CASE STUDY

United States of America

Aerospace

Transducers

Boeing Commercial Airplane Group
Investigations of Airframe Noise

The name Boeing is synonymous with the production of state-of-the-art aircraft for both civil and military use and its products are sold to airlines and airforces throughout the world. There is constantly increasing focus on the environmental effects of aircraft noise, from governments, airport authorities, airlines and the general public. During takeoff, noise levels are dominated by engine noise while during approach and landing, noise levels result from both the engine and the airflow over the airframe.

Boeing's relationship with Brüel & Kjær began over thirty years ago. Since the mid 1990s, Boeing has used arrays of standard and specially designed Brüel & Kjær microphones in hard-wall pressurised wind tunnels to determine the airframe noise of aircraft designs using models. The acoustic measurements are currently made at frequencies up to 88 kHz.

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Brüel & Kjær thanks James R. Underbrink of Boeing's Noise Engineering Laboratory for his help with the writing and editing of this case study.

Noise Engineering Laboratory

Boeing's Noise Engineering Laboratory in Seattle, Washington, was established coincident with the introduction of the Boeing 707 jet transport in the late 1950s. With a staff of around thirty-five, the laboratory measures all aspects of both civil and military airplane noise. Noise measurement and analyses made on civil aircraft include:

- interior noise – cockpit, passenger cabin, crew and galley areas
- community noise – produced by the engine and airframe
- material testing – carpets, panels, insulation, etc.
- all noise and vibration related components in the aircraft
- sound quality
- airport ramp noise – with the auxiliary power unit running
- troubleshooting – noise from doors seals, toilets, etc.

Fig. 1
Boeing's Noise Engineering Laboratory in Seattle

Airlines purchasing new or refurbished aircraft generally specify the maximum levels of interior noise within the passenger cabin permitted at different stages of a flight. The Noise Engineering Laboratory ensures compliance with these specified parameters.

With military designs, the focus is on an aircraft's stealth qualities, its acoustic signature, noise experienced by the pilot and crew, and the noise of the aircraft while on the ground, such as on the deck of an aircraft carrier, or at the airfield.

Boeing has used Brüel & Kjær products for over thirty years, including microphones and preamplifiers, spectrum analyzers, calibrators and noise source generators.

Experience and Expertise

Fig. 2
Jim Underbrink is an Associate Technical Fellow in Boeing's Noise Engineering Laboratory

James R. Underbrink is an Associate Technical Fellow in Boeing's Noise Engineering Laboratory Dynamic Data Systems and Methods Group. Jim has worked at Boeing since completing his education some 19 years ago.

He has a Bachelor's degree in mathematics and physics from the University of Washington, a Master's degree from the University of Washington in applied mathematics, and a further Master's degree in acoustics from Pennsylvania State University. He is responsible for instrumentation, systems, and measurement technique development, and operation for both laboratory and field testing.

Jim is an expert in the design and development of dynamic data systems, especially in the software, hardware and scientific applications for aeroacoustic measurement technology. Jim designs the phased arrays of microphones used when making acoustic measurements in pressurised wind tunnels.

Jim says, "On new aircraft, especially large 'heavy jets', environmental issues are very important and airlines want to avoid fees for exceeding noise limits imposed at airports. Airframe noise is a critical factor during approach and landing. Over the years, engine noise has been consistently reduced. Now, the noise generated by the airframe is about the same as from the engine at some overhead positions and therefore there is great focus on this."

Noise Measurements in Pressurised Wind Tunnels

Traditionally, airframe noise tests were conducted in specialised acoustic test facilities with anechoic (non-echoing) test sections. Boeing started working with phased array measurement techniques (beamforming) back in the mid 1990s. Jim, together with his colleague Robert P. Dougherty, presented some of their breakthrough work in a paper on phased array design at Noise-Con 96. Now with phased arrays of microphones, scale models can be tested in a pressurised wind tunnel to accurately emulate the full-size aircraft, using full-scale wind speeds. Boeing is one of a small number of companies around the world that are developing and using this cutting-edge technology.

