the structure itself.

Accelerometers are the most widely used sensors for detecting these vibrations. They are applied in:

- Ground-based tests (such as wind tunnels).
- Flight tests (for in-service measurement).
- Structural dynamics studies (to evaluate mechanical response).

Their ability to measure vibration accurately across a broad range of test environments makes them indispensable in aerodynamic and aeroacoustic research.

Several accelerometer types are used in aerodynamic and aeroacoustic testing. While all serve to measure vibration, some technologies are more suited to specific testing needs .

Piezoelectric Accelerometers (ICP® or IEPE)

ICP® (Integrated Circuit Piezoelectric) accelerometers are the most widely used in aerodynamic and aeroacoustic testing. They specialize in dynamic measurements and are ideal for capturing high-frequency vibrations.

Key Advantages of ICP® Accelerometers for Aerodynamic and Structural Testing

These accelerometers feature ultra-lightweight designs to minimize mass loading on delicate models, along with a wide frequency response with high sensitivity and low noise to capture both subtle and rapid vibration events. A stable, low-impedance output ensures clean signals even over long cable runs, and rugged construction delivers reliable performance in demanding test environments. Flexible adhesive or stud mounting options support quick, adaptable installation.

Typical Performance Characteristics:

- Sensitivity ranges from near-DC to several kilohertz.
- TEDS (Transducer Electronic Data Sheet) for quick sensor identification.
- Very low base strain sensitivity for improved accuracy.
- Compatibility with large sensor arrays for complex programs.
- Cost-effective design for high-volume testing.

	**356A15** Triaxial, high sensitivity, ceramic shear ICP® accelerometer, 100 mV/g, 2 to 5k Hz, titanium housing, 4-pin connector
	**356A16** Triaxial, high sensitivity, ceramic shear ICP® accelerometer, 100 mV/g, 0.5 to 5k Hz, aluminum housing, 4-pin connector
	**356B18** Triaxial, high sensitivity, ceramic shear ICP® accelerometer, 1000 mV/g, 0.5 to 3k Hz, 4-pin connector
	**333B30** Modal array, ceramic shear ICP® accelerometer, 100 mV/g, 0.5 to 3k Hz, 10-32 side connector, stud mount
	**333B50** Modal array, ceramic shear ICP® accelerometer, 1000 mV/g, 0.5 to 3k Hz, 10-32 side connector, 5-40 stud mount

Table 1: Examples of ICP® accelerometers used for structural or modal testing, demonstrating typical sizes and mounting options.

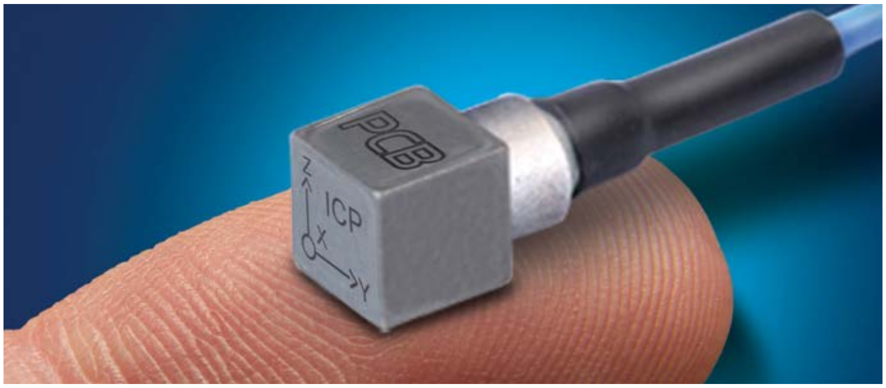


Figure 2: Miniature ICP® accelerometer designed for vibration measurements on small-scale models and components, such as those used in wind tunnel tests.

KEY INSIGHT

Accelerometers are essential in aerodynamic and aeroacoustic testing. While MEMS accelerometers have niche uses, ICP® accelerometers remain the preferred choice for most vibration measurements due to their accuracy, durability, and versatility in both laboratory and operational environments.

How ICP® Accelerometers Work

ICP® accelerometers use a piezoelectric crystal sensing element (quartz or ceramic), paired with a seismic mass and preload mechanism. As the structure accelerates, the mass stresses the crystal, producing an electrical signal. This signal is then converted into a low-impedance voltage output by built-in electronics.

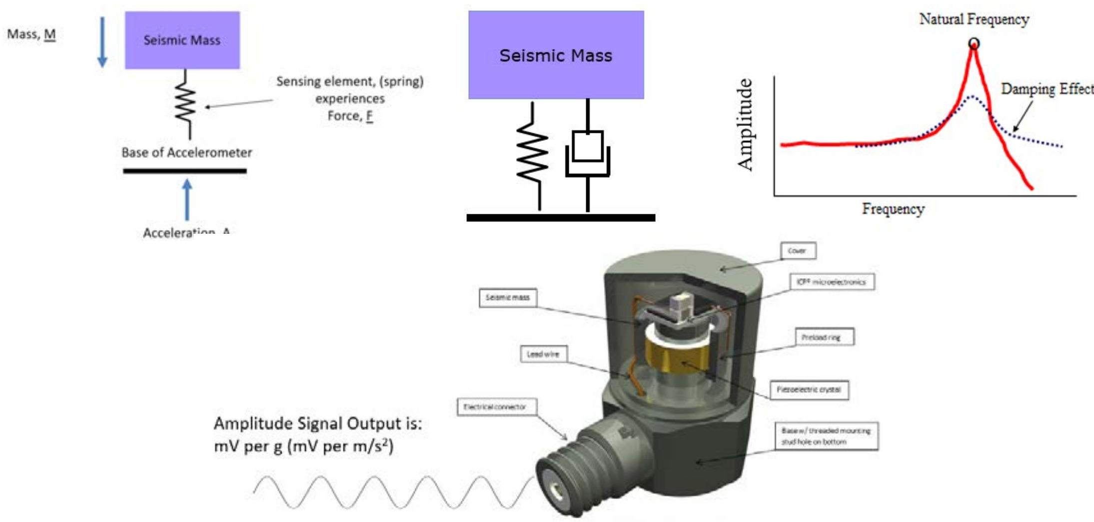


Figure 3: Schematic diagram illustrating the operating principle of an ICP® accelerometer, showing its sensing crystal, seismic mass, and internal electronics.

MEMS-Based Accelerometers

Micro-Electro-Mechanical Systems (MEMS) accelerometers are generally compact and cost-effective, but they are not as commonly used in aerodynamic and aeroacoustic testing, where dynamic performance and wide frequency range are often required. They are typically categorized as either capacitive or piezoresistive types:

Variable Capacitive (VC) MEMS accelerometers can measure both static and dynamic accelerations. They are often used in low-frequency or quasi-static measurements, like aircraft flutter testing and buffeting.

Piezoresistive MEMS accelerometers are more suitable for high frequency and high acceleration applications, such as shock or crash testing. While they provide DC response and durability, they typically lack the bandwidth and sensitivity required for detailed aerodynamic or aeroacoustic vibration analysis.

4.2 STRAIN SENSORS [14] [15]

When airflow moves around a structure, it can cause deformation. Measuring this structural strain provides critical data for understanding how aerodynamic forces interact with the object.

Strain measurements are often used to analyze structural behavior under aerodynamic loads, support vibration and fatigue studies, and validate computational models of structural response. While strain is traditionally measured with resistive strain gages, piezoelectric strain sensors are increasingly used in dynamic testing due to their fast response and reusability.

Figure 4: PCB Model 740B02 ICP® dynamic strain sensor designed for structural testing applications.

Key Advantages of Piezoelectric Strain Sensors for Dynamic Testing

Piezoelectric strain sensors provide significant benefits over conventional resistive strain gages in dynamic testing. They deliver a high signal-to-noise ratio, enabling clear, accurate measurements even in challenging environments. Their wide frequency response allows engineers to capture rapid strain changes, while minimal sensitivity to temperature variations ensures stable results across diverse test conditions.

These sensors are also reusable, making them cost-effective for repeated test campaigns. Installation is straightforward: they are typically bonded to flat surfaces using cyanoacrylate adhesive and can be easily removed after testing. Proper surface preparation—cleaning, drying, and degreasing—is essential for reliable adhesion and precise measurements.

Typical Performance Characteristics:

- Sensitivity: 50 mV/με.
- Frequency range: approximately 0.5 Hz to 100 kHz.
- Rugged titanium housing for durability and protection.
- Not intended for static or long-duration load measurements.

Piezoelectric strain sensors operate with an ICP® amplifier, which converts the electrical charge from the piezoelectric element into a voltage proportional to strain. They measure in-plane normal strain along its length.

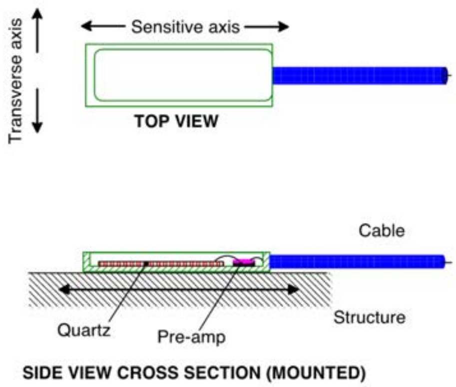


Figure 5: Construction and mounting of the PCB Model 740B02 piezoelectric strain sensor, showing the sensitive and transverse axes.

Frequency Response and Accuracy Considerations

Accuracy depends on several factors:

- The modulus of elasticity of the test structure. Softer materials may reduce actual sensitivity compared to calibration values.
- Cable length and capacitance, which can limit high-frequency performance.
- The strain wavelength relative to sensor size. For accurate measurements, the strain wavelength should exceed the sensor length.

The strain wavelength can be estimated using the following formulas [16]:

$$\lambda = c / f$$

where c is the speed of sound and f is the frequency.

As a practical guideline:

$$f = 0.1 \cdot c / L$$

where L is the sensor length.

Transverse Sensitivity and Shear Strain Rejection

Quartz-based piezoelectric strain sensors are designed to minimize sensitivity to strain in unintended directions, and inherently insensitive to pyroelectric (thermal) disturbances. These characteristics make them ideal for dynamic testing applications where directional accuracy is critical.

The **PCB Model 740B02** is an excellent choice for taking dynamic strain measurements because:

- It provides a primary sensitivity of 50 mV/με along its sensing axis.
- It has a very low transverse sensitivity of -1.9%. For instance, if the sensitivity is 50 με along the sensing axis, the sensitivity transverse to this axis will be only -0.95 mV/με.
- It shows zero sensitivity to in-plane shear strain, due to its quartz crystal construction.

Calibration is performed in controlled laboratory environments using cantilever beam setups mounted between two foil strain gages in order to measure sensitivity of the material under test. (see **Figure 6**). These specifications are verified by mounting the sensor at different angles during calibration—specifically at 0° and 90°—as shown in **Figure 7**.

KEY INSIGHT

Piezoelectric strain sensors, such as the **PCB Model 740B02**, provide reliable, high-performance strain measurements for aerodynamic and structural testing. Their low transverse sensitivity, strong signal quality, and reusability make them an excellent choice for capturing precise strain data under aerodynamic loads.

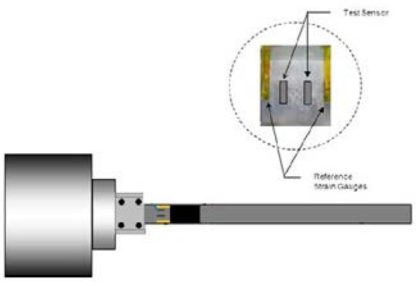


Figure 6: PCB provides a calibration certificate for each sensor using a steel cantilever beam (26 x 2 x 0.25 in) to verify strain sensor sensitivity.

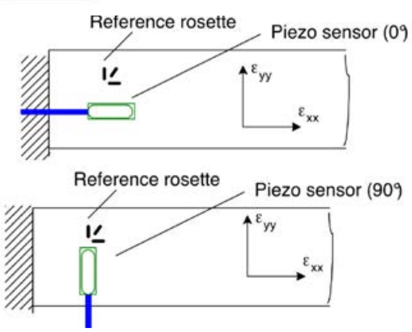


Figure 7: Verification of transverse sensitivity by rotating the sensor between 0° and 90° orientations during testing.

4.3 FORCE SENSORS

Force sensors are critical for measuring the loads and moments acting on structures during aerodynamic testing. These sensors are frequently used to quantify directly, if proper mounted, forces such as lift, drag, and side forces, as well as moments (rotational forces) about each axis. Measurements like these are essential for understanding stability, control, and structural loading during wind tunnel tests, model validations, and structural response evaluations.

Key Advantages of Piezoelectric Sensors for Dynamic Force Measurements

These sensors offer very high stiffness, comparable to solid steel, to minimize deflection during measurements. Their wide dynamic range and fast response make them well-suited for capturing sudden or high-frequency forces with precision. ICP® designs provide stable signals over long cable runs, remain insensitive to cable motion and triboelectric noise, and are ideal for continuous or unattended monitoring in demanding environments, all while reducing total system cost through simplified electronics and standard cabling.

Typical Performance Characteristics:

- Very high stiffness to minimize deflection.
- Wide dynamic range with fast response.
- Quasi-static force measurement within the discharge time constant.
- Excellent repeatability for dynamic testing.
- Stable signals over long cable runs with minimal loss.

Charge Mode vs. ICP® Force Sensors

Piezoelectric force sensors are available in two configurations:

Charge mode sensors produce a high-impedance electrical charge output. They require an external charge amplifier to convert the signal to a usable voltage and are favored for high-temperature environments.

ICP® (Integrated Circuit Piezoelectric) sensors have built-in microelectronic amplifiers that convert the charge signal into a low-impedance voltage output within the sensor itself. This simplified system setup allows for the use of longer cables, and makes ICP® sensors easier to integrate with modern data acquisition systems.

Both types rely on the same quartz piezoelectric sensing elements, but the choice between charge mode and ICP® depends on factors such as temperature range, measurement duration, and system requirements.

How Piezoelectric Force Sensors Work

Most force sensors used in these applications rely on quartz piezoelectric sensing elements to detect applied forces with high precision and fast response. Typical construction includes:

- Thin quartz crystals stacked between metal base plates.
- A preload mechanism (using a threaded stud or sleeve) to maintain constant pressure on the crystals for consistent operation.
- A hermetically sealed housing for protection in harsh environments.

A schematic diagram showing piezoelectric force sensor construction is shown in **Figure 8**.

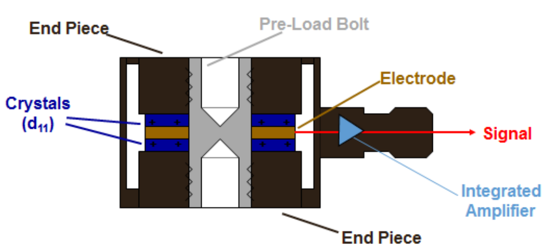


Figure 8: Schematic diagram and example of a piezoelectric force sensor, showing internal construction with quartz crystal elements and preload components.

When force is applied to the sensor, it compresses the quartz crystal elements inside, which generates an electrical charge proportional to the applied force. In ICP® models, this charge is immediately converted into a voltage output within the sensor housing. This design provides a fast, stable signal that makes piezoelectric force sensors ideal for capturing dynamic, rapidly changing forces in challenging test environments.

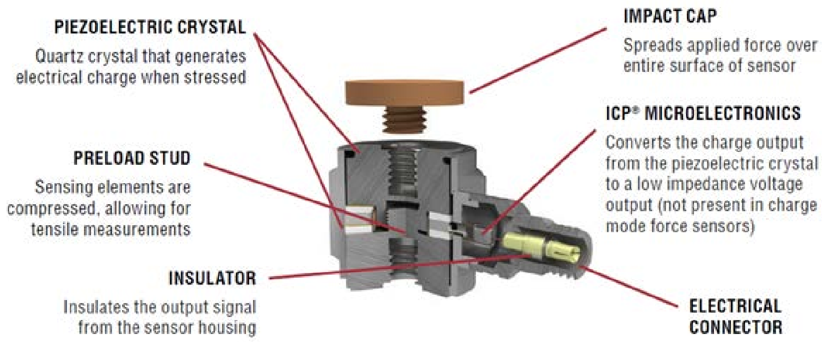


Figure 9: Illustration of a typical piezoelectric force sensor design, highlighting the mechanical stack and housing components.

