

New experiences and sensors technologies for aero-acoustic and aerodynamic flight test

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Abstract

Aerodynamics and aeroacoustics are two tightly interwoven disciplines that together explain how air moves around and go into objects—and the noise that results. By combining insights from both, engineers can design aircraft structures that are not only more efficient but also quieter and more reliable. Aero-acoustic and aerodynamic testing play an important role in both ground and flight testing for any aircraft. The tests are performed using a suitable measurement system composed of sensors and data acquisition systems to analyze the signal coming from the sensors. Sensors play a crucial role in these types of tests. In this paper, three different advanced dedicated testing sensors technologies are illustrated with relative case studies in ground and flight test applications:

1. The flat microphone and case study for aero-acoustic flight test. The challenge in this experiment was to employ a measurement microphone already used for ground acoustic testing, this time in flight, with the inherent issues of fuselage mounting. After a necessary technical introduction to the sensor technology, its use will be illustrated in a subsonic wind tunnel and subsequently in flight testing with real case study/experience on field.

2. The unique design of PR pressure sensors for flights pressure distribution with its sculptured diaphragm. 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. Measurements of this pressure distribution are performed both in ground tests (wind tunnels) and in flight test. In both cases, precision pressure sensors are used. Part of this section is to describe the unique and specific design of piezoresistive pressure sensor's sensitive part as well as the additional advantage, among many others, of being suitable for use in both wind tunnels and flight tests.

3. The newest design of ICP piezoelectric pressure sensors for hypersonic flight studies. Hypersonic flights aerodynamic studies need extensive testing on ground primarily in relative hypersonic wind tunnel. This new sensor design has technical advantages on ground test wind tunnels. A case is reported based on this new design. Finally, we show how the same sensor can be used in experimental flights under those hypersonic conditions.

Key words: Pressure, sensors, aerodynamic, aero-acoustic, ICP®.

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Following a necessary introduction regarding pressure sensor technologies, this manuscript focuses on three new projects and the

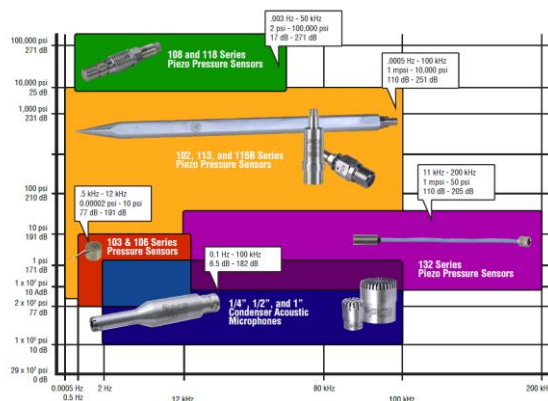
associated experiences in aerodynamic and aero-acoustic measurements.

Accordingly, the table of contents is as follows:

- Pressure Sensor Technologies Introduction
- Aero-acoustic Sensors and Flight Experience
- Piezoresistive Pressure Sensor Design and Benefits
- New Miniature Pressure Sensors for Hypersonic Testing

Pressure Sensor Technologies Introduction

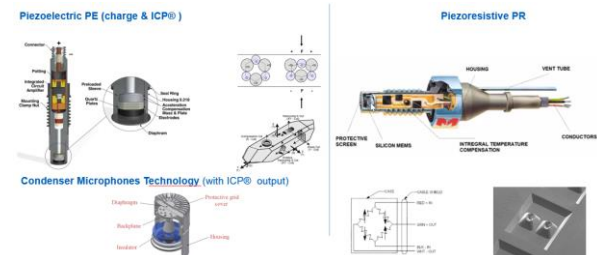
Pressure sensors play a crucial role in all aerodynamic and aero-acoustic measurements. Pressure sensors are the most common starting point, as they provide essential data for assessing flow behavior, calculating aerodynamic forces, and evaluating sound generation. In many cases, velocity measurements 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 aero-acoustic loads. In general, pressure sensors can be based on various technologies (excluding those for purely static measurements, which are not the subject of this brief work): precision measurement microphones, piezoelectric pressure sensors, and piezoresistive pressure sensors. [1]



The plot above illustrates the various types of dynamic sensors; notably, we observe measurement microphones, which—despite measuring very low dynamic pressure values characteristic of acoustic levels—can indeed be classified as dynamic pressure sensors, given that the measurement of acoustic events is, in essence, a measurement of dynamic pressure, albeit at very low dynamic levels.

Naturally, in the case of dynamic sensors as well, the underlying technologies vary

considerably: ranging from condenser microphones designed for precision acoustic measurements to piezoelectric sensors—specifically ICP types—suited for measuring virtually any form of purely dynamic pressure. In the following figure, we summarize the three types of technologies presented in this work: condenser microphones, piezoelectric dynamic pressure sensors, and piezoresistive sensors for measuring static and dynamic pressure.