Reynolds Number

Reynolds number, the ratio of inertial to viscous forces, is an important dimensionless quantity used to establish similarity between model-scale and full-scale testing. For model-scale airplanes, this ratio is smaller than for full-scale airplanes (under similar atmospheric conditions). Changing the fluid medium is a convenient way of testing at higher Reynolds numbers. Several tunnels around the world can be pressurised to increase fluid density. As a result, by using models in these pressurised wind tunnels, the aerodynamic effects of airflow over a full size structure can be more accurately replicated. Reynolds number effects on acoustic sources are still being studied, but the desire to conduct acoustic tests simultaneous with aerodynamic testing has motivated the implementation of this capability at Boeing.

Fig. 3
Model of Boeing 747 installed in the QinetiQ (DERA) 5 metre pressurised low-speed wind tunnel at Farnborough, England

Jim explains, "Back in the 1970s, airframe noise research was generally carried out using the whole-airplane approach. Aero-acoustic testing in pressurised wind tunnels was not feasible but recent advances in acoustic measurement technology using phased arrays of microphones placed flush in the wall of the test section have enabled us to acquire noise data using models in hard-wall pressurised wind tunnels. These days, airframe noise research is generally focused on the components on an airframe that produce noise."

He continues, "These items include the flaps, landing gear, and high lift leading edge devices. By carrying out test and analyses on the airframe noise created by a design using models in a pressurised wind tunnel, we can include noise data at the design stage of a new aircraft. We are continually improving our knowledge and techniques, and the data from the model tests is used to design quieter airplanes."

Tests are made on models with a scale from around 5% upwards, and also on the individual component parts of the airframe which can be up to full size, subject to size limitations within the wind tunnel. Most model test objects are made in house at Boeing.

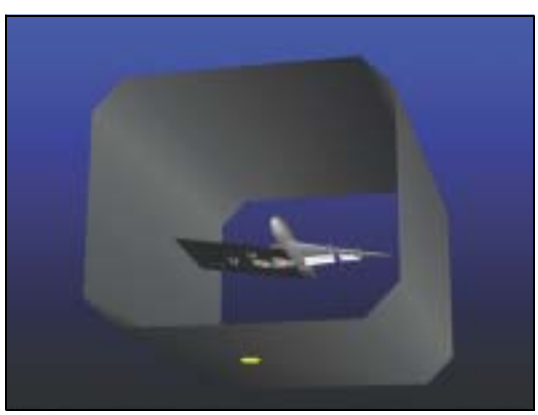


Fig. 4
Rendering showing wind tunnel cross section, model, array (yellow spot) and noise source map projected onto the model

Jim says, "Until about 1994, we used conventional phased arrays of microphones set up, for example, in regular lattice configurations. These arrays met our requirements but only over a limited frequency range. Now, we use logarithmic spirals of microphones as these perform well over a sufficiently wide frequency range to give quality test data. The multiarm spiral has been found to be superior to the single arm configuration."

He adds, "It is necessary to work at very high acoustic frequencies as the frequency of the noise created using a scale model is inversely proportional to the size of the model. As an example, if noise is measured at 50 kHz using a one-tenth scale model, this equates to 5 kHz on the full size object."

Typical airframe noise is a significant contributor to certification noise levels within the range of 500 Hz to 6 kHz. Airplane certification noise regulations require data in the frequency range from 45 Hz to 11.2 kHz.

Microphone Development

Microphones are generally designed to have a flat frequency response. Variations in atmospheric pressure are known to affect the microphone's response and therefore correction factors can be applied to compensate for changes in atmospheric pressure.

With the advent of the use of pressurised wind tunnels for acoustic testing, Boeing asked Brüel & Kjær to investigate the response of its 1/4-inch Microphone Type 4136 at several pressures, up to six atmospheres.