Figure 10: PCB Model 260B02 is an ICP® triaxial force ring sensor capable of measuring forces along three orthogonal axes. Requires external preload with mounting stud.

Force Sensors in Wind Tunnel and Structural Testing

Piezoelectric force sensors are widely applied in wind tunnel testing to directly measure the aerodynamic forces acting on scaled models. They are also used in structural tests for vibration and shock response evaluations.

Triaxial or multi-component force sensors (shown in **Figure 10**) allow simultaneous measurement of forces along multiple axes, providing comprehensive insights into complex aerodynamic force interactions.

KEY INSIGHT

Piezoelectric force sensors—available in both charge mode and ICP® configurations—offer fast, accurate solutions for measuring dynamic and quasi-static forces in aerodynamic and structural testing.

4.4 MEASUREMENT MICROPHONES

Unlike microphones used for audio recording, measurement microphones are specifically designed for high precision. They offer flat frequency response, stable sensitivity across environmental conditions, and well-documented calibration traceability, making them suitable for both laboratory and operational tests.

Condenser Microphones for Aerodynamic and Aeroacoustic Testing

Condenser microphones are designed to accurately measure low-pressure acoustic signals, making them indispensable for evaluating sound fields around objects, analyzing noise generated by airflow and turbulence, and assessing the acoustic effects of design changes.

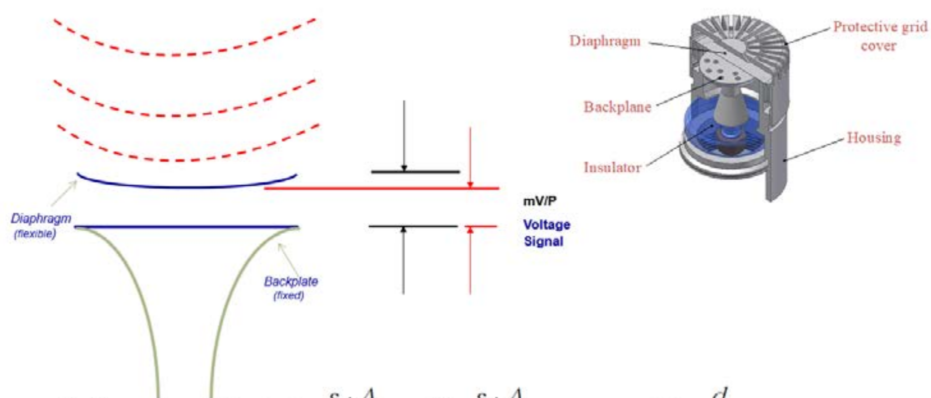
How Condenser Microphones Work

Condenser microphones measure sound by detecting changes in capacitance between two closely spaced plates: a thin, flexible diaphragm and a rigid backplate. As sound waves impact the diaphragm, it deflects slightly, changing the distance between the plates. This change alters capacitance of the system, which in turn affects the electrical signal output.

To detect these changes, a bias voltage must be applied across the plates. This voltage creates an electric field within the capacitor, allowing the system to convert capacitance changes into an electrical signal proportional to the sound pressure level.

There are two common ways to apply this polarization. **Externally polarized microphones** use an external power supply to maintain the required bias voltage, while **pre-polarized microphones** use an embedded electret material that provides a built-in static charge, eliminating the need for an external source.

In both cases, the operating principle remains the same: as the diaphragm moves, it changes the distance between the plates. That change is converted into a measurable voltage, which directly corresponds the incoming sound.



$$E \cdot C = Q_0 \qquad (E_0 + e) \cdot \frac{\varepsilon \cdot A}{D_0 + d} = E_0 \cdot \frac{\varepsilon \cdot A}{D_0} \qquad e = E_0 \cdot \frac{d}{D_0}$$

Figure 11: Illustration of the working principle of a condenser microphone.

The equation in **Figure 11** describes the real-time electrical response of the capacitor, and consists of the following inputs:

A = Area of capacitor plate
C = Instantaneous capacitance between plates
Do = Distance between plates at rest position
d = Displacement of moveable plate (diaphragm) from rest position
E = Instantaneous voltage between plates
Eo = Polarization (bias) voltage
e = Voltage change caused by diaphragm displacement
Qo = Constant charge on plate capacitor
ε = Dielectric constant of air

Condenser Microphone Design, Construction, and Calibration

A condenser microphone's internal components are carefully engineered for stability, accuracy, and longevity. The diaphragm and backplate form the core sensing element. Surrounding components, including a protective grid cap and insulating elements, protect the microphone from mechanical damage and environmental contaminants while maintaining electrical isolation. A cross-sectional view of the components is shown in **Figure 12**.

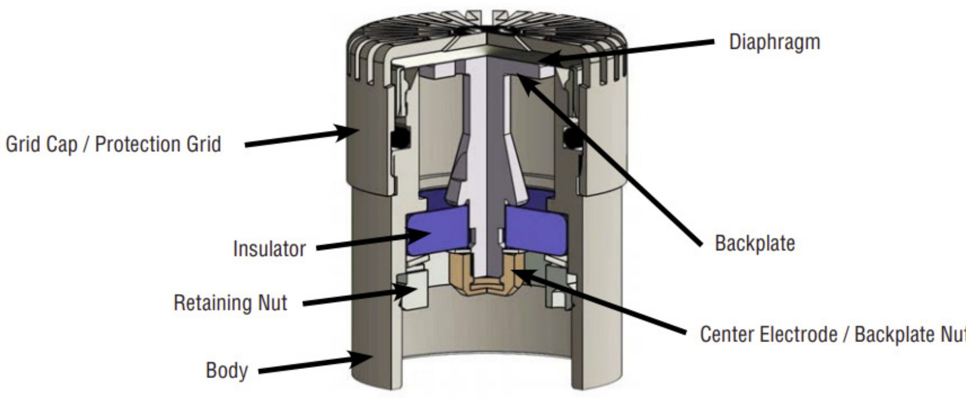


Figure 12: Cross-sectional view of a condenser microphone, detailing internal components such as the diaphragm, backplate, and insulator.

All parts are housed within a precision-machined body designed to minimize distortion and provide a consistent response across a wide frequency range. Each microphone is calibrated to ensure accurate, repeatable performance, with traceability to fundamental physical standards.

Microphone Preamplifiers and System Integration

Microphone preamplifiers ("preamps") are required to connect a measurement microphone to a voltmeter, sound meter, or data acquisition system. This component converts the high-impedance signal from the microphone into a low-impedance signal suitable for transmission over long cables.

It is important to remember that overall specifications of a microphone and preamplifier combination are determined by the most limiting characteristics of either component. Many systems combine the microphone cartridge and preamplifier into a single, factory-calibrated unit to simplify installation and ensure measurement traceability. **Figure 13** shows a typical microphone-preamplifier system.

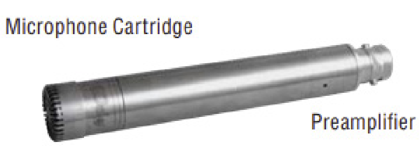


Figure 13: PCB Series 378 condenser microphone system with integrated preamplifier.

Specialized Microphone Types for Aerodynamic and Aeroacoustic Testing

While standard condenser microphones cover most test needs, several specialized microphone types are available for specific applications.

Electret microphones are commonly used in large-scale microphone arrays or preliminary tests where lower cost and ease of deployment are priorities. Although their frequency response and noise floor are not as refined as high-end condenser microphones, they offer a practical solution for high-channel-count measurements or non-critical testing environments. **Figure 14** shows an example of an array-style electret microphone system.

Figure 14: PCB Series 130F array-style electret microphones for high-channel-count acoustic testing.

Piezoelectric microphones offer the durability required to withstand very high sound pressure levels. These sensors use quartz or ceramic elements and are specifically designed for extreme acoustic environments such as blast or shock wave testing. While they have higher noise floors than condenser microphones, they are best suited for specialized tests where ruggedness is prioritized over sensitivity. **Figure 15** shows an example of a piezoelectric acoustic pressure sensor.

Figure 15: PCB Series 106B piezoelectric acoustic pressure sensor for high-intensity sound measurements.

Surface microphones provide an effective solution for tests requiring measurements of airflow or boundary layer noise on surfaces. These low-profile microphones are designed for flush mounting, and allow accurate surface acoustic pressure measurements measurements with minimal disturbance to the flow field. **Figure 16** shows an example of a surface microphone.

Figure 16: PCB Model 130B40 surface microphone for flush mounting and flow noise measurements.

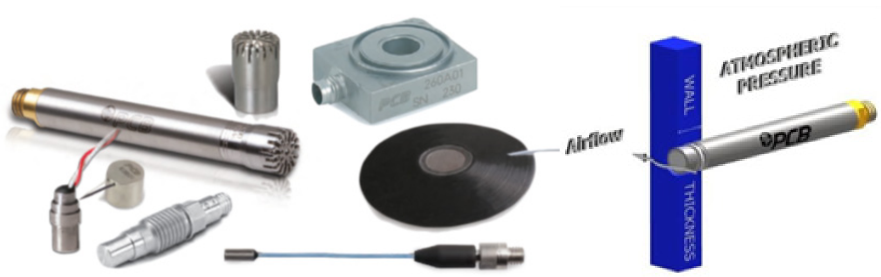


Figure 17: Examples of condenser microphones, pressure sensors and force sensors, all with ICP® output.

Selecting the Right Microphone

Choosing the correct microphone for aerodynamic and aeroacoustic applications depends on factors such as frequency range, desired sensitivity, environmental conditions, physical mounting limitations, and dynamic range requirements. Microphone selection charts, such as the one shown in **Figure 18**, can help engineers compare models and select the most suitable option for their specific testing needs.

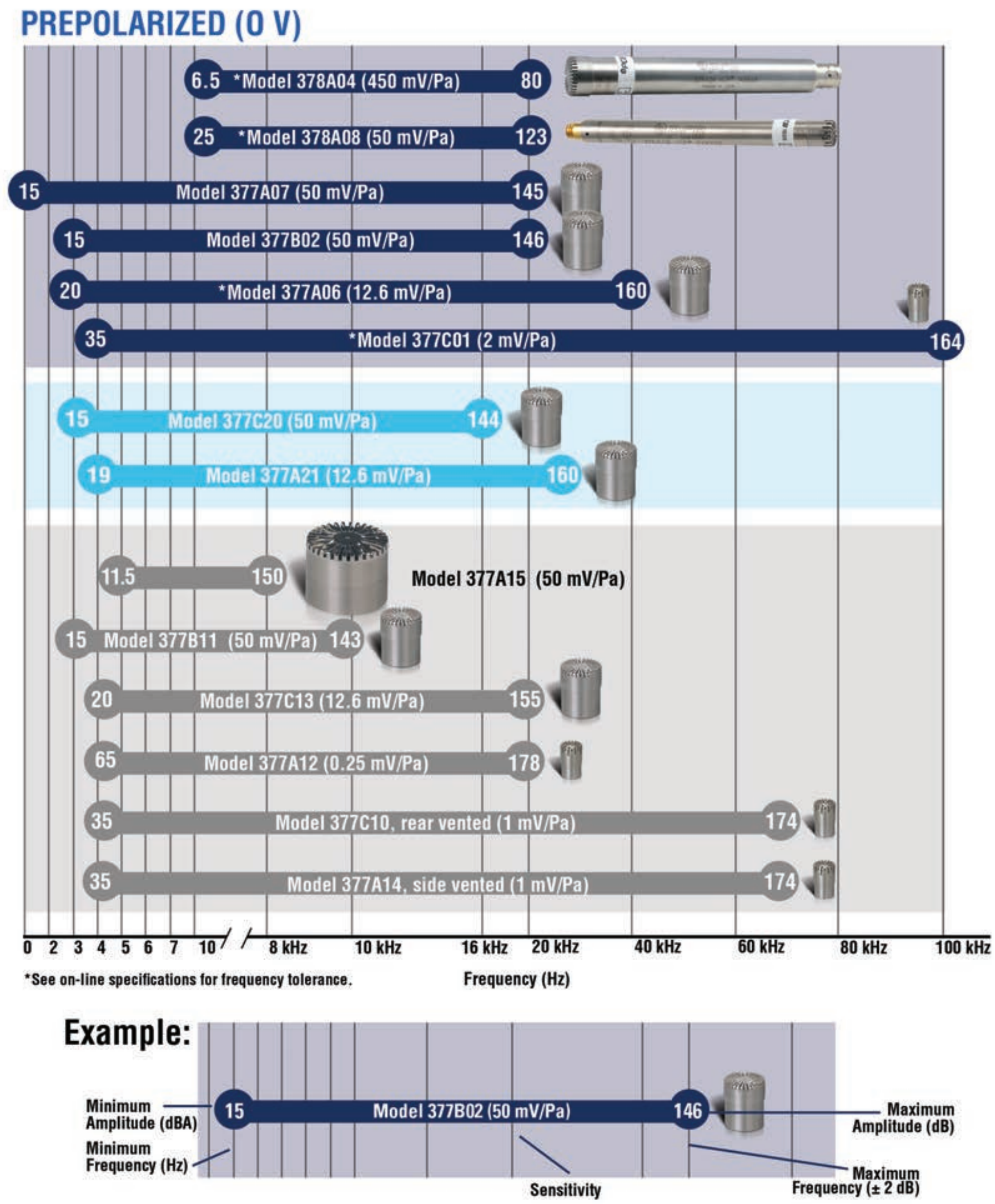


Figure 18: Condenser microphone selection chart.

4.5 PRESSURE SENSORS

Pressure measurement plays a central role in both aerodynamic and aeroacoustic testing. In the following sections, we highlight two key sensor technologies: piezoelectric sensors, designed for dynamic pressure measurements, and piezoresistive sensors, which are capable of both static and dynamic measurements.

Piezoelectric Pressure Sensors: Charge Mode and ICP®

Piezoelectric pressure sensors are designed for dynamic pressure measurements, particularly in applications involving rapid pressure fluctuations. They rely on quartz or ceramic sensing elements that generate an electrical charge in response to changes in pressure. These sensors excel in capturing high-frequency, short-duration pressure events, making them a key tool for studying fast-flowing or transient aerodynamic phenomena.

There are two common configurations for piezoelectric pressure sensors:

Charge mode sensors produce a high-impedance charge output and require an external charge amplifier to condition the signal.

ICP® sensors integrate miniature electronics within the sensor housing to convert the charge signal into a low-impedance voltage output, simplifying system integration and making them the more commonly used option in most aerodynamic and aeroacoustic tests. Examples of ICP® sensors are shown in Figure 19.

Common Applications

Piezoelectric pressure sensors are an indispensable tool for researchers analyzing high-frequency, short-duration pressure events, making them a key tool for studying fast-flowing or transient aerodynamic phenomena. Most widely used applications include:

- Shock waves and blast testing.
- High-speed aerodynamics and compressible flows.
- Combustion dynamics and propulsion systems.
- Transient pressure monitoring in engines, turbines, and test facilities.

How Piezoelectric Pressure Sensors Work

The fundamental design of piezoelectric pressure sensors centers on a robust, high-stiffness structure capable of withstanding extreme pressure environments. As illustrated in **Figure 20**, the key components include:

- A diaphragm that transmits pressure forces to the sensing element.
- A piezoelectric crystal that produces an electrical signal in response to pressure changes.
- A preload mechanism that maintains consistent force on the sensing element for linear response and long-term stability.
- Hermetically sealed housings that protect the internal components from environmental contaminants and allow operation in harsh conditions.

This design ensures extremely fast response times and excellent resistance to mechanical shock and vibration. The high mechanical stiffness also minimizes sensor deflection under load, preserving measurement accuracy during rapid events.

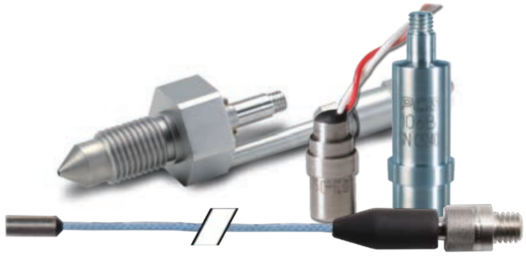


Figure 19: Examples of ICP® pressure sensors for aerodynamic and aeroacoustic applications.