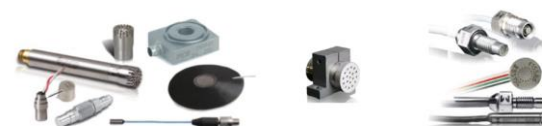
Below, however, is the same type of summary image, but featuring real-world examples of pressure sensors corresponding to the technologies summarized in the previous image. Below, however, is the same type of summary image, but featuring real-world examples of pressure sensors corresponding to the technologies summarized in the previous image.



Purely for the sake of brevity, we will not dwell on a detailed explanation of each technology, but instead refer the reader to the relevant bibliography. We will therefore proceed to delve into the core of several new sensor designs and the associated experiences.

1. Aero acoustic sensors Type Style and Size

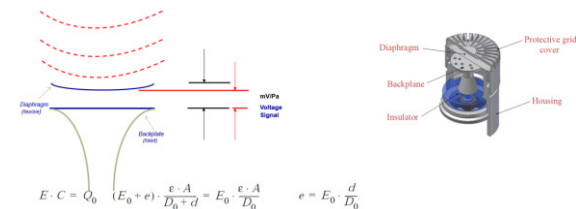
In aero-acoustic measurements, all three of the sensor technologies mentioned above can be employed—as once again illustrated in the following image. [2]



Condenser microphone working principle

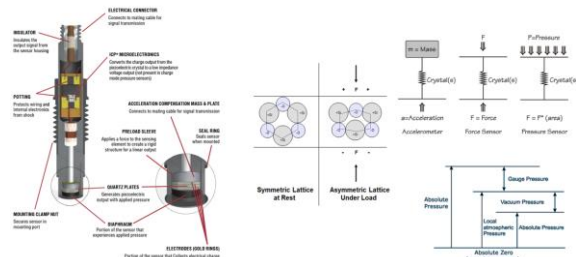
Briefly put, precision condenser microphones operate—as the name suggests—on the principle of a capacitor. One will observe two plates: one fixed (a rigid backplate, which must necessarily be electrically charged) and the

other very thin (a diaphragm, which is free to move in response to incoming sound waves). The operation of this sensor bears a certain resemblance to that of the human ear, wherein the signal emerging from the inner ear travels to the brain as an electrical signal to be analyzed; similarly, with these microphones, the outgoing AC electrical signal is directed to a signal analyzer—or data acquisition system—for processing.



Piezoelectric pressure sensors.

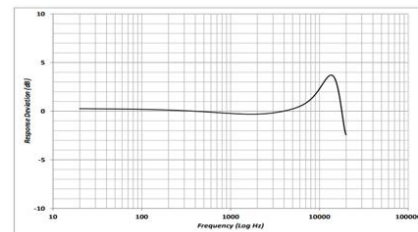
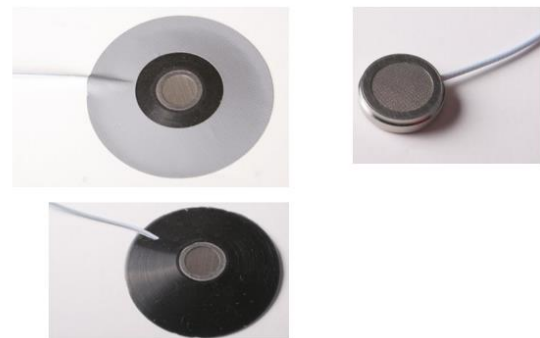
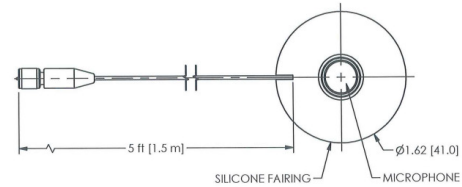
Piezoelectric sensors measure dynamic pressure—much like the precision microphones just described—except that the pressure levels they measure are significantly higher, ranging from high-end acoustic pressure values to extremely high pressure levels associated with ballistic or explosive testing. Piezoelectric sensors are inherently high-impedance charge-output devices; however, ICP type so preamplified pressure sensors with low impedance output are widely used today due to the substantial advantages their application offers. Later, we will examine a highly specialized example designed for hypersonic testing, featuring an even more innovative design. The operating principle is based on the concept of piezoelectricity, wherein a piezoelectric crystal—quartz, in the case of such sensors—coupled with a seismic mass and held together by a clamping ring, provides a solid foundation for generating precise outputs in pC (charge mode) or mV (for ICP) corresponding to the instantaneous level of the dynamic pressure under measurement.