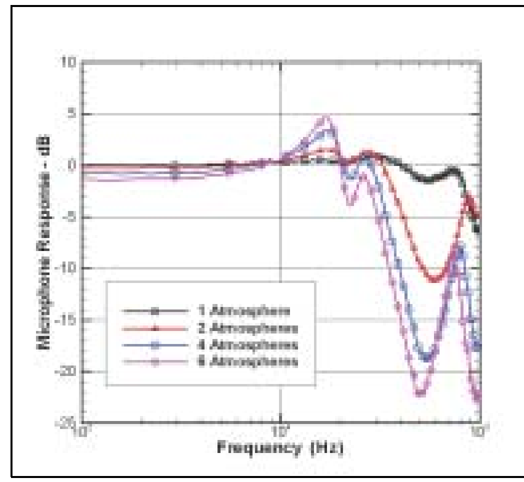


Fig. 5
Microphone Type 4136 frequency response plot at various pressure levels

A plot of the response is shown in Fig. 5. It can be seen that the response is rather flat up to a frequency of about 10 kHz, but then the shape of the curve changes significantly under increased pressure. At a pressure of six atmospheres, the microphone has a gain of 5 dB in sensitivity at 15 kHz. At 50 kHz, the microphone has a drop in sensitivity of some 25 dB.

This reduction in sensitivity is exacerbated by:

- for flush-mount in-flow applications, the flow-noise spectrum is highest in level at low frequencies and tapers off as the frequency increases. By 50 kHz, boundary layer flow noise in a low-speed wind tunnel is typically 40 to 50 dB down from the level at 1 kHz
- atmospheric attenuation of sound increases with frequency
- airframe noise sources tend to be lower in level at high frequencies

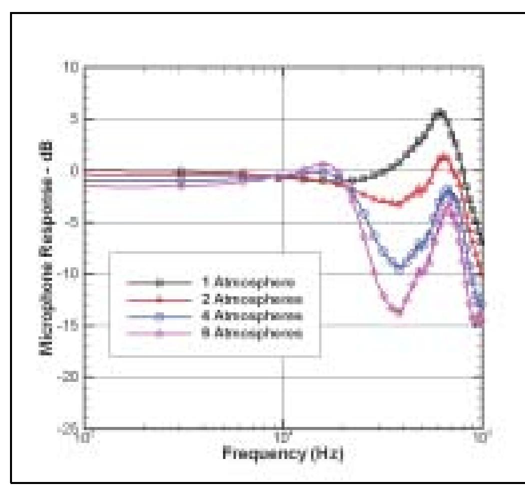


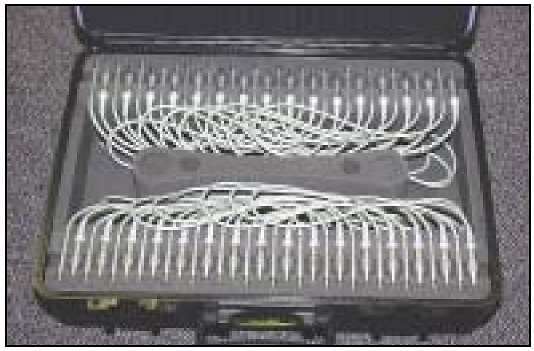
Fig. 6
Microphone Type 4938-W-001 frequency response plot at various pressure levels

As a result of its investigations, Brüel & Kjær began development of a new 1/4-inch microphone. The goal – to have an improved, flatter frequency response under high air pressures at high acoustic frequencies.

Many measurements were made and more than fifty different prototypes were produced. It was found to be impossible to make a microphone with a totally flat frequency response that did not change with pressure variations. However, the selected design had the smallest and highly predictable variation in gain at the relevant frequencies of interest.

The final model has a special backplate to remove damping effects. The construction was changed to make the new microphone slightly shorter and to place the static pressure equalisation area as close as possible to the diaphragm. Brüel & Kjær applied its knowledge of precision laser welding technology to assemble the diaphragm of the microphone and provide good flush-mounting characteristics. The variation on the face of the microphone is typically 0.004 inches (0.10 mm).

Fig. 7
Together with their preamplifiers and fitting adaptors, the microphones are stored and transported in specially made cases



The temperature-controlled, clean-room manufacturing facilities at Brüel & Kjær are vitally important in ensuring that all microphones are manufactured under optimal conditions.