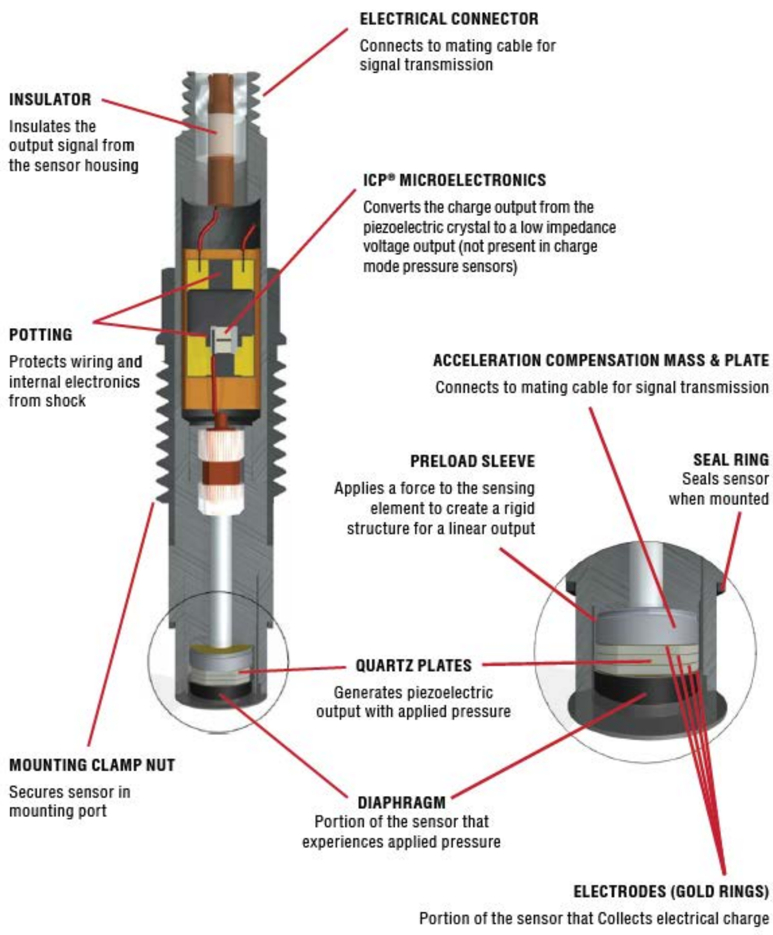


Figure 20: Typical piezoelectric pressure sensor construction.

Piezoresistive Pressure Sensors

Piezoresistive (PR) pressure sensors are widely used in aerodynamic and aeroacoustic testing because of their ability to measure both static and dynamic pressures. Their versatility makes them essential for tests involving steady-state pressures, low-frequency unsteady pressures, or a combination of both.

Common Applications

- Ground and flight tests requiring simultaneous static and dynamic pressure data.
- Wind tunnel testing for steady and unsteady surface pressures.
- Engine inlet distortion testing and compressor stall detection.
- Studies of low-frequency unsteady flow and structural oscillations.
- Internal flow measurements within propulsion systems and ducted flows.

How Piezoresistive Pressure Sensors Work

Piezoresistive pressure sensors work by detecting changes in electrical resistance caused by mechanical strain in the sensor's diaphragm. When pressure is applied, the diaphragm deflects, inducing strain in embedded piezoresistive elements. The resulting change in resistance is converted into an electrical signal proportional to the applied pressure.

Early PR pressure sensors used metallic diaphragms with bonded strain gages, which were functional but had limited sensitivity and larger physical size. Over time, these were replaced by silicon-based designs, where piezoresistive elements are diffused directly into a silicon diaphragm.

Silicon-based sensors offer several advantages:

- Greater sensitivity.
- Improved thermal stability.
- Smaller size, allowing dense sensor arrays.
- Better long-term reliability.

This evolution has led silicon piezoresistive sensors to become the industry standard for combined static and dynamic pressure measurements.

The Sculptured Diaphragm Design

A major advancement in piezoresistive sensor design is the sculptured diaphragm, developed by Endevco®, a product line acquired by PCB Piezotronics in 2019 [17]. As shown in **Figures 21 and 22**, the sculptured diaphragm features carefully engineered recesses and thickness variations that concentrate stress precisely at the sensing regions.

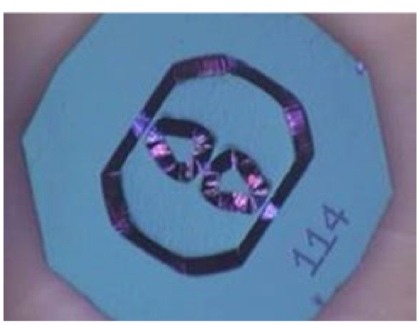


Figure 21: Scanning electron microscope (SEM) image of a sculptured diaphragm used in Endevco piezoresistive pressure sensors.

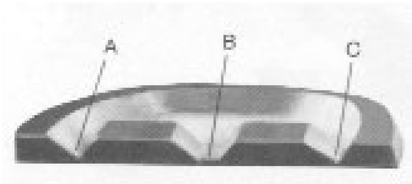


Figure 22: Cross-sectional photomicrograph of the sculptured diaphragm, highlighting stress concentration zones designed to maximize sensitivity.

These diaphragms are made from single-crystal silicon, an anisotropic material whose physical and chemical properties vary depending on the crystalline direction. This directional behavior offers several design advantages, including:

- **Higher Sensitivity**: Concentrating stress in key areas increases sensitivity by nearly a factor of two compared to flat diaphragms. Suitable for ranges as low as 1 PSI and as high as 20,000 PSI.
- **Improved Linearity**: Stress distribution within the sensing elements is optimized for better linearity across the full pressure range.
- **Enhanced Mechanical Efficiency**: By directing strain exactly where needed, the diaphragm reduces measurement errors caused by unwanted mechanical effects.
- **Material Stability**: Single-crystal silicon ensures consistent, predictable performance under repeated thermal and mechanical cycling.
- Compact, rugged designs suitable for harsh environments and space constraints.

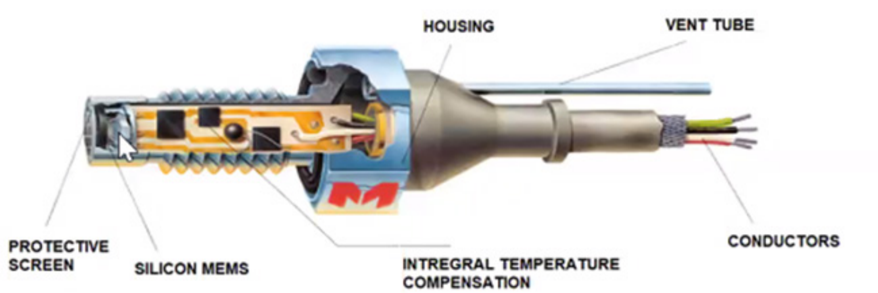


Figure 23: Typical piezoresistive (PR) pressure sensor construction.

Two popular Endevco sensor families for aerodynamic pressure measurements include the **8507** series (gage) and the **8515** series (absolute). **Figures 24 and 25** show the compact form factor of Models 8507C and 8515C, respectively.

A key performance benefit of sculpted silicon diaphragms is their improved linearity. For instance, the Endevco Model 8515C features a nonlinearity of 0.2% and can be used up to three times its measurement range and remain within 1% linearity.

Micromachined silicon also supports significant sensor miniaturization. Compared to stainless steel diaphragm sensors, these designs offer a much smaller footprint without sacrificing performance. This is particularly valuable in tightly packed wind tunnel models or embedded flight test configurations.

Figure 24: Endevco Model 8507C: A flush-mount pressure sensor measuring just 2.5 mm in diameter.

Figure 25: Endevco Model 8515C is used for surface-mount applications and measures 6.33 mm in diameter and 0.76 mm thick.

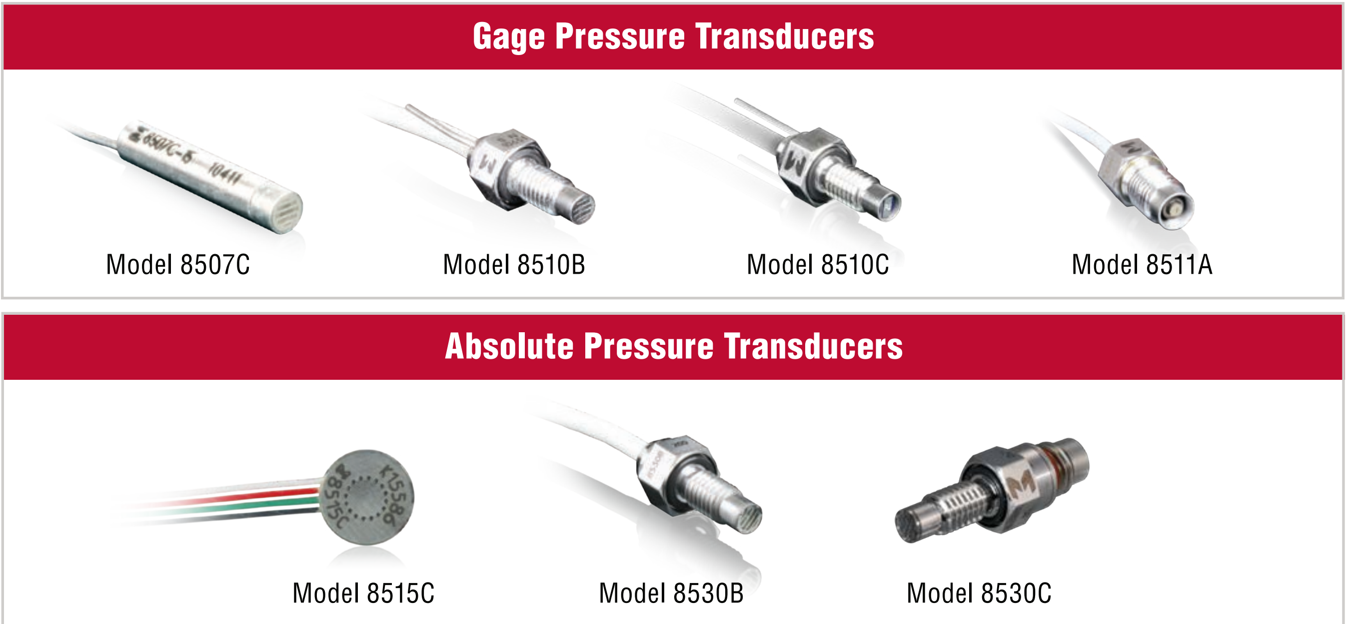


Figure 26: Examples of piezoresistive pressure sensors with varying specifications for a broad range of aerodynamic and aeroacoustic applications.

4.6 HIGH-TEMPERATURE SENSORS

High-temperature pressure and acoustic sensors are essential for evaluating propulsion systems such as gas turbines, rocket engines, afterburners, and other combustion environments. These tests involve extreme heat, high mechanical stress, and rapid pressure fluctuations.

A key challenge in these environments is diagnosing combustion-acoustic instability, a dangerous feedback loop in which unsteady heat release interacts with the acoustic modes of the chambers [18]. This interaction can amplify pressure oscillations, potentially leading to structural fatigue, performance degradation, or catastrophic failure. Pressure fluctuations may arise from multiple sources, including vortex shedding, fuel injection instability, or acoustic coupling with chamber geometry. In some systems, active control strategies, such as modulated fuel flow, are also employed to reduce instability.

While computational models have improved, physical testing remains essential for capturing the complex interactions between heat release and pressure oscillations under real-world conditions. The success of such tests depends on measurement instruments that can survive harsh conditions while delivering accurate, reliable data. Therefore, engineers require sensors that can:

- Withstand extreme temperatures, static pressures, and mechanical vibrations.
- Measure pressure oscillations from tens of hertz to several kilohertz.
- Operate reliably in long-duration or high-load tests without signal degradation.

High-Temperature Dynamic Pressure Sensors

Dynamic pressure sensors specifically designed for high-temperature applications are an essential tool for combustion instability testing.

There are two main categories of sensors used for this purpose. The first category is **quartz-based piezoelectric pressure sensors**, which are capable of continuous operation at temperatures up to 500 °F (260 °C). These sensors are often chosen for moderate-temperature environments where their dynamic range and sensitivity are sufficient. When paired with water-cooled adaptors, quartz-based sensors can be deployed in higher-temperature applications, extending their usable temperature range.

The second category consists of **UHT-12™ crystal-based pressure sensors**, which are purpose-built for extreme thermal conditions. These sensors can continuously operate at temperatures up to 1400 °F (760 °C), making them ideal for the harshest environments, such as combustors, afterburners, and other high-temperature propulsion components.

Both sensor types are engineered to maintain high accuracy under challenging conditions. Typical design features include:

- Welded hardline cables for mechanical and signal integrity.
- Hermetically sealed housings for long-term durability.
- Optional water-cooling systems for additional thermal management.

UHT-12™ models are specifically optimized to minimize signal drift and ensure reliable data throughout prolonged tests. Example models (shown in **Figure 27**) include:

PCB Model 176A31: Differential charge output, UHT-12™ crystal technology, rated for continuous use up to 1400 °F (760 °C) without cooling.

PCB Model 176A33: Single-ended version of the 176A31, also rated for continuous use up to 1400 °F (760 °C) without cooling.

Figure 27: PCB 176 Series high-temperature pressure sensor with UHT-12™ crystal technology.

High-Temperature Measurement Microphones

In addition to pressure sensors, high-temperature microphones play a critical role in combustion system testing, particularly for capturing acoustic signatures, resonances, and unsteady pressure fluctuations. These measurements help characterize combustion noise and support the identification of thermoacoustic instabilities.

The **Endevco Model 2510** (see **Figure 28**) is a piezoelectric microphone designed specifically for these extreme environments. It operates continuously from –67 °F to 500 °F (–55 °C to 260 °C) and can measure sound pressure levels from 100 to 180 dB, with sensitivity across both low- and high-frequency acoustic components.

To maintain performance under high thermal and mechanical stress, the sensor features a thick ceramic diaphragm and thermal insulation between the transducer and mounting surface. These design elements reduce heat transfer and improve stability in elevated temperatures. The sensor body is hermetically sealed to prevent damage from moisture, combustion byproducts, and other environmental contaminants.

Model 2510 also incorporates vibration compensation within the sensing element, helping to isolate true acoustic signals from mechanical noise. It requires an external charge amplifier for operation, allowing flexible signal conditioning while preserving dynamic range and fidelity.

Figure 28: Endevco Model 2510 high-temperature piezoelectric microphone designed for combustion noise testing.

Common Applications

- Combustion noise testing in gas turbines and jet engines.
- Acoustic mode identification in combustors and exhaust ducts.
- Research and development of thermoacoustic instability suppression techniques.
- Noise measurement during rocket launch.

KEY INSIGHT

High-temperature pressure and acoustic sensors are essential for capturing accurate data in extreme environments. Their durability under heat, pressure, and vibration makes them vital for combustion instability studies and advanced propulsion and energy research.

5. WIND TUNNELS

Most aerodynamic and aeroacoustic testing is performed in wind tunnels. Wind tunnels are specialized facilities that generate controlled airflow with known conditions such as velocity, temperature, and turbulence. This allows engineers to study aerodynamic and acoustic behavior under well-defined and repeatable circumstances. Boundary layers in a wind tunnel (i.e., the viscous regions that develop near the walls) can also be precisely controlled with careful design and flow conditioning.

Unlike real-world testing, where the object moves through the air, in a wind tunnel the test object remains stationary while the air moves around it. This setup allows engineers to maintain consistent conditions regardless of external weather.

Compared to real operating conditions, tunnel-generated airflow is typically smoother, with lower turbulence, fewer side gusts, and reduced environmental noise. While this controlled environment is highly beneficial for many studies, it may not fully replicate complex, coupled behaviors or random effects that can arise in real-world scenarios.

Due to physical size limitations, models tested in wind tunnels are often scaled-down versions of full-size objects, particularly for large systems like aircraft. As a result, some fine geometric details may be simplified.

Common Wind Tunnel Measurements and Tests

Wind tunnels support a wide range of measurement types. These include direct measurements of forces and moments acting on the test object, as well as pressure and force-based methods used to evaluate overall aerodynamic performance. Additionally, wind tunnels are frequently used for diagnostic purposes through pressure and velocity measurements that help characterize the flow field around the object.