Surface microphone

Returning to condenser microphones, the example presented below features a flush-mounted microphone—complete with an integrated preamplifier—designed for measuring sound pressure on a surface. Such measurements are widely utilized in fields such

as the automotive industry—for both road and laboratory testing—as well as, more generally, in subsonic wind tunnels. The specific application we wish to highlight here, however, involves the deployment of this type of sensor in flight testing for the very first time, thereby making this class of microphone accessible for such applications.



Test in operating conditions. Flight test: acoustic. [3]

This experiment, conducted by the University of Naples in collaboration with technicians from Leonardo, involved external in-flight acoustic measurements on a new tiltrotor aircraft. The details of this experiment can be found in a dedicated paper available on the website www.pcb.com; here, we present only a summary of the key details and conclusions. The challenge lay in utilizing this specific microphone—chosen for its accessibility in terms of both ease of use and cost-effectiveness—by mounting multiple units on the external fuselage of a tiltrotor aircraft. The primary challenge to be addressed—with technical support provided by Dr. Salzano of PCB Piezotronics USA regarding the sensor's application—concerned the mounting method on the fuselage. The objective was to prevent the

microphone from detaching during flight, an occurrence that would have posed serious risks not only to the integrity of the measurements but also to the safety of the flight itself. After extensive study, a solution was finally devised utilizing a specialized, high-adhesion tape that—crucially—also allowed for easy removal upon the conclusion of the test campaign. A second challenge involved verifying whether this standard microphone could accommodate the maximum sound pressure dynamic range expected during flight operations. This challenge was ultimately validated by the test results, which demonstrated that the maximum measured pressure levels approached—but never exceeded—the microphone's operational limits. Consequently, for the moderate cruise speeds typical of rotorcraft, we can affirm that this solution represents a technically and economically viable approach, thereby extending the application of this technology beyond the ground-based testing to which it had previously been confined.



Table 1 Flight test conditions

Flight condition	Speed (kt)	Altitude (ft)	RPM
I	135	20,000	478
II	135	20,000	478
III	140	20,000	478
IV	145	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

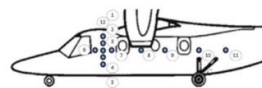


Figure 2 Layout diagram of external microphones

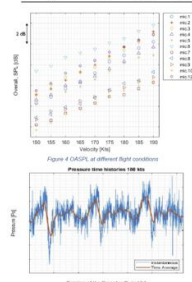


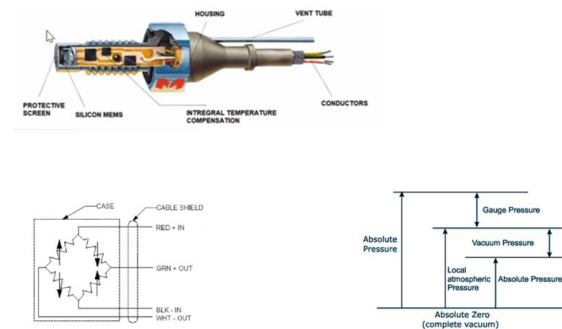
Figure 4 Overall RMS at different flight conditions

Piezoresistive Mems pressure sensors

2. Piezoresistive Mems pressure sensors.

Another type of pressure sensors is based on MEMS (microelectromechanical system) technology. These types of sensors utilize silicon—specifically the diaphragm—as their sensing element; they can be manufactured in compact dimensions, though their primary characteristic is the capability to measure both

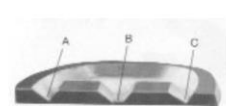
static and dynamic pressure.



The specific Endevco design we wish to highlight here centers on a unique diaphragm structure: it is sculpted to create high-stress zones where the sensing elements are applied, resulting in heightened sensitivity—a crucial factor in such bridge-type sensors, where a doubling of sensitivity represents a significant advantage in numerous testing scenarios, as well as in signal transmission and the signal-to-noise ratio.



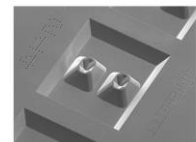
Photograph of diaphragm taken with scanning electron microscope 0.05 in. (1.25 mm) O.D.



Photomicrograph of diaphragm section through notches and islands



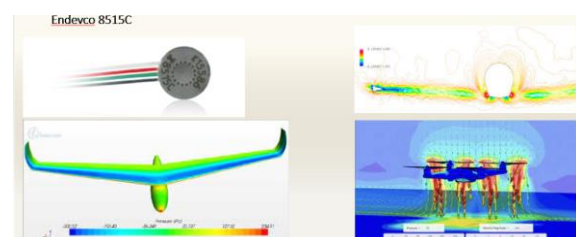
Photograph of diaphragm, glass-bonded to heavy silicon ring, 0.1 in (2.5 mm) O.D. by 0.02 in (0.5 mm) thick.