The result was the 1/4-inch Microphone Type 4938-W-001. The microphone's response is shown in Fig. 6. As can be seen, the new microphone does not have the same magnitude of sensitivity loss as the standard 1/4-inch microphone.

Fig. 8
Boeing has a large number of Brüel & Kjær microphones

The new microphone is externally polarized (200 V). The maximum loss in sensitivity is only 15 dB and correction factors for the microphone's response under various pressures are applied to all test data.

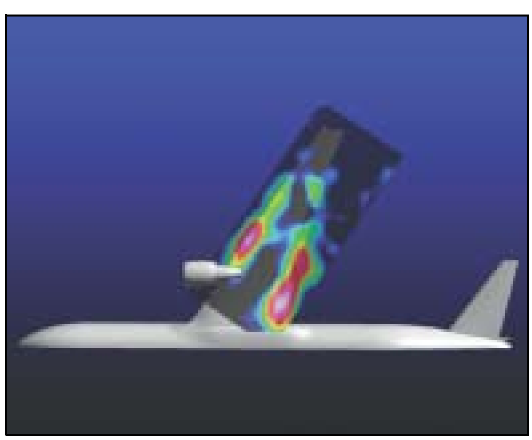
A new, shorter Preamplifier Type 2670-W-001, compatible with Type 4938-W-001 was also produced. This avoided mounting problems and provided a long line drive capability – up to 295 feet (90 m) without line loss.

The measurement system has a dynamic range upper limit of 157.5 dB at 80 kHz. The sensitivity of the new microphone starts rolling-off at about 60 kHz but it is usable beyond 80 kHz.

Boeing placed its first order for a number of Microphones Type 4938-W-001 in March, 1998. The Type 4136 microphones, originally used for phased array work, are still in regular use for general acoustic measurements.

Practical Testing

Fig. 9
Boeing 767 source map from a test in QinetiQ's 5 metre pressurised low-speed wind tunnel



Boeing has designed an adaptor, constructed from brass and nylon, that allows the microphones to be accurately flush-mounted in the array with a tight push fit.

Jim explains, "It is desirable to eliminate as much flow noise as possible and therefore we have made a number of tests to check the effects of microphone protrusion and recession from the wind tunnel wall. Our fitting adaptor enables the microphones to be located very precisely."

He continues, "Many microphones are used in each array because the noise sources we are trying to measure are typically much lower in level than the boundary layer noise at the microphone diaphragms. More microphones also improve the array's dynamic range, and its ability to distinguish a source from the array noise floor. I have designed and used logarithmic spiral arrays with up to 251 microphones."

Jim says, "The installation of a large number of microphones can be difficult in some wind tunnels as they typically have limited available space. There is often restricted cable access from the microphones to the data acquisition equipment. These issues can be especially important in pressurised wind tunnels as they are contained within a pressure vessel, and therefore the ability to pass signals through the vessel is limited by the number of installed channels in the existing patch panels. Aeroacoustic measurements using several hundred channels were not considered when most pressurised wind tunnels were designed."

Important factors that must be considered include:

- Flow noise – this can be 10 to 20 dB above the noise to be measured.
- The testing hardware must be unobtrusive and must not adversely affect the acoustic or aerodynamic measurements
- Noise must be measured under the right aerodynamic conditions
- Reverberation when measuring in hard-wall wind tunnels must be considered when designing the setup within the wind tunnel
- Pressure leakage within the wind tunnel – to maintain a constant Reynolds number, air is continually pumped into the tunnel. The air pumping system is noisy and therefore tests are generally made during short periods of time when the air pressurisation system is inactive

Fig. 10
DC-10 half model installed in the NASA Ames 12 foot pressure wind tunnel - the microphone array panel can be seen in the wall on the left

Source location measurements at 80 kHz require that microphone positions relative to one another be known with an accuracy of up to 0.003 inches (0.076 mm). Coordinate-measuring machines are used to survey manufactured array panels to achieve this level of accuracy.