Common test applications include:

- Drag and lift measurements for aircraft, helicopters, missiles, and race cars.
- Force and moment analysis of airfoils and wings.
- Static and dynamic stability tests of aircraft and missiles.
- Surface pressure distribution mapping.
- Propeller and rotor performance (torque, thrust, power, efficiency).
- Engine performance evaluations for air-breathing propulsion systems.
- Wind-induced force and pressure studies on buildings, towers, bridges, and vehicles.
- Heat transfer characterization in engines and aircraft.

Wind Tunnel Configurations

Wind tunnels are categorized by their airflow circulation systems:

- **Open-loop tunnels (Eiffel type)**: Air is drawn from the surrounding environment, passed through the test section, and then expelled back into the environment.
- **Closed-loop tunnels (Göttingen type)**: Air is recirculated through a closed loop, improving energy efficiency and allowing better control of temperature and humidity (see **Figure 29**).

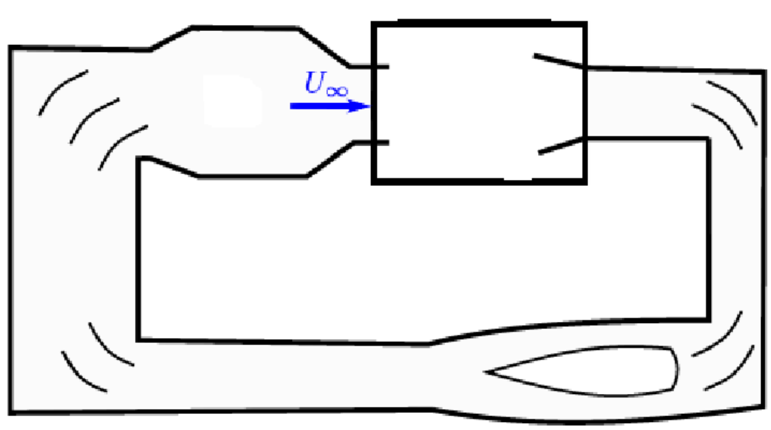


Figure 29: Top-view schematic of a closed-loop wind tunnel [2].

The test section within the wind tunnel can also vary in design:

- **Fully guided (closed) test sections**: Airflow is enclosed on all sides by solid walls. This setup prevents shear layers from developing but allows boundary layers to form along the walls. Fully guided test sections are typical in smaller-scale aeronautical tunnels and are standard for transonic and supersonic tunnels.
- **Partially guided (plenum) test sections**: Flow is guided only along certain surfaces—typically the floor—while the other boundaries are open to a plenum. This three-quarter-open design (shown in **Figure 30**) is common for tests involving buildings, road vehicles, and trains.
- **Fully open test sections**: These allow the flow to exhaust freely into the surrounding plenum without guiding walls. Though historically common, this design is now rarely used due to its low energy efficiency.

In general, the test section configuration has little effect on the types of instrumentation used but can influence flow characteristics, particularly for tests involving optical methods such as particle tracking or seeding.

Figure 30: Van tested in a partially guided (plenum) test section of the GIE-S2A semi-acoustic automotive wind tunnel [2].

Wind Tunnel Orientation and Flow Speed

Wind tunnels can be configured either horizontally or vertically. The choice of orientation generally has little effect on test outcomes, except in cases where buoyancy forces are under investigation.

The achievable flow speed is a critical design factor. Higher velocities require more powerful systems and can impose additional challenges such as:

- Air temperature drops due to expansion at high speeds, which can lead to icing or condensation.
- Restricted test durations in high-speed facilities, especially those relying on pressurized reservoirs for supersonic and hypersonic testing.

Seeding for Flow Visualization

Some wind tunnel tests require **seeding**—the introduction of small particles into the airflow to enable optical flow visualization techniques. These particles must be light enough to follow the airflow accurately, with low inertia to prevent settling. An example of the seeding method is shown in **Figure 1**.

Common seeding materials include olive oil droplets and artificial smoke particles, both of which are lightweight enough to follow the airflow's motion faithfully. These substances are selected specifically for their ability to remain suspended in the flow, allowing them to act as effective visual tracers. Seeding enables techniques such as particle image velocimetry (PIV) and flow visualization photography, where the movement of these particles reveals detailed information about flow patterns and behavior.

Blockage Effects and Corrections

Although properly designed wind tunnels minimize interference with measurements, corrections are sometimes needed to account for the test object's effect on airflow—particularly for objects occupying a significant portion of the test section's cross-sectional area.

This phenomenon, known as **aerodynamic blockage**, occurs when the model alters the flow field, leading to increased local velocities and changes in pressure distribution. If uncorrected, this can result in overestimated aerodynamic forces such as drag.

The **blockage ratio**—the ratio of the model's frontal area to the test section's cross-sectional area—quantifies this effect. A common correction method is **Cooper's correction**, which adjusts the measured drag coefficient based on the blockage ratio and model geometry to better approximate results from open-air (unconfined) conditions.

5.1 MEASUREMENT CONSIDERATIONS BY FLOW REGIME

Mach Number Classification

Wind tunnels are typically classified by the Mach number (Ma), which is the ratio of flow velocity to the speed of sound in the test medium (usually air). This classification corresponds to distinct aerodynamic flow regimes:

- **Subsonic tunnels**: Ma < 0.8.
- **Transonic tunnels**: 0.8 < Ma < 1.2 (This regime is marked by the coexistence of subsonic and supersonic regions, with shock waves occurring at their interfaces).
- **Supersonic tunnels**: 1.2 < Ma < 5.0.
- **Hypersonic tunnels**: Ma > 5.0 (This regime involves extreme compressibility, shock waves, and aerodynamic heating).

Airflow below Ma ~ 0.3 is generally considered incompressible, as density variations are negligible. Many low-speed wind tunnels operate in this regime for automotive, rail, and civil aerodynamics, where compressibility effects are minimal.

KEY INSIGHT

Wind tunnel classifications directly influence the types of tests that can be performed and the selection of measurement systems, making them fundamental to aerodynamic and aeroacoustic research.

As the Mach number increases, compressibility effects become more significant. This rise in windspeed also causes changes in static pressures and thermal conditions within the test section, which can affect both sensor selection and measurement accuracy.

The following sections detail how different Mach regimes—subsonic through hypersonic—affect wind tunnel design, operation, and measurement.

Subsonic Wind Tunnels (Ma < 0.8)

Subsonic wind tunnels, defined as facilities operating at Mach numbers up to 0.8, are widely used in aerodynamic testing for applications such as vehicle design, aircraft development, and investigations of flow behavior. These tunnels provide essential data on aerodynamic forces—including drag, lift, and moments—which enables engineers to optimize designs prior to real-world deployment.

A subsonic wind tunnel generates a controlled airstream within a closed test section at flow velocities ranging from 0 to 0.8 Ma. Its primary components include a fan or compressor to drive the airflow, a nozzle section to accelerate the flow, a test section where the model is mounted, and a diffuser to recover pressure after the test section.

The airflow in the tunnel is often thermally conditioned to minimize environmental variability and ensure repeatable results. Flow acceleration through the nozzle follows **Bernoulli's principle** [4], where velocity increases as pressure decreases. Airspeed is typically controlled through variable fan speed or by adjusting the geometry of the nozzle section or test section.

Within the test section, models are subjected to the airstream for measurement of surface pressures and aerodynamic forces such as lift, drag, and moments. Flow visualization techniques, such as smoke lines, tufts, or particle image velocimetry (PIV), are employed to analyze flow structures.

Techniques for Laminar Flow Generation

Subsonic wind tunnels are often designed to produce laminar (smooth and streamlined) flow conditions with minimal turbulence or vorticity. Several techniques are used to promote laminar flow:

- Honeycomb grids at the tunnel inlet break up large-scale turbulence into small, short-lived vortices that dissipate quickly.
- Flow straighteners align the flow and minimize irregularities before the test section; mesh filters can also remove small particles and disturbances.
- Porous materials absorb residual flow instabilities.
- Smooth test section walls help prevent turbulence at the boundary layer.
- Active flow control devices, such as suction or blowing systems, may be used to stabilize the boundary layer and control its thickness.

Acoustic Testing in Subsonic Wind Tunnels

Some subsonic wind tunnels are specifically designed for acoustic testing. These facilities use anechoic or semi-anechoic test sections lined with sound-absorbing materials such as foam or porous panels on the walls and ceilings. This design minimizes sound reflections within the tunnel.

Anechoic designs are critical for aeroacoustic testing, where the goal is to measure noise generated by airflow or aerodynamic forces. The controlled acoustic environment allows for accurate sound measurements, free from interference by ambient or reflected noise, ensuring reliable results for studies focused on aerodynamic noise.

Flow-Induced Noise Reduction: Techniques for Microphones in Subsonic Wind Tunnels

Wind tunnel noise measurement is a common practice in both the aerospace and automotive industries. In low-speed tunnels, the sound pressure levels measured by microphones are significantly affected by the airflow passing across the microphone diaphragm [22]. In such conditions, the dynamic pressure field includes both the acoustic pressure and the pressure induced by the airflow.

To isolate the acoustic component of the measurement, three main types of microphone accessories are used: grid caps, windscreens, and nose cones. For application examples and detailed recommendations, refer to section 8.1 of this handbook.

Transonic Wind Tunnels (Ma 0.8 to 1.2)

Transonic wind tunnels are designed to replicate flow conditions at Mach numbers between 0.8 and 1.2. This flow regime is unique because both subsonic and supersonic flow features coexist around the test object, resulting in complex aerodynamic phenomena such as shock wave formation, boundary layer separation, and unsteady pressure fluctuations.

In contrast, subsonic wind tunnels do not exhibit shock waves, and the flow is generally more stable and easier to maintain as laminar, although boundary layer separation and unsteady effects can still occur. In the transonic regime, compressibility effects dominate and are the primary concern for testing.

Transonic wind tunnels simulate flow scenarios where localized shock waves and flow separation occur around parts of the test object, even though the overall flow may remain subsonic. These conditions arise as the free-stream velocity approaches the speed of sound. Transonic flows are inherently unstable, and managing shock wave formation without inducing transitions back into fully subsonic flow is a significant challenge. Shock waves can lead to rapid changes in pressure, temperature, and flow velocity within the test section.

To regulate airflow near Mach 1, transonic wind tunnels typically incorporate variable-geometry nozzles that allow precise control over the airflow speed. The test section often includes perforated or slotted walls to reduce shock wave reflection and better approximate unbounded flow conditions. These tunnels also require high-pressure air supply systems or vacuum chambers to maintain proper flow conditions at higher speeds.

Additional flow conditioning techniques are used to ensure flow quality, including honeycomb structures and mesh screens to minimize turbulence and improve flow uniformity prior to the test section.

For flow visualization, transonic wind tunnels commonly employ **Schlieren imaging** (see **Figure 35**) to observe shock wave formation and dynamic pressure changes. High-frequency pressure and force sensors are essential for capturing the rapid fluctuations inherent in transonic flow conditions.

Supersonic Wind Tunnels (Ma > 1.2)

Supersonic wind tunnels operate at Mach numbers above 1.2 and are also governed by compressible flow theory. However, their design and operational characteristics differ significantly from those of subsonic and transonic tunnels.

Supersonic flow is generated using a convergent-divergent (de Laval) nozzle. In the converging section, the air is compressed until it reaches Mach 1 at the throat (sonic blockage). Beyond that throat, the divergent section accelerates the flow to supersonic speeds. The maximum Mach number achieved in the test section depends on the nozzle's geometry and the ratio of total (stagnation) pressure to static pressure.

Supersonic wind tunnels require significant energy input, typically achieved by discharging a high-pressure storage tank upstream of the test section. Some designs also incorporate vacuum chambers downstream to further increase the pressure gradient, enabling higher flow speeds. The actual flow velocity in the test section is determined by the pressure differential between these upstream and downstream systems.

Because of the high energy demands, supersonic wind tunnel tests—especially those conducted in blowdown-type tunnels—are usually of short duration. In order to maintain flow quality:

- Flow conditioning screens are installed at the tunnel inlet.
- Precise alignment of the test section with the nozzle is required to maintain uniform supersonic flow.
- Solid-walled test sections are typical, but some tunnels use contoured or shaped walls to accommodate expected shock and expansion wave structures.

Due to the intense heating effects caused by compression and aerodynamic friction, many supersonic wind tunnels require thermal conditioning systems or the use of low-temperature air to protect the test equipment and instrumentation during operation.

Hypersonic Wind Tunnels (Ma > 5.0)

Hypersonic wind tunnels are designed to simulate airflow conditions at Mach 5 and above. At these extreme speeds, real-gas effects—such as the dissociation and ionization of air molecules—become significant. As a result, compressibility and heat transfer dominate the flow behavior, making them primary concerns in hypersonic testing.

Hypersonic wind tunnel testing is primarily conducted for re-entry vehicles, space mission hardware, and high-speed aerospace systems.

Types of Hypersonic Wind Tunnels

Hypersonic wind tunnels fall into two main categories based on how airflow is generated:

- **Continuous-flow tunnels** provide a sustained stream of hypersonic airflow, typically powered by high-energy heating and compression systems. Their extreme energy requirements make them rare and costly to operate.
- **Blowdown tunnels**, by contrast, use high-pressure reservoirs to release preheated air at very high velocities. Although test durations are shorter, these facilities are easier to operate and are more common in research settings.

In addition to these two categories, some specialized facilities use shock tubes or pulse tunnels, which create very brief hypersonic flows by rapidly releasing high-pressure gas into a low-pressure test section. These systems produce short-duration, high-speed flows suitable for specific types of experiments.

Key Operating Characteristics

In all types of hypersonic tunnels, airflow is accelerated through a highly precise convergent-divergent nozzle. Much higher pressure and temperature conditions are required compared to subsonic or supersonic tunnels, and due to extreme cooling during rapid expansion in the nozzle, air is often preheated before entering the tunnel to prevent condensation. Despite their specialized nature, the overall design and operating principles of hypersonic wind tunnels are broadly similar to those of supersonic tunnels, particularly in terms of flow generation and nozzle design.

The following sections will summarize key research findings on sensors used for measurements in hypersonic wind tunnel testing.

Acoustic Pressure Sensors for Hypersonic Wind Tunnels [19] [20] [21]

A key aerodynamic phenomenon in hypersonic flight is **boundary layer transition:** the shift from laminar (smooth) flow to turbulent flow along the surface of a vehicle. This transition significantly increases aerodynamic heating and drag. Accurate measurement of boundary layer transition is essential for validating modern modeling and prediction methods used in the design of hypersonic vehicles.

However, this transition remains poorly understood, and even small pressure fluctuations in hypersonic wind tunnels can complicate analysis. Minor acoustic pressure oscillations in the boundary layer contribute to increased skin friction and heating, sometimes doubling the heating levels. These oscillations can also alter boundary layer behavior near control surfaces, affecting flow separation and vehicle stability.

Boundary layer transition is a major consideration for structural and thermal protection system design. A better understanding of this phenomenon enables engineers to design lighter and more fuel-efficient vehicles with improved payload capacity and structural integrity.

Sensor Challenges

Second-mode frequencies observed in hypersonic wind tunnel models can exceed several hundred kilohertz, requiring pressure sensors with:

- Resonant frequencies above 1 MHz.
- Extremely high sensitivity to detect minute pressure changes—often just a few hundred Pascals—in low-pressure test environments.

Traditional absolute pressure sensors, including strain gage and piezoresistive types, have historically been limited in frequency response because of protective screens placed over their sensing elements. These screens, intended to prevent debris damage, typically limit the bandwidth to around 25 kHz.

Hot-wire anemometry has also been used for decades in boundary layer studies. However, hot-wire sensors are too fragile for hypersonic conditions, require frequent compensation for air density and humidity changes, and lack the fast response needed for second-mode frequency analysis.

Advances with Modern Acoustic Pressure Microsensors

Modern acoustic pressure microsensors, such as the **PCB Model 132B38** (see **Figure 31**), have significantly advanced hypersonic boundary layer research. This sensor features:

- Resonant frequency above 1 MHz.
- Acoustic pressure resolution of 7 Pascals.
- Compact 3 mm diameter and 7 mm length, enabling easy installation on small hypersonic test models.

The Model 132B38 uses a miniature piezoelectric crystal (less than 1 mm in diameter) as its sensing element. Without requiring a diaphragm or screen in front, the sensor:

- Achieves exceptional rise times due to the absence of mass-damping elements.
- Has an integrated ICP® amplifier, converting the signal to a low-impedance output.
- Incorporates a decoupling capacitor in the power supply to remove the DC bias voltage from the output.
- Internally sets a discharge time constant defining the high-pass response (high-pass frequency 11 kHz).