Sculpted pressure sensor diaphragms for increased sensor output and low linearity error

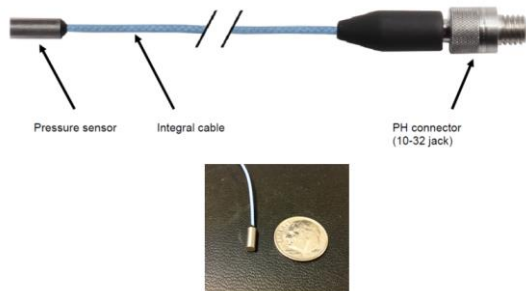
Flight test: pressure distribution.

One of the most common applications of such sensors—particularly those utilizing this sculpted-diaphragm design—is undoubtedly in flight testing, where they are used to measure pressure distribution on surfaces such as aircraft wings. The sensitivity of these sensors—which exceeds standard levels—combined with their inherent reliability and extremely compact dimensions, has contributed to their widespread adoption, particularly for such testing applications; the Model 8515C, shown in the accompanying figure, is a prime example.

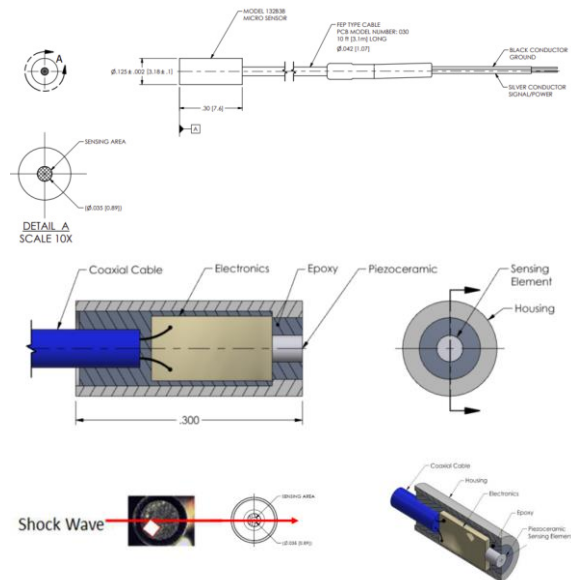


3. High Frequency Acoustic Pressure Sensors new design.

[4] Returning to the dynamic pressure sensors we present here a new design of an innovative sensor, for measurement of short wavelength pressure pulses, 132B38 piezoelectric ICP® micro pressure sensor features 0.5 microsecond response. The sensor's micro-second response time accurately measures pressure peaks from fast rising shock waves and very high frequency pressure phenomena. The 1mm diameter sensing element allows measurement of short wavelength incident pressure waves. A short time constant filters off the static component of wind tunnel pressure, allowing differentiation of consecutive pulses.



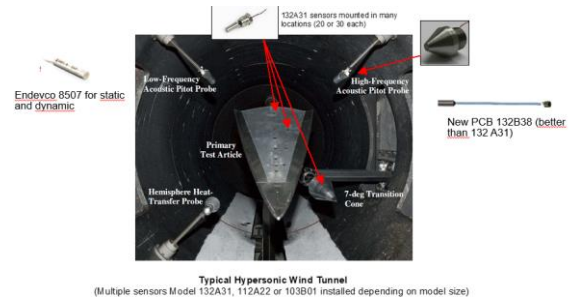
One of the key features of this new sensor, compared to previous versions, is the diaphragm, which features a centered—rather than eccentric—sensing element. This design enables more precise measurements, given the extreme wavelength conditions of the pressures involved in such types of measurements. [6]



Highest speed wind tunnels Aerodynamic, Flight pressure distribution.

[5] The application of this specific sensor under conditions of extreme hypersonic velocity is the subject of the experiment we wish to summarize here. In this instance—described in a paper

referenced in the extensive bibliography of the manual under point [1] the predecessor model, the 132A31, had already been installed in a hypersonic wind tunnel, yielding results deemed satisfactory by the author; however, with the new design—specifically the centered configuration mentioned above—measurement precision can be further enhanced.



Conclusions and/or Future Work

- There are several advantages with such piezoresistive Mems pressure sensor sculpted diaphragm design such better linearity, better sensitivity and stability advantages
- The advantage of new model 132B38 ICP acoustic pressure sensor it essentially lies in having the new model, the piezoelectric element centered with respect to the sensor body, thus allowing for much more reliable and precise measurements compared to the previous one which had the decentralized or eccentric piezoelectric element.
- Future works:
 - extended low frequency unit ~100 Hz
 - new package, case isolated, low frequency, increased resonant frequency

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