Individual microphone sensitivities are determined for each microphone channel prior to installation in the array panel using a calibrator such as a pistonphone.

The entire array is calibrated in-place using a calibration source that is omnidirectional over the array aperture. This process provides amplitude and phase information for the installed measurement system. This information is critical to successful noise source mapping.

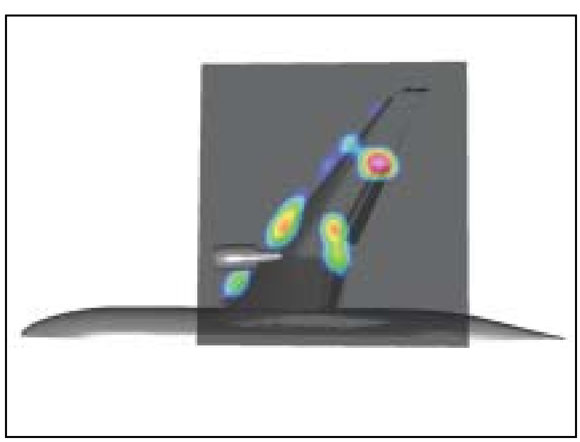


Fig. 11
Noise source map of DC-10 half model from a test in the NASA Ames 12 foot pressure wind tunnel

Jim says, "In the future, we would like to consider using prepolarized microphones. This could greatly decrease the cost per channel of an acoustic phased array measurement capability, allowing us to increase to several hundred or even a thousand channels. We would also like to increase the maximum frequency at which we can measure. This is currently limited to 88.3 kHz by the complete data acquisition system."

He adds, "The ability to measure at frequencies above 100 kHz would enable us to test our scale models at the high end of the frequency range corresponding to full-scale frequencies of interest."

Data Handling and Reporting

During a typical test, noise data is acquired for about ten seconds. This is digitised to disk in real-time and processed by a "super computer" using a cluster of computers running under the Linux operating system. Ten seconds of noise acquisition with an 88 kHz data bandwidth using an array of 200 microphones results in about 800 MB of data. This requires a huge amount of RAM and computer processing power.

The data are archived on a magnetic optical drive. It is also placed onto a networked archive file system.

Jim says, "The data can be processed in a myriad of ways. We save the raw data so we can go back and process it by various methods depending on what we learn from the first and successive processing efforts. Though we have some standardised processing techniques, sometimes we need to explore the data in new ways."

The Benefits

Jim concludes, "The work we do in the Noise Engineering Laboratory improves the decision making process. It enables us to reduce the development time on new designs and derivatives of existing aircraft types. We can develop more efficient lower cost designs and choose the configuration that gives the lowest noise level with the required aerodynamic performance."

Key Facts

- There is constantly increasing focus on the environmental effects of aircraft noise, from governments, airport authorities, airlines and the general public
- During takeoff, noise levels are dominated by engine noise, while during approach and landing, noise levels result from both the engine and the airflow over the airframe
- Boeing's relationship with Brüel & Kjær began over thirty years ago
- Since the mid 1990s, Boeing has used arrays of standard and specially designed microphones in hard-wall pressurised wind tunnels to determine the airframe noise of aircraft designs using scale models
- Boeing is one of a small number of companies around the world that are developing and using this cutting-edge technology
- It is necessary to work at very high acoustic frequencies as the frequency of the noise created using a scale model is inversely proportional to the size of the model
- Airplane certification noise regulations require data in the frequency range from 45 Hz to 11.2 kHz
- At Boeing's request, Brüel & Kjær has developed a new 1/4-inch microphone with an improved, flatter frequency response under high air pressures at high acoustic frequencies
- Many microphones are used in each array – a logarithmic spiral array using 251 microphones has been designed and used to make airframe noise measurements in a low-speed, hard-wall wind tunnel
- "The work we do in the Noise Engineering Laboratory improves the decision making process. It enables us to reduce the development time on new designs and derivatives of existing aircraft types. We can develop more efficient, lower cost designs and choose the configuration that gives the lowest noise level with the required aerodynamic performance."

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