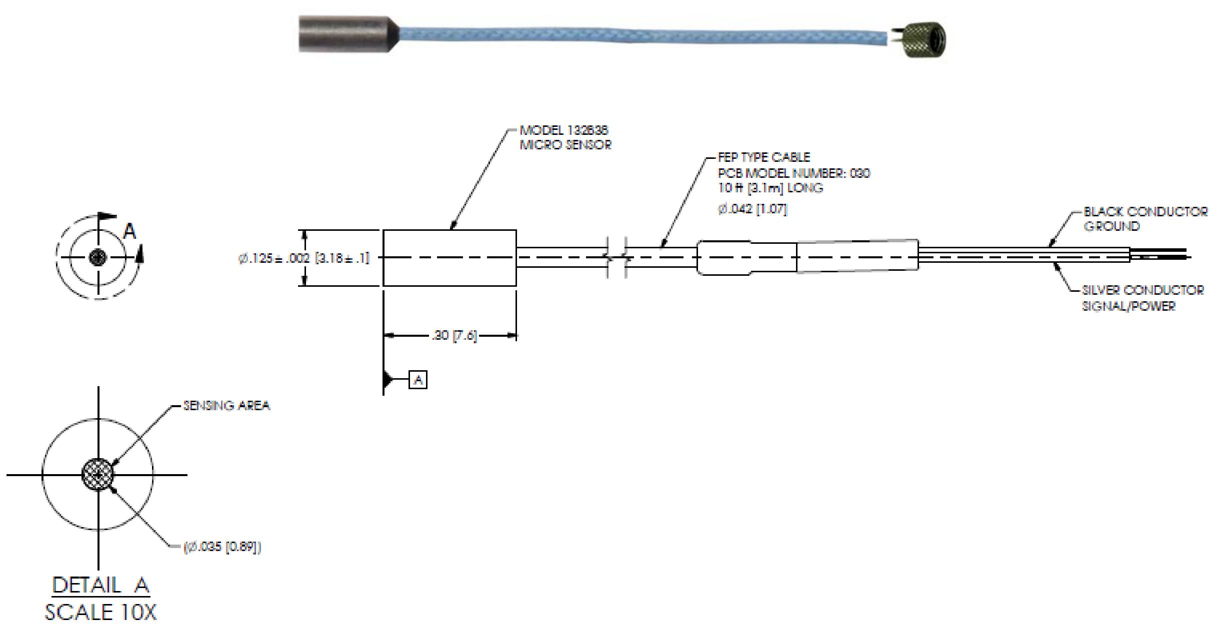


Figure 31: PCB Model 132B38 acoustic pressure microsensor—photo and technical drawing.

The PCB Model 132B38 microsensor can be flush-mounted on the surface of the test model, achieving an incident rise time of less than 3 microseconds; alternatively, it can be mounted in a pitot-style configuration to monitor overall tunnel noise, with a rise time under 0.5 microseconds.

The fast response is achieved by placing the rigid ceramic sensing element close to the shock wave, allowing it to directly bear the surface load during shock propagation without being limited by diaphragms or screens.

Impact on Hypersonic Research

Due to its unique combination of speed, sensitivity, and compact size, the PCB Model 132B38 enables improved analysis of second-mode shock wave frequencies and provides valuable insights into boundary layer transition mechanisms in hypersonic wind tunnels.

Additional methodology for quantifying freeform disturbances that complicate boundary layer transition analysis is presented in section 8.2 of this handbook.

6. RECOMMENDED SENSOR MODELS FOR WIND TUNNEL TESTING

PCB Piezotronics offers a broad range of sensors specifically designed for aerodynamic and aeroacoustic testing in wind tunnels. These include static and dynamic pressure sensors, piezoelectric force sensors, and prepolarized microphones, all of which enable engineers to accurately characterize the behavior of aircraft, rockets, and other test models within the wind tunnel environment.

Sensor selection depends on the specific objectives of the test, as well as the flow regime of the wind tunnel. **Table 2** summarizes recommended sensor models from PCB Piezotronics and Endevco for use in wind tunnels operating across different Mach number ranges, from subsonic to hypersonic speeds.

SENSORS FOR WIND TUNNEL TESTING					
PCB / Endevco Model	**Model #**	**Subsonic**	**Transonic**	**Supersonic**	**Hypersonic**
Prepolarized Microphone	377A14	x			
Microphone System	378A14	x			
Surface Microphone (Preamplifier incorporated)	130B40	x	x		
Acoustic Pressure Sensor	103B01	x	x		
High Resolution ICP® Pressure Sensor	112A22		x	x	
Mini ICP® Pressure Sensor	112M362		x	x	
Micro ICP® Pressure Sensor	132B38				x
PR Pressure Sensors (Gage)	8507	x	x	x	x
PR Pressure Sensors (Absolute)	8515	x	x	x	x
Piezoelectric Force Sensor	260A01	x	x	x	x

Table 2: A summary of sensor models produced by PCB Piezotronics and Endevco for various wind tunnel applications.

Figure 32: Aircraft model mounted in a wind tunnel for aerodynamic and aeroacoustic testing.

Sensor Types and Applications

Wind tunnel testing frequently involves a combination of sensor types, including:

- **Acoustic pressure sensors**, such as high-resolution and miniature ICP® pressure sensors, which are used to capture dynamic pressure fluctuations and noise.
- **Piezoresistive pressure sensors**, which provide accurate measurements of static and fluctuating pressures, particularly in regions with high-pressure gradients or unsteady flow conditions.
- **Prepolarized microphones**, including surface-mounted and pressure-field designs, which are used to measure sound pressure levels in aeroacoustic studies.
- **Piezoelectric force sensors**, which are commonly integrated into force balances to measure aerodynamic forces such as lift, drag, and pitching moments.

6.1 MICROPHONES FOR WIND TUNNEL TESTING AND ANALYSIS

Side-Vented Pressure Field Microphone

PCB Model 377A14 is a side-vented pressure field microphone designed for flush-mounted applications, such as cavities, tubes, panels, or wind tunnel walls, where internal and external pressures may vary significantly (see **Figure 33**). It is particularly well suited for high-level, high-frequency measurements in wind tunnels.

For optimal performance, the microphone should be used with the **PCB Model 426A05** ventless preamplifier, or as an integrated microphone and preamplifier system **Model 378A14**, which pairs the microphone and preamplifier together.

Model 377A14 is a prepolarized design. When combined with a preamplifier, it operates on ICP® sensor power or any IEPE constant current supply. This modern design is especially advantageous for portable measurements or use in humid environments. Additional benefits include compatibility with standard coaxial cables and interchangeability with other ICP® sensors (such as accelerometers, pressure sensors, and force sensors), which helps to reduce setup time and minimize channel cost.

Main specifications include:

- 1/4” pressure microphone.
- Open circuit sensitivity: 1.0 mV/Pa.
- Dynamic range: >174 dB.
- Noise: <35 dB.
- Frequency range: 4 Hz to 70,000 Hz.
- IEC 60651 Type 1 compliant.
- IEC 61672 Class 1 compliant for premium sound level meter use.
- Calibration traceable through PTB; ISO 9001 and ISO 17025 certified; A2LA accredited.

Figure 33: PCB Model 377A14 prepolarized microphone.

Low-Profile Prepolarized Surface Microphone

PCB Model 130B40 is a compact, cost-effective ICP® microphone designed for measuring true surface pressure (see **Figure 34**). Its design is optimized for applications involving wind-induced noise. The microphone can be flush-mounted or adhesively mounted on flat or curved surfaces, and its low profile—only 1/8” (3 mm) in height—enables measurements in locations where traditional microphones cannot fit.

The design includes a built-in preamplifier and an integrated 1.5-meter (5-foot) cable with a 10-32 microdot coaxial connector. The microphone vent is located at the surface for easy atmospheric pressure equalization. Additionally, a water- and dust-resistant mesh grid cap makes it well suited for harsh environments such as tire wells and other exposed locations.

Main specifications include:

- ICP® prepolarized microphone and preamplifier combination.
- Dynamic range: 35 dB to 142 dB (150 dB before clipping).
- Operating temperature range: -40 °F to +176 °F (-40 °C to +80 °C).
- Compact 1/8” (3 mm) height for tight installations.
- Water- and dust-resistant mesh grid for durability in harsh environments.
- Supplied standard with TEDS IEEE P1451.4 capability.

Figure 34: PCB Model 130B40 prepolarized surface microphone.

6.2 PRESSURE SENSORS FOR WIND TUNNEL TESTING AND ANALYSIS

Pressure sensors are among the most widely used instruments in wind tunnel testing for aerodynamic and aeroacoustic analysis. This section focuses on technologies capable of capturing both static and dynamic pressures within the wind tunnel environment—specifically, piezoresistive and piezoelectric pressure sensors. Sensors designed for purely static pressure measurements, such as differential pressure sensors, are not covered here.

The following examples present pressure sensor models commonly applied in wind tunnel tests, along with their key technical specifications.

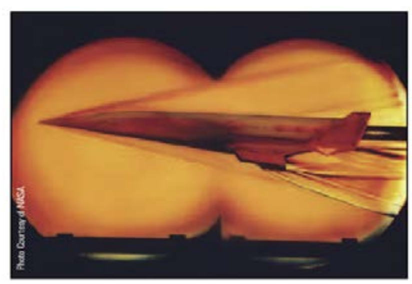


Figure 35: Supersonic wind tunnel test of a fighter-style aircraft model.

Flight-Tested ICP® Acoustic Pressure Sensors

PCB Series 103B ICP® Acoustic Pressure Sensors (see **Figure 36**) are designed to measure pulsating, transient, and turbulent acoustic phenomena on aircraft, rockets, and similar structures. These sensors are widely used in aerospace applications to measure dynamic and acoustic pressures.

The ICP® microelectronics provide low-impedance, high-voltage output and are robust against shock events, such as those encountered during stage separations.

Main specifications include:

- Measurement range: 3.00 psi (180.3 dB).
- Sensitivity: 1500 mV/psi (217.5 mV/kPa).
- Resolution: 0.00002 psi (77 dB).
- Low-frequency response (-5%): 5 Hz.
- Resonant frequency: ≥13 kHz.

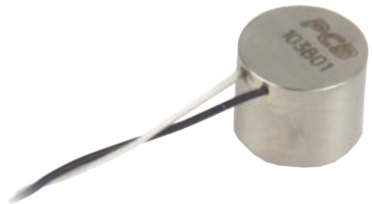


Figure 36: PCB Model 103B01 acoustic ICP® pressure sensor, designed for dynamic and acoustic pressure measurements on aircraft and rocket models.

Miniature High-Sensitivity ICP® Pressure Probe: PCB Model 112A22

PCB Model 112A22 (see **Figure 37**) is designed to measure small dynamic pressures—including turbulence, cavitation, pulsations, and high-intensity sound—particularly in harsh environments.

This sensor can detect pressure variations from 0.001 psi to 50 psi (111 to 205 dB in air) under static pressures ranging from full vacuum to 500 psi. Its internal acceleration compensation helps minimize sensitivity to vibration.

Main specifications include:

- Measurement range: 50 psi (345 kPa).
- Sensitivity: 100 mV/psi (14.5 mV/kPa).
- Resolution: 0.001 psi (0.007 kPa).
- Low-frequency response (-5%): 0.5 Hz.
- Resonant frequency: ≥250 kHz.

Figure 37: PCB Model 112A22 miniature high-sensitivity ICP® pressure probe, designed for small dynamic pressure measurements in harsh environments.

Acoustic Micro ICP® Pressure Sensor

PCB Model 132B38 (see **Figure 38** and **39**) is an acoustic micro-pressure sensor optimized for hypersonic wind tunnel testing. Its compact design—0.125-inch (3 mm) diameter and 0.3-inch (7 mm) length—makes it ideal for installation in small-scale models.

With a resonant frequency exceeding 1 MHz and pressure resolution of 7 Pa, this sensor can detect shock wave fronts with high precision. It is designed for high-speed applications such as boundary layer transition studies and shock wave detection. Its fast response time of 0.5 microseconds allows it to accurately track rapid pressure peaks, filtering out static tunnel pressures to isolate dynamic phenomena. Its short time constant filters out static wind tunnel pressure, allowing differentiation between consecutive pulses.

Figure 38: PCB Model 132B38 acoustic micro ICP® pressure sensor, optimized for hypersonic wind tunnel testing and small-scale models.

Main specifications include:

- Measurement range: 50 psi (345 kPa).
- Sensitivity: 140 mV/psi (20.3 mV/kPa).
- Resolution: 0.001 psi (0.007 kPa).
- Low-frequency response (-5%): 11 kHz.
- Resonant frequency: ≥1000 kHz.
- Compact form factor for embedded applications.
- Very high-frequency response and centered sensing element for improved accuracy.

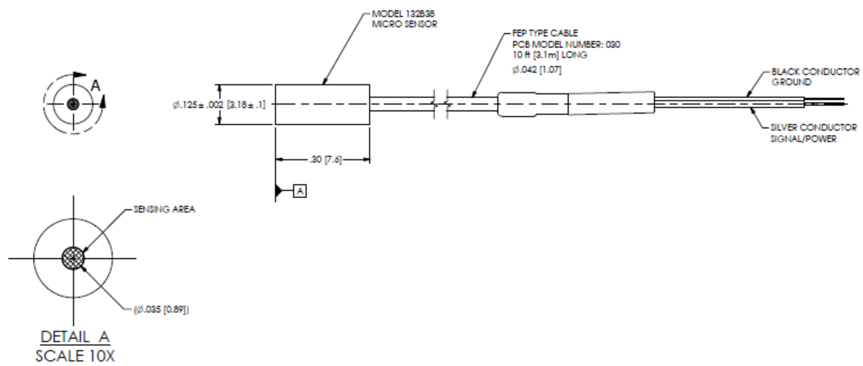


Figure 39: Technical drawing of PCB Model 132B38 pressure sensor.

Piezoresistive Pressure Sensors

In addition to quartz ICP® piezoelectric pressure sensors, PCB also offers piezoresistive models through the Endevco product line. These sensors are designed for a wide range of applications—from airflow measurements to high-intensity acoustic testing—and are characterized by their fast response times, high output signals, and excellent signal-to-noise ratios. They are capable of measuring both static and dynamic pressure.

Two specific models previously introduced—the Endevco 8507 and 8515—are highlighted again here due to their frequent use in wind tunnel testing for aerodynamic and aeroacoustic evaluation.

Endevco 8500 Series Overview

The Endevco 8500 Series features a silicon diaphragm design that delivers extremely high output signals, broad frequency response, and excellent linearity with virtually no hysteresis. These sensors are capable of measuring both static and dynamic pressure, making them versatile tools for a wide range of aerodynamic and aeroacoustic tests. Models are temperature compensated from 0 to 200 °F (-18 to 93 °C) and are available in a variety of ranges, including gage pressure options from 0–1 psig up to 0–20,000 psig and absolute pressure options from 0–15 psia up to 0–2000 psia.

Each sensor is supplied with a calibration certificate compliant with ISO/IEC 17025, ensuring traceable, reliable performance for critical test programs.

Endevco Model 8507C: Miniature High-Sensitivity Pressure Sensor with Broad Frequency Response

The Endevco Model 8507C is rugged, miniature piezoresistive pressure transducer with a broad frequency response. It features a compact 0.09-inch (2.3 mm) cylindrical housing and is available in pressure ranges from 1 to 15 psig, with full-scale outputs up to 300 mV.

Key features include:

- Active four-arm strain gage bridge diffused into a sculpted silicon diaphragm for maximum sensitivity and wide frequency response.
- Self-contained hybrid temperature compensation for stable performance over 0 °F to 200 °F (-18 °C to +93 °C).
- Excellent linearity (up to 3× full scale), high shock resistance, and stability during temperature transients.
- Flush-mountable on curved surfaces, with no need for threaded mounting.
- Designed for use in difficult-to-access installation locations.

Endevco 8515C: Rugged, Miniature High-Sensitivity Pressure Sensor

The Endevco Model 8515C is a rugged, miniature piezoresistive pressure transducer available in full-scale ranges of 15 and 50 psia. It has an extremely compact design, measuring just 0.03 inches thick by 0.25 inches in diameter (0.76 mm × 6.3 mm).

Key features include:

- Full-scale output of 200 mV with high overload capability (up to 3× full scale).
- High frequency response and low base strain sensitivity.
- Excellent thermal stability.
- Flush-mountable on flat or curved surfaces with minimal impact on airflow.
- Protective screen for shielding against particle impacts.
- Optional airflow-smoothing rubber fairing (PN 30042) for flight tests.

Design takeaways: Both the Model 8507C and Model 8515C are well suited for aerodynamic testing on scale models in wind tunnels, where compactness, high performance, and resilience to harsh conditions are critical.

6.3 FORCE SENSORS FOR WIND TUNNEL TESTING AND ANALYSIS

Accurate force measurement is essential for evaluating aerodynamic performance in wind tunnel testing. These measurements are used to determine lift, drag, side forces, and moments such as pitch, yaw, and roll—critical data for understanding how a model behaves across varying angles of attack.

Traditionally, these loads were measured using strain gage-based balances, which perform well for long-duration, steady force measurements. However, modern aerodynamic studies increasingly require dynamic data to capture rapidly changing or unsteady forces. Piezoelectric force sensors meet this need with their high stiffness, fast response, and ability to capture transient events such as aerodynamic impacts and oscillating loads.

Compared to conventional strain gage systems, piezoelectric force balances offer several advantages:

- Higher structural rigidity.
- Reduced cross-talk between individual force components.
- Higher natural frequencies, ideal for studying unsteady aerodynamic behavior, including aeroelasticity.
- Ability to measure very small force fluctuations independently of preload or steady flow loads.

Note: Piezoelectric systems are generally less suitable for long-duration steady force measurements, due to their time constant limitations under constant loading.

Triaxial ICP® Quartz Force Sensors

The **PCB Model 260B01** (see **Figure 40**) is a triaxial ICP® quartz force sensor commonly used for dynamic wind tunnel balance applications. Its rigid design withstands repetitive loading without fatigue while maintaining excellent repeatability and precision across repeated test cycles.

To ensure accuracy, mounting systems and their support structures are carefully shaped to minimize added drag and turbulence, reducing the risk of test interference.

- Sensitivity (z-axis): 2.5 mV/lb (0.56 mV/N).
- Sensitivity (x, y-axes): 10 mV/lb (2.2 mV/N).
- Compression range (z-axis): up to 1000 lb (4500 N).
- Compression range (x, y-axes): up to 500 lb (2200 N).
- Side-oriented 4-pin connector.
- Low-frequency response: 0.01 Hz.
- Resonant frequency: 90 kHz.

Figure 40: PCB Model 260B01 triaxial force sensor, designed for dynamic wind tunnel balance applications.

Advanced Force Balance Applications

Recent wind tunnel force balance designs now utilize arrays of triaxial piezoelectric load cells—also referred to as dynamic force sensors—to create highly stiff, sensitive, and accurate systems. These advanced designs offer:

- Up to 350% increase in frequency response compared to conventional strain gage balances.
- Comparable accuracy to strain gage-based systems.
- Up to 400% increase in sensitivity for detecting small forces.

Calibration results have demonstrated excellent linearity, both in the primary measurement axes and in the interaction terms. This allows any coupling effects between axes to be corrected using linear interaction models, ensuring high-quality force and moment measurements even in complex aerodynamic tests.

Wind Tunnel Sensor Selection: Key Takeaways

The sensors introduced in the previous section represent the most commonly used solutions for aerodynamic and aeroacoustic testing in both ground-based wind tunnels and in-flight conditions. While purely static pressure sensors are widely used in aerospace testing, they were intentionally excluded here to focus on versatile models that support both static and dynamic pressure measurements.

The Endevco piezoresistive pressure sensors—particularly the 8507 and 8515 models—stand out for their compact size and broad applicability across test environments. These sensors can be integrated into both scale and full-size structures and are well suited for capturing detailed pressure behavior in wind tunnels and in flight. The flush-mount 8515 model is especially valued in flight testing for its minimal impact on surrounding flow.

As shown earlier in **Table 2**, sensor suitability depends on wind tunnel flow regimes. In addition to pressure sensors, flush-mounted microphones such as the PCB Model 130B40 are often used for acoustic measurements. This microphone is compatible with both model-scale and full-size structures, and its use in flight testing is demonstrated in section 8.4 of this handbook.

7. TESTS IN OPERATING CONDITIONS

Unlike controlled wind tunnel tests, aerodynamic tests conducted under real-world operating conditions involve numerous interacting variables—some correlated, others independent—that are often difficult or impossible to control. These tests may yield results that don't fully reflect typical conditions, but they provide valuable insight into vehicle behavior under actual operational environments, including rare or extreme cases.

Such tests are essential for validating simulation and wind tunnel predictions under the complete spectrum of fluid dynamic effects present in real environments. However, these tests tend to have lower repeatability due to environmental variability, as well as logistical and cost constraints that limit sample sizes.

Typical variables affecting these tests include:

- Meteorological factors: Temperature, pressure, humidity, wind speed, wind direction.
- Surface effects: Road or ground roughness, vegetation, nearby structures.
- Operational factors: Speed, maneuvering, interactions with other vehicles or infrastructure.

7.1 AUTOMOTIVE TESTING

In the automotive industry, aerodynamic and aeroacoustic tests are routinely performed on proving grounds or dedicated test tracks. Engineers use these tests to evaluate aerodynamic forces such as drag, lift, and crosswind sensitivity, as well as aerodynamic noise under real driving conditions.

On-road tests are essential because they reveal performance differences not always captured by computational fluid dynamics (CFD) or wind tunnel tests. Increasingly, regulatory standards for emissions and electric vehicle range also require on-road verification.

Typical instrumentation includes:

- **Pressure Sensors**: Devices such as **Endevco 8515C** (non-destructive) or pressure taps to map surface pressure and infer forces like lift and drag. Often combined with flow velocity sensors.
- **Interior Microphones**: In-cabin microphones (e.g., **PCB Model 378B02**) assess noise levels inside the vehicle, helping locate tonal or broadband noise sources affecting passenger comfort.
- **Exterior Microphones**: Flush-mounted microphones like **PCB Model 130B40** capture external unsteady pressure fluctuations from flow around mirrors, A-pillars, or the windshield base.

Some setups also use microphone booms that sweep across exterior regions during tests to map noise spatially via beamforming techniques.

7.2 RAILWAY TESTING

Many of the same aerodynamic and acoustic testing methods are applied to high-speed trains. Railway testing is complicated by the range of operating environments, from open countryside to tunnels, viaducts, and urban corridors. These varying conditions cause aerodynamic challenges such as transient pressure waves, drag fluctuations, crosswind sensitivity, and aeroacoustic noise.

Typical instrumentation includes:

- **Pressure Sensors**: Flush-mounted sensors like **Endevco 8515C** along train noses, sides, and roofs to capture rapid pressure changes for structural and passenger comfort evaluations.
- **Flow Monitoring**: Surface-mounted pressure sensors assess boundary layer development, separation points, and turbulent structures.
- **Exterior Microphones**: Rugged PCB microphones (e.g., **Model 130A24**) for broadband and tonal noise assessment, including pass-by tests with ground-based arrays for noise localization.
- **Interior Microphones**: Cabin arrays for monitoring sound transmission paths and cabin noise levels.

7.3 AERODYNAMIC TESTING IN REAL FLIGHT CONDITIONS

Flight testing remains a cornerstone of aerodynamic validation for aircraft of all types—from conventional fixed-wing planes to helicopters and emerging electric vertical takeoff and landing (eVTOL) vehicles. Unlike wind tunnel testing, which is limited by wall effects and model scaling, flight tests provide data under actual atmospheric conditions. These tests account for all real-world phenomena, including turbulence, unsteady flows, and dynamic control surface activity.

Despite advances in computational methods, direct numerical simulations (DNS) of full aircraft flows remain computationally impractical, particularly for resolving turbulence across all scales. This makes flight testing essential for capturing the complete aerodynamic performance of an aircraft.

Flight tests are conducted across the full operational envelope, including low-speed takeoff and landing, high-altitude cruise, and high-speed maneuvering.

Typical instrumentation includes:

- **Surface Pressure Sensors**: Flush-mounted sensors for pressure mapping on wings, fuselage, or tail surfaces, supporting aerodynamic force/moment calculations.
- **Fast-Response Sensors**: For studying unsteady phenomena like buffet and shock motion during transonic phases.
- **Interior Microphones**: For assessing passenger comfort and internal noise paths.
- **Exterior Microphones**: For noise measurement on components like landing gear and flaps, and during ground-based flyover testing.

Helicopters and rotorcraft pose additional challenges due to strong aerodynamic interactions between the rotors and the airframe. Test instrumentation for these vehicles often includes pressure sensors near rotor blade leading edges to measure blade loading, strain gages to track blade deflection, and accelerometers to monitor vibratory loads from the rotor system. Microphones are also deployed both inside the cabin and on the aircraft exterior to capture structure-borne and aerodynamic noise.

Sensor selection for flight testing requires careful consideration. Sensors mounted inside the aircraft typically need high sensitivity and low noise levels to detect subtle pressure and acoustic effects. Exterior sensors, in contrast, must withstand extreme conditions, including temperature fluctuations, high-speed airflow, and structural vibrations.

All flight instrumentation must comply with stringent aerospace safety and certification requirements, especially for tests conducted on operational or certifying aircraft.

Pressure Distribution Measurements

Measuring pressure distribution during flight is essential for understanding how airflow interacts with an aircraft or structure. Surface pressure directly determines the aerodynamic forces and moments acting on a vehicle, making it one of the most critical measurements in flight testing.

By collecting pressure data across the surface of a flying vehicle, engineers can calculate forces such as lift, drag, and pitching or rolling moments through integration of local pressures. These measurements are also essential for validating CFD models, particularly in cases involving complex flow separations or unsteady aerodynamic phenomena.

Pressure distribution testing also plays a key role in aeroacoustic studies. While steady pressure measurements help identify regions of high aerodynamic loading—often associated with noise sources—unsteady pressure data provides deeper insights into the mechanisms of noise generation.

Steady and unsteady pressure measurements serve complementary roles. Steady measurements reveal the mean aerodynamic loading and highlight large-scale flow features such as shock waves, separation points, and reattachment zones. Unsteady measurements capture time-varying phenomena like vortex shedding, turbulent boundary layer instabilities, and unsteady shock motion, making them essential for analyzing acoustic sources.

Two different types of sensors are required for these measurements:

Piezoresistive pressure sensors are commonly used for steady pressure measurements because they can measure static pressures down to 0 Hz (DC).

Piezoelectric pressure sensors are preferred for unsteady measurements due to their rapid response and high sensitivity over broad frequency ranges.

Time-resolved pressure data is particularly valuable for locating acoustic sources and analyzing their spectral characteristics. Unsteady surface pressures also provide detailed information about turbulence, flow instabilities, and aeroacoustic emissions.

Key Considerations for Flight Testing

Successful pressure distribution measurements during flight require careful planning:

- **Sensor Selection**: Engineers must balance sensitivity, robustness, and frequency response to match the flow phenomena being studied.
- **Thermal Stability**: Sensors must be temperature-compensated to handle the wide thermal ranges encountered during flight.
- **Acceleration Compensation**: This reduces errors caused by aircraft motion and vibration.
- **Installation**: Sensors should be flush-mounted or otherwise installed to minimize flow disturbances, while still complying with flight safety standards.

In some flight campaigns, ground-based systems such as microphone arrays or acoustic cameras are also deployed to capture far-field noise during flybys. These systems must be rugged enough to withstand environmental exposure at remote test locations.

> **KEY INSIGHT**
>
> In-flight pressure measurements are critical for analyzing aerodynamic loads and noise sources. Steady and unsteady data provide complementary insights, and sensor selection is key to ensuring accuracy under flight conditions.

Surface-mounted microphones and pressure sensors remain among the most versatile tools for flight testing, allowing engineers to capture both steady and unsteady pressure data with minimal interference to the flow. An application can be found in section 8.4 of this handbook.

Flight Test: Pressure Distribution

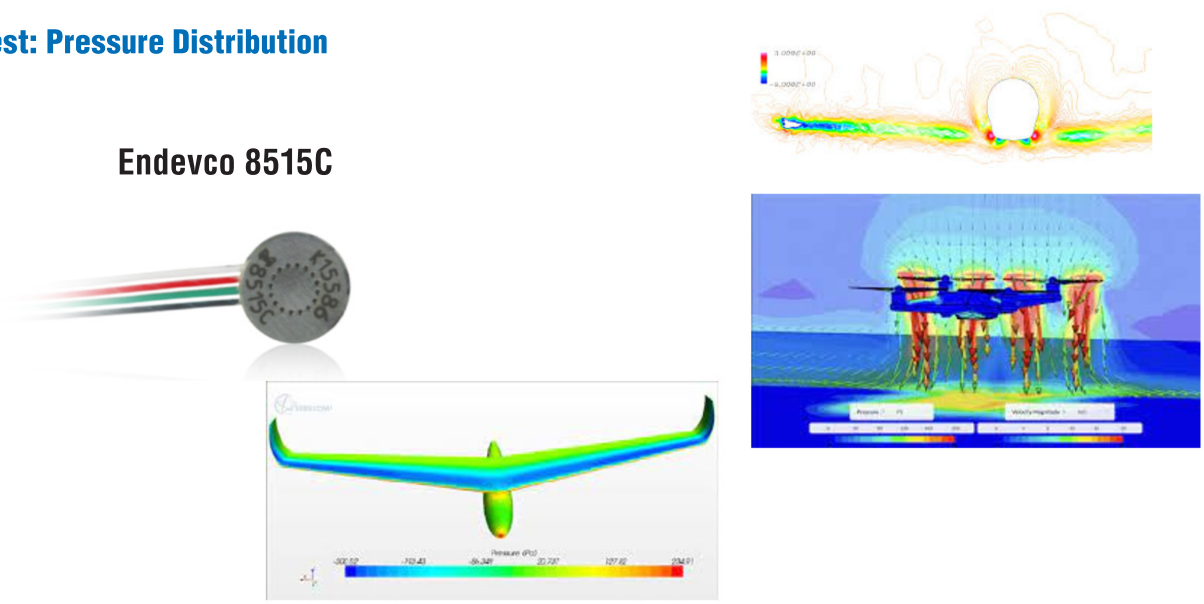


Figure 41: Example of flight pressure distribution testing using the Endevco 8515C piezoresistive pressure sensor.

8. EXPERIMENTAL STUDIES

8.1 A STUDY OF MICROPHONE CONFIGURATION IN SUBSONIC WIND TUNNELS [22]

An experimental study was conducted to evaluate microphone performance under various conditions and determine the most suitable configurations for different flow scenarios.

Test Setup

Figure 42 shows the test setup in a subsonic wind tunnel, including 10 microphones mounted on one wall, with a speaker mounted on the opposite wall to serve as a sound source.

Sensors Evaluated

In-flow microphones used:

- PCB Model 378B02 (3 units).
- PCB Model 378C01 (3 units).

Flush-mounted microphones used in turbulent flow:

- PCB Model 378A14 (side-vented, 2 units).
- PCB Model 130B40 (surface-mount, 2 units).

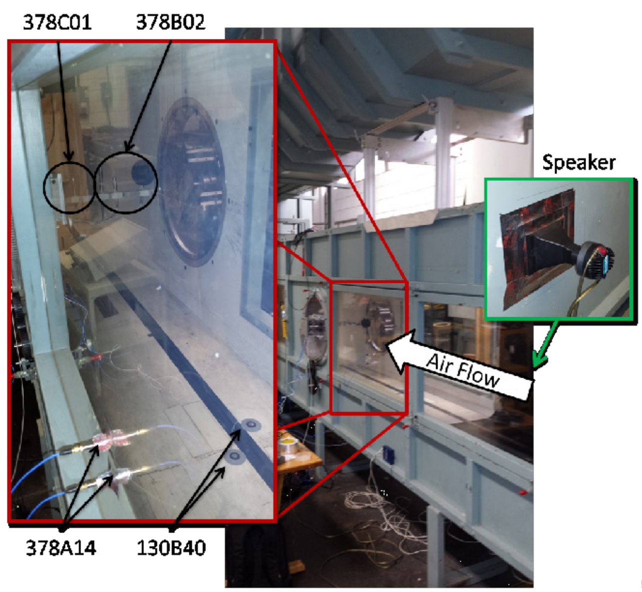


Figure 42: Test configuration in subsonic wind tunnel showing relative positions of microphones and speaker.

Procedure

The test procedure evaluated microphone performance under a range of airflow conditions. Airflow speeds were set to 0, 16, 40, and 88 km/h, allowing for comparison across both still air and progressively higher velocities. To study different flow characteristics, two types of flow were tested: laminar flow and turbulent flow.

Turbulent conditions were created by placing a tubular screen upstream of the microphones, which disrupted the airflow and introduced controlled turbulence. Additionally, to simulate real-world acoustic environments, a speaker was positioned upstream of the microphone to serve as an acoustic source. This setup enabled simultaneous evaluation of the microphones' response to both airflow and external sound stimuli.

Figure 43 illustrates the microphone mounting configurations, showing both head-on and parallel orientations relative to the airflow, with and without the use of turbulence generators. In the diagrams, the airflow direction is into the page.

Figure 43: Microphone mounting configurations: head-on (left) and parallel (right) orientations, with (lower) and without (upper) turbulence generators. Flow direction is into the page.

Test Conclusions and Recommendations

The study yielded several practical recommendations:

- For microphones located within the flow field, it is recommended to always use a windscreen or nose-cone accessory to minimize flow-induced noise.
- In head-on laminar flow, the nose cone is the most effective accessory for reducing noise.
- In turbulent flow and parallel laminar flow, the windscreen is generally preferable.
- Microphone diameter should be selected based on the required system noise floor and frequency response, as windscreens and nose cones were found to be equally effective regardless of microphone size.
- For flush-mounted microphones, side-vented pressure microphones typically exhibit a lower noise floor than low-profile surface microphones.
- When non-destructive mounting is required, low-profile surface microphones provide a practical option despite their higher noise floor, as they do not require drilling holes into the test structure.

Table 3 summarizes the recommended microphones and accessories for various flow and mounting conditions based on the PCB instrumentation tested in this study.

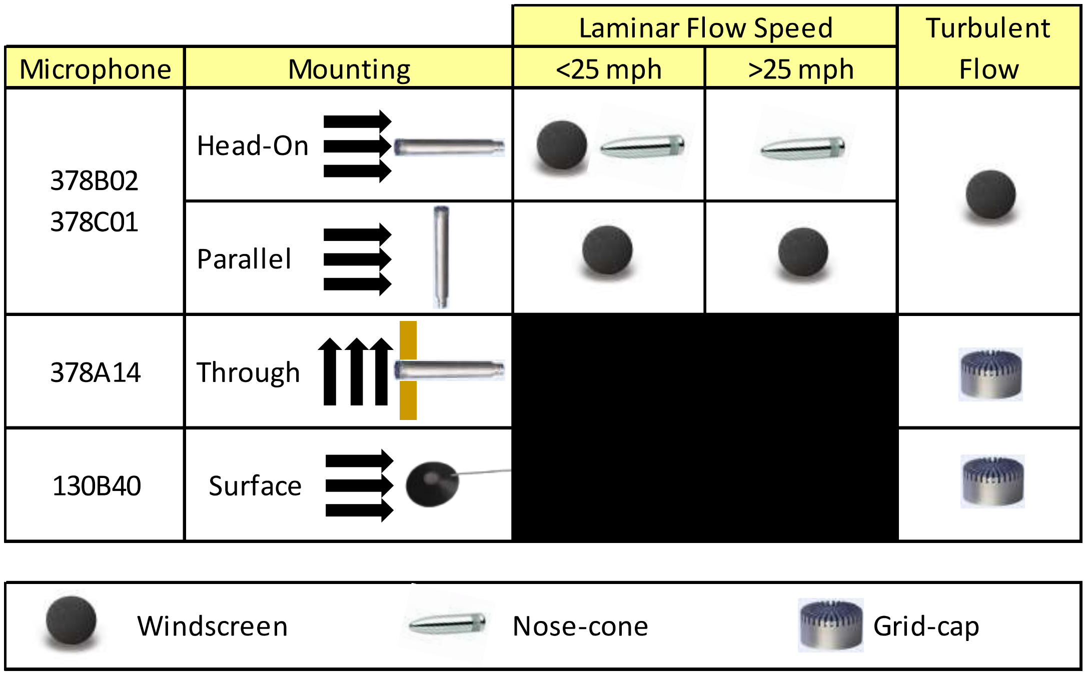


Table 3: Summary of optimal microphone configurations and accessories for different flow scenarios and mounting types using PCB instrumentation.

8.2 IMPROVED MEASUREMENTS OF "TUNNEL NOISE" PRESSURE FLUCTUATIONS [23]

The Arnold Engineering Development Center (AEDC) Hypervelocity Wind Tunnel No. 9 has been a critical facility for hypersonic vehicle development for more than 30 years. It provides high-quality aerodynamic and aerothermal data for high Mach and Reynolds number simulations.

While Tunnel 9 can replicate flight-level Reynolds numbers and naturally transitioning boundary layers, small pressure fluctuations—often referred to as "tunnel noise"—can complicate the analysis of boundary layer transition.

To better characterize these freestream disturbances, researchers performed pitot acoustic measurements using flush-mounted pitot probes across a wide bandwidth (0 to 1 MHz) within the Mach 10 nozzle at a nominal Reynolds number of 2×10^6 per foot. This dataset helps quantify freestream acoustic noise under flight-representative conditions.

Tunnel Noise and Test Facility Overview

All conventional hypersonic wind tunnels exhibit some level of freestream pressure disturbances. These originate from the turbulent boundary layer along the nozzle walls, radiating broadband acoustic noise into the flow field along Mach lines. Such disturbances are far greater in ground-test facilities than in actual flight and can affect critical viscous phenomena, such as:

- The natural transition from laminar to turbulent boundary layers.
- Other turbulent flow behaviors affecting aerodynamic heating and stability.

As these effects are crucial to hypersonic vehicle design, Tunnel 9 personnel continue to investigate freestream disturbances through high-fidelity pitot acoustic measurements.

Tunnel 9 is a blowdown facility using pure nitrogen as the test gas and can operate at Mach 7, 8, 10, and 14. **Figure 44** illustrates the operational envelope, showing equivalent Reynolds number altitudes versus Mach number.

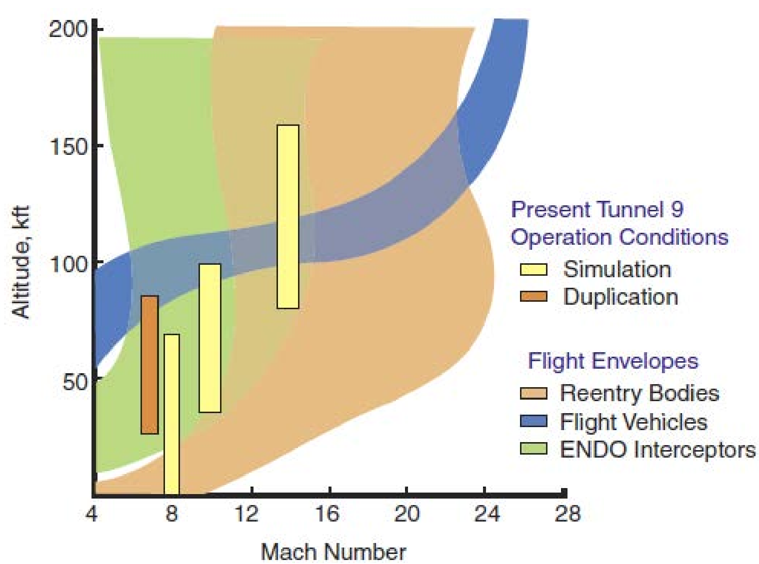


Figure 44: Operational envelope of AEDC Hypervelocity Wind Tunnel No. 9 showing equivalent Reynolds number altitudes versus Mach numbers.

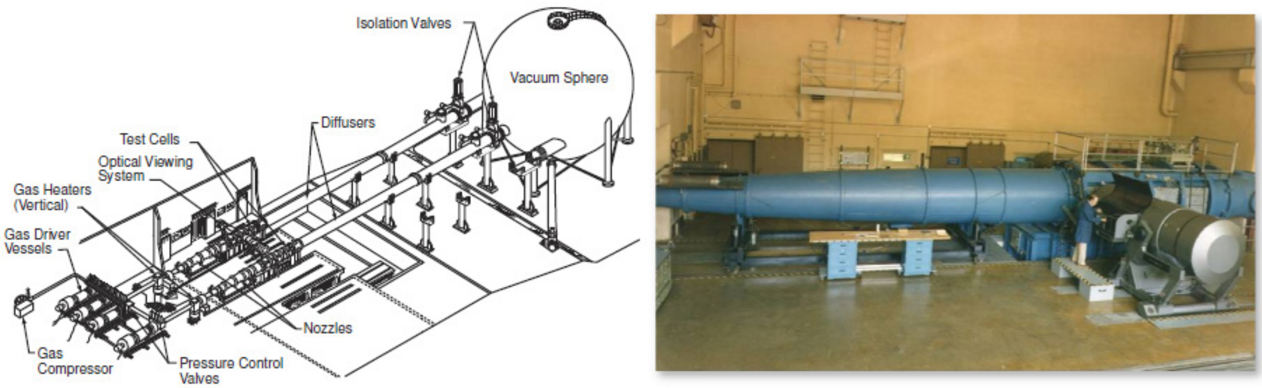
Facility Features

The facility includes a large-scale test section measuring over 12 ft long with a 5 ft diameter, capable of accommodating advanced aerodynamic, thermal, and force/moment testing.

Several nozzle configurations are available to support a range of hypersonic conditions:

- **Mach 10 and 14**: 40 ft long, 60-in. diameter exit.
- **Mach 8**: 40 ft long, 35-in. diameter exit.
- **Mach 7**: 7.3 ft long, 11.3-in. diameter exit.

Both the Mach 7 and 8 nozzles can operate in freejet mode when paired with the 60-in. diameter test cell. **Figures 45 and 46** show a facility schematic, nozzle configurations, and typical test setups.



a. Facility schematic. b. Test Cell and Mach 10 nozzle.

Figure 45: Overview schematic of Tunnel 9 showing nozzle and test cell configuration.

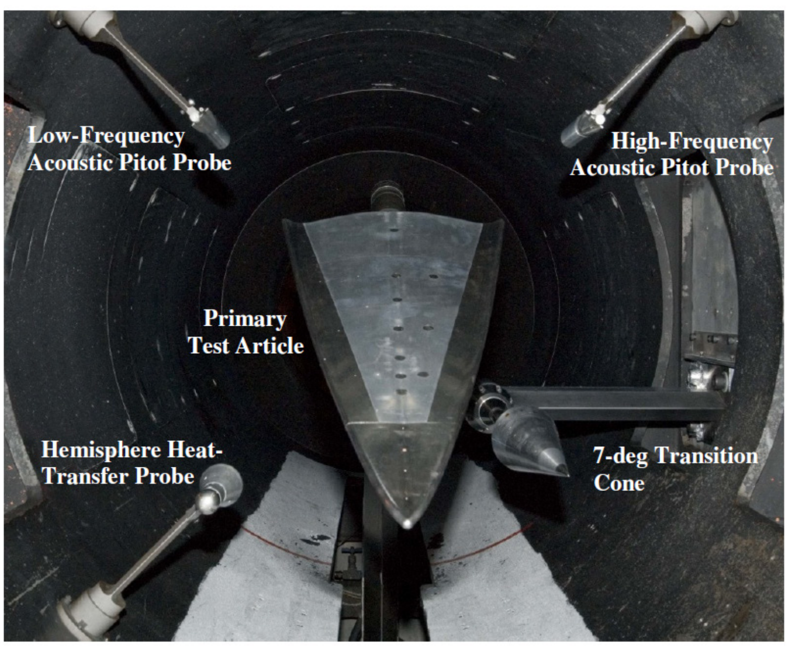


Figure 46: Typical Tunnel 9 test cell setup for aerodynamic testing.

Pressure Measurement Techniques

Freestream pressure fluctuations were measured using two types of pressure sensors. DC-coupled piezoresistive absolute pressure transducers were used for low-frequency measurements. These were fitted with protective B-screens to shield the sensing elements from debris, though their usable bandwidth was limited to about 25 kHz.

For higher frequencies, AC-coupled **PCB Model 132A31** piezoelectric pressure sensors were employed. These sensors have no protective screens and feature a 0.762 mm × 0.762 mm piezoelectric crystal bonded directly to the sensing surface. Their frequency response extends from 11 kHz to beyond 1 MHz. Each sensor was connected to a **PCB Model 482A22** signal conditioner for data acquisition and calibrated using a shock tube with a single-point calibration method.

Study Results and Applications

This study demonstrated a robust methodology for gathering pitot acoustic data under extreme test conditions. The current probe setup enables routine pitot acoustic measurements during Tunnel 9 test programs without interfering with primary test objectives.

Future work includes expanding datasets across a broader range of Mach and Reynolds numbers, and studying spatial variations of tunnel noise throughout the test cell.

Additional Sensor Considerations

Although the study used piezoresistive sensors from another manufacturer, improved performance could potentially be achieved with the **Endevco Model 8507** due to its:

- Higher output (200 mV full-scale) and better signal-to-noise ratio.
- Greater overrange protection (up to 3× full scale).
- Higher burst pressure and shock resistance.
- Lower acceleration sensitivity.
- Comprehensive individual temperature compensation.

Model 132A31 has been succeeded by Model 132A38, which features a redesigned, centered sensing element for improved overall performance. Additional details on Model 132A38 can be found in section 6.2 of this handbook.

8.3 INFLUENCE OF MOUNTING ON THE ACCURACY OF PIEZOELECTRIC PRESSURE MEASUREMENTS FOR HYPERSONIC BOUNDARY LAYER TRANSITION [24] [25]

Mounting methods play a critical role in the accuracy and performance of piezoelectric pressure sensors used for hypersonic boundary layer transition (BLT) studies. Proper mounting affects key sensor characteristics, including:

- Sensitivity.
- Frequency response.
- Effective sensing area.
- Resistance to electrical, magnetic, and mechanical interference.
- Stability under structural strain and vibration.

In hypersonic testing, where precise detection of rapid pressure fluctuations is essential, mounting becomes even more critical.

Sensors Evaluated

Testing with **PCB Model 132B38** microsensors, commonly used in BLT studies, demonstrated how mounting methods can significantly influence pressure measurement results.

The 132B38 microsensor is comprised of cylindrical piezoceramic crystal potted in an epoxy matrix, a microelectronic preamplifier integrally bonded to the crystal, and a coaxial signal cable, all enclosed in a tubular stainless-steel housing (see **Figures 46 and 47**). By miniaturizing the piezoceramic, a high resonant frequency is achieved, enabling fast response. The 132B38 element diameter is 0.035” (0.81 mm) and this length is equal to the wavelength in air at a frequency of 422 kHz (at 20°C).

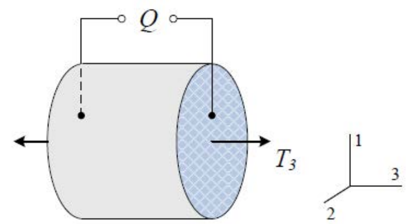


Figure 47: Piezoceramic charge output schematic.

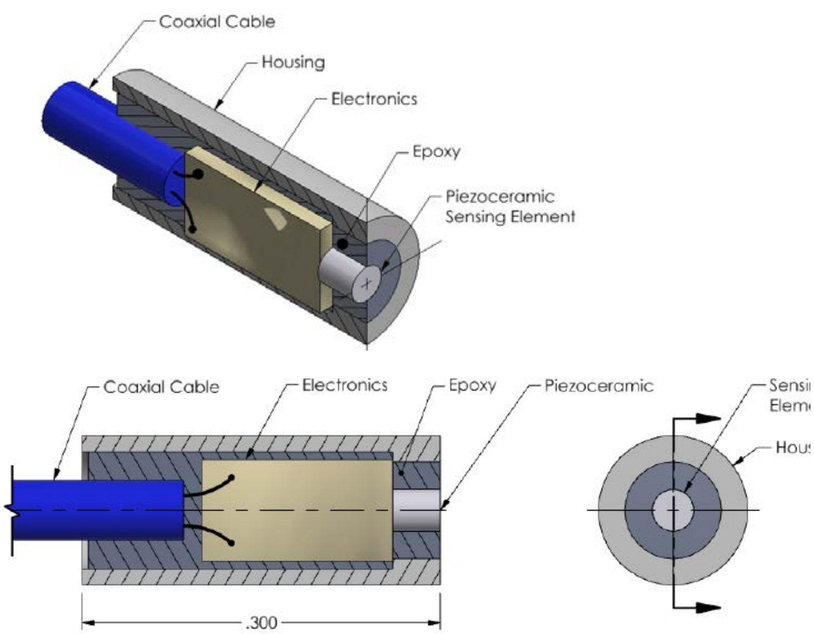


Figure 48: Construction diagram of PCB Model 132B38.

Experimental Setup for Mounting Techniques

To evaluate how sensor mounting affects dynamic behavior, two common installation methods were tested using a shock tube setup. Sensitivity and frequency response were derived from the step response of a known pressure event generated in a **PCB Model 901A10** shock tube (see **Figure 49**). The sensor under test (SUT) was mounted in two different locations (shown in **Figure 50**):

- **Incident position**: Flush with the sidewall of the shock tube.
- **Reflected position**: At the closed end of the shock tube.

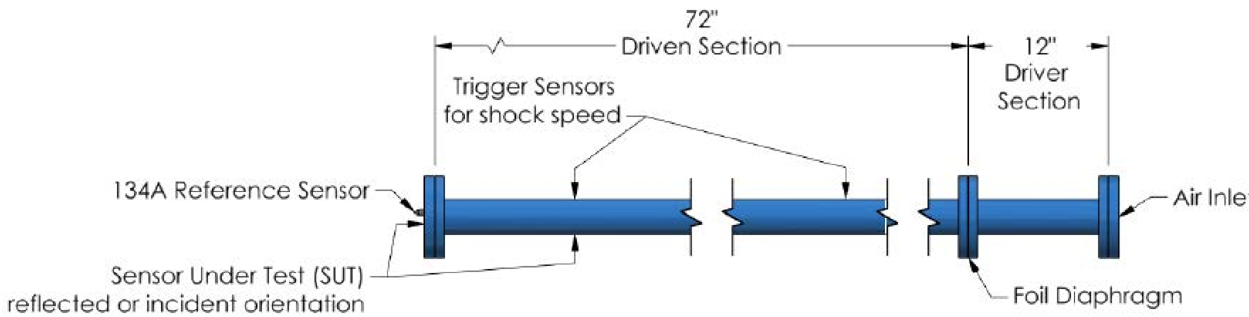


Figure 49: Outline of PCB Model 901A10 shock tube calibration system.

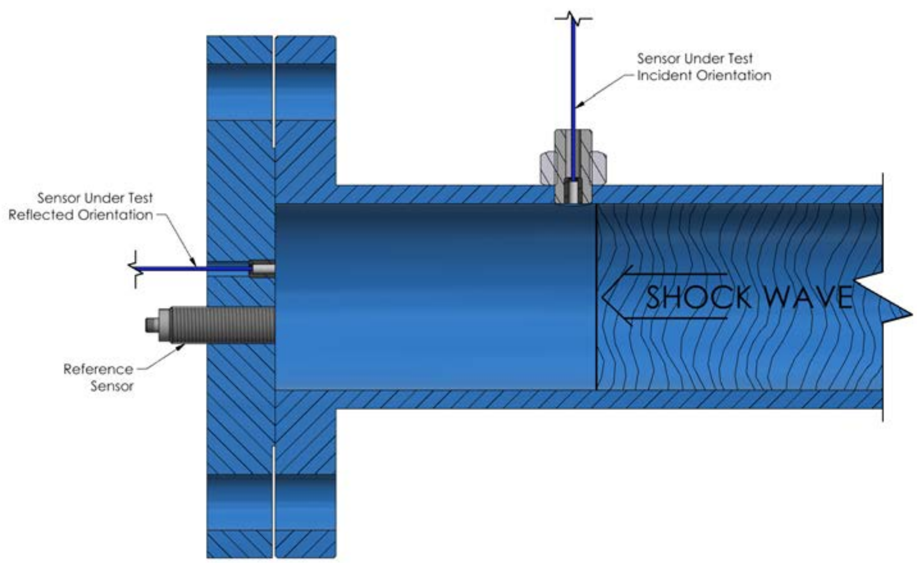


Figure 50: Sensor mounting orientations for testing.

These locations were selected to assess sensor performance under both direct and reflected pressure wave conditions. Two mounting methods were compared (shown in **Figure 51**):

- **Adhesive Mounting**: The sensor was bonded directly into a precision-machined hole, following the manufacturer's standard installation guidelines.
- **Rubber Sleeve Mounting**: The sensor was installed within a rubber isolator, a method commonly used by researchers to reduce the transmission of structural vibration.

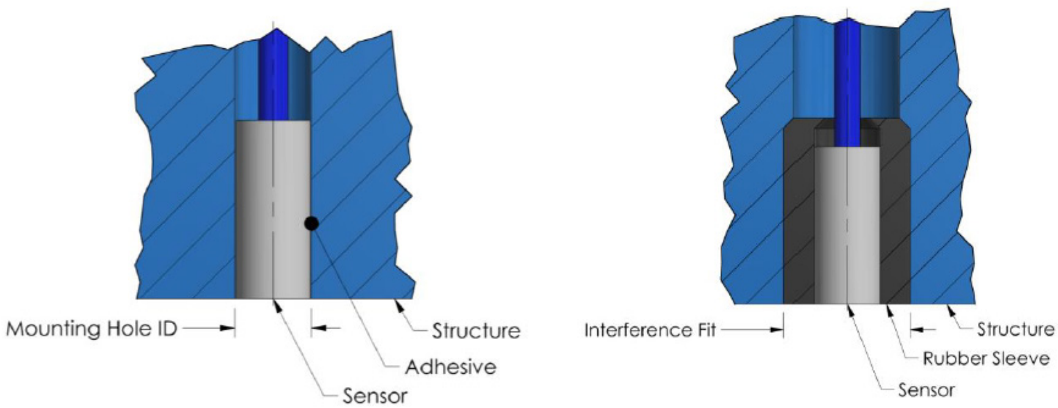


Figure 51: Comparison of adhesive mounting (left) and rubber sleeve mounting (right).

Study Results and Recommendations

The study found that mounting method significantly affects pressure sensitivity and frequency response :

- Adhesive mounting generally provides better sensitivity and more predictable frequency response, though it may also increase susceptibility to structural strain.
- Rubber sleeve mounting can dampen high-frequency response but helps reduce sensitivity to vibration and mechanical noise, making it useful in certain test environments.

For hypersonic boundary layer transition (BLT) testing, mounting should be chosen based on the primary measurement objective. Adhesive mounting is recommended for applications requiring maximum sensitivity and fast frequency response, while rubber sleeve mounting may be preferable when structural vibrations or hardware constraints are a concern. Regardless of method, mounting choices should always be evaluated during calibration, as they directly influence both the accuracy and consistency of test results.

8.4 TILTROTOR ACOUSTIC DATA ACQUISITION USING PCB 130B40 ICP® SURFACE MICROPHONES [26]

A notable example of aeroacoustic testing involves structural-acoustic measurements on a Leonardo Helicopters tiltrotor aircraft. These tests were performed as part of the aircraft's civil certification program, focusing on identifying and reducing interior cabin noise.

Noise Sources and Test Objective

During flight, fluctuating external pressures—caused by propulsion systems and airflow around the fuselage—can induce structural vibrations. These vibrations generate noise inside the cabin, potentially affecting passenger and crew comfort. Testing is critical for mitigating such noise through design modifications.

The external pressure sources acting on the tiltrotor primarily include:

- **Rotor Noise**: Generated by the large wingtip rotors; typically tonal, highly directional, and dominant near the rotor plane.
- **Boundary Layer Noise**: Caused by turbulent airflow along the fuselage, increasing with flight speed and contributing significantly to internal cabin noise.

Test Setup

Twelve **PCB Model 130B40** ICP® surface microphones were installed on the aircraft's fuselage. Each microphone features a 13 mm diaphragm and a 3 mm height for flush surface mounting (shown in **Figure 52**).

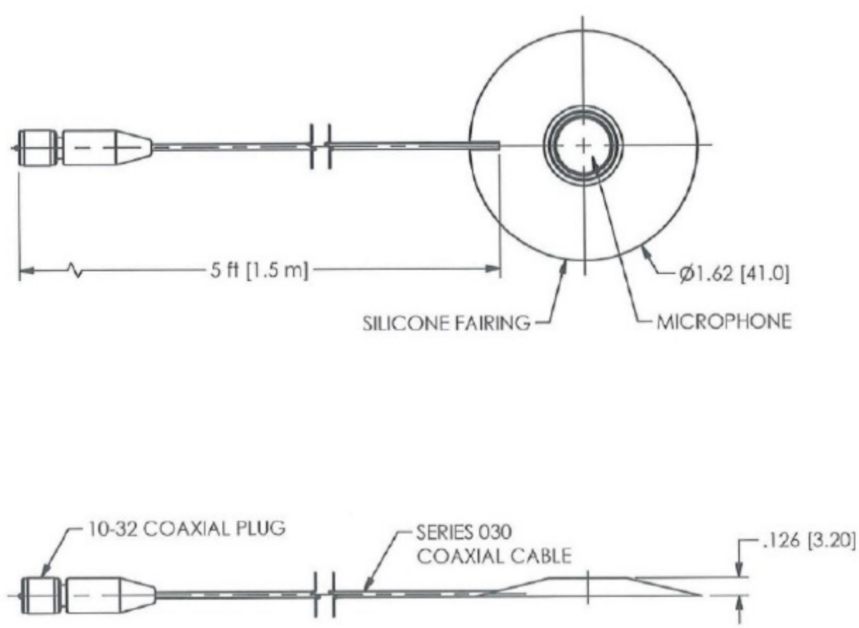


Figure 52: PCB Model 130B40 surface microphone dimensions.

Eleven microphones were mounted along the port side, with one on the starboard side to verify measurement symmetry. The microphone placement followed a T-shaped pattern to capture acoustic variations along both the longitudinal and transverse axes of the fuselage (as shown in **Figures 53 and 54**).

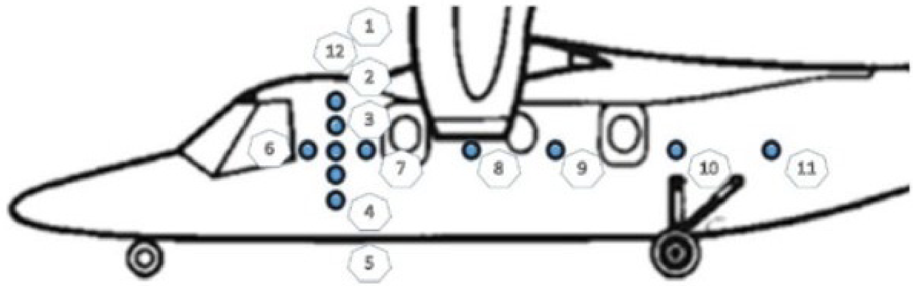


Figure 53: Layout diagram of external microphone locations on fuselage.

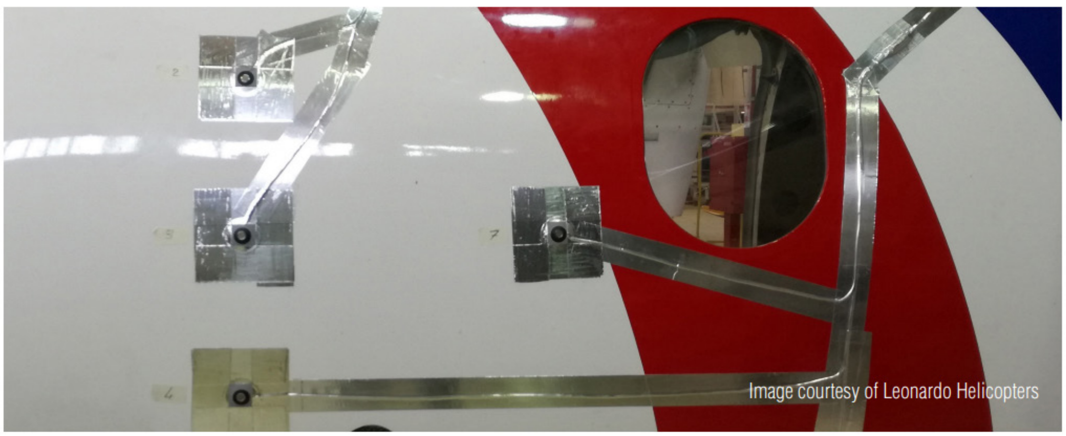


Figure 54: Photograph of external microphone installation on tiltrotor aircraft (courtesy of Leonardo Helicopters).

Data was collected over 30-second intervals at each of the nine flight conditions listed in **Table 4**. The focus was on steady cruise and altitude conditions; therefore, transitional phases such as conversion (hover-to-cruise) were excluded from noise measurements.

Flight condition	Speed (kt)	Altitude (ft)	RPM
I	150	20,000	478
II	155	20,000	478
III	160	20,000	478
IV	165	20,000	478
V	170	20,000	478
VI	175	20,000	478
VII	180	20,000	478
VIII	185	20,000	478
IX	190	20,000	478

Table 4: Flight test conditions used for acoustic measurements.

Test Results

The measured data revealed clear trends in Overall Sound Pressure Level (OASPL):

- Highest noise levels were recorded near the rotor plane.
- OASPL decreased progressively forward and aft of the rotor plane.
- A near-linear relationship was observed between OASPL and flight speed.

Figure 55 illustrates OASPL as a function of flight speed for all 12 microphones. These results demonstrate the effectiveness of flush-mounted surface microphones for mapping external acoustic fields in flight conditions. The same approach could also be adapted for conventional aircraft or even ground vehicles to study noise generation and transmission paths.

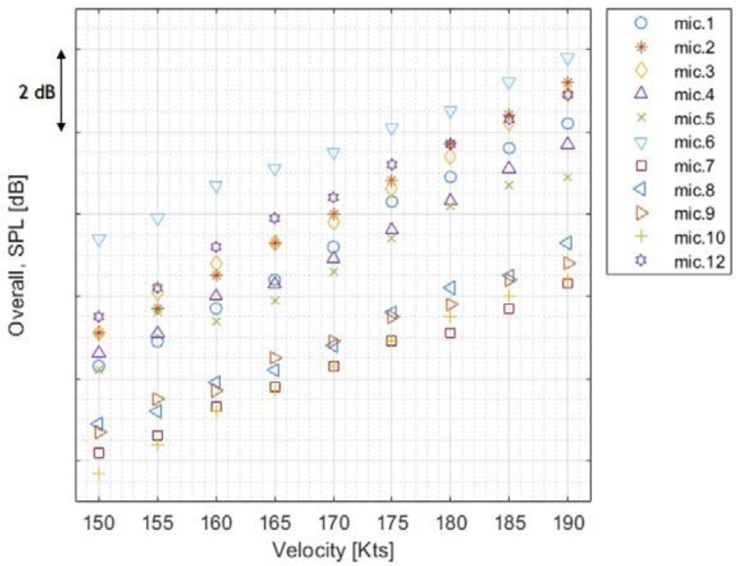


Figure 55: OASPL measurements at different flight conditions for all microphones.

9. CONCLUSIONS

Aerodynamic and aeroacoustic testing continues to advance, but the core challenges remain unchanged. Engineers still need to understand airflow behavior, aerodynamic forces, and noise sources—and they must rely on precise, reliable measurements to validate designs and improve performance. As this handbook has shown, selecting the right sensor is central to obtaining high-quality data in wind tunnels, on the ground, and in flight.

Today's testing environment is shaped by several converging trends. The growing complexity of vehicles like eVTOLs, UAS, and hypersonic aircraft brings unconventional geometries and new environmental extremes. At the same time, sensor technology itself is evolving, with modern designs offering improved temperature stability and smaller sizes to enable more efficient test setups and enhance data fidelity.

Still, even the most advanced equipment cannot replace expertise. Accurate test results continue to depend on thoughtful sensor selection, careful mounting, and proper calibration. In this way, the fundamentals of good testing remain as vital as the technologies pushing it forward.

For additional sensor selection resources, technical documentation, and product information, visit www.pcb.com.

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