Development of a sonic boom measurement system at JAXA

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The Japan Aerospace Exploration Agency (JAXA) is actively conducting supersonic transport research toward the realization of civil supersonic aircraft. Technology that precisely measures sonic booms is essential to demonstrating JAXA's sonic boom reduction concept in the planned drop tests of a research aircraft. This is a part of the D-SEND Program (**D**rop Test for **S**implified **E**valuation of **N**on-Symmetrically **D**istributed sonic boom). Capturing detailed multichannel sonic boom histories to validate aircraft design concepts that reduce sonic booms, is necessary for next-generation supersonic transport. The first step was the development of a ground based real-time monitoring and data-logging system that measures sonic booms indoors and outdoors as well as the resulting vibration of the windows and walls of the test buildings at the Northern European Aerospace Test range in Sweden. The ground-based measurement system is being expanded to include an aerial measurement system distributed at altitudes up to 1,000 m to reduce the effects of atmospheric turbulence. This system will be based on stand-alone computers controlled via wireless LAN distributed aloft for making high-accuracy audio frequency measurements. The objective is to accelerate the development of civil supersonic aircraft by demonstrating the low-boom design technology in planned drop tests.

1 Introduction

Quiet supersonic flight over land appears increasingly viable, both technologically and economically, based on significant advancements in aircraft shape. JAXA has proposed some "low-boom" concepts that can reduce the sonic boom by half compared to the Concorde airliner. Efforts have been initiated to revise the rules prohibiting overland supersonic flight. To gain approval for overland flight operations, certification standards and criteria for acceptable supersonic overland flight need to be developed. Technology that can accurately measure sonic booms is a key to getting these rules revised.

The JAXA D-SEND Project Team was established with the purpose of conducting flight demonstrations of "low sonic boom design technology" which is considered a high priority issue for R&D on silent supersonic technology carried out by the JAXA Aviation Program Group's Supersonic Transport Team.

This project, called "D-SEND (Drop test for Simplified Evaluation of Non-symmetrically Distributed sonic boom)," consists of developing the tools necessary for the flight demonstration (such as test pieces to be dropped and the aerial boom measurement system) as well as performing the drop test.

JAXA's goal is to demonstrate through flight tests the feasibility of its "low sonic boom design concept" as a global leader in the R&D of this environmentally responsible technology. JAXA also aims to establish an aerial boom measurement method that could contribute to the deliberation of international standards for sonic booms for next generation supersonic transport currently under examination.

2 Measuring Sonic Booms

JAXA needed a flexible, expandable instrumentation system to handle a variety of microphones and accelerometers with different setups for different channels. Reliability was very important because flight tests are costly, last up to one hour, require multiple simultaneously sampling channels, and need real-time monitoring and data review. The system also needed to be convenient to use. Post-recording data extraction and analysis were important because only a portion of the data recorded is useful and they needed to time stamp and align data obtained with different systems at different locations.

2.1 Acoustic properties of sonic booms

A sonic boom is the change in air pressure observed when the shock wave produced by the sharp compression of air around an aircraft flying at a supersonic speed (speed faster than the propagation speed of sound) propagates and reaches the ground. This pressure change vibrates a person's eardrum and is perceived as an explosive type sound.

Sonic booms cover a wide frequency range with overall infrasonic components of less than 1 Hz and rapid pressure rises greater than 10 kHz. They also offer a wide dynamic range of over 200 Pa (140 dB SPL) and a small pressure fluctuation in "post-boom noise" of less than 0.1 Pa (74 dB SPL). Impulsive noise is caused by initial and final abrupt pressure rises.

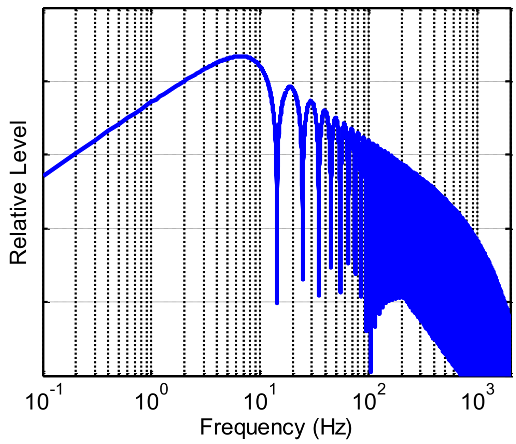

Figure 1: Acoustic content of a sonic boom.

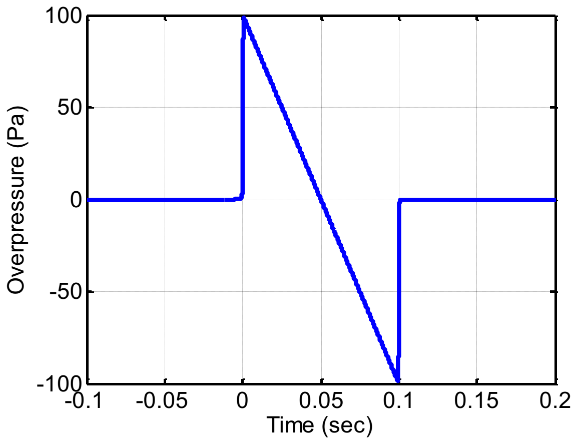

Figure 2: Sonic boom signature.

2.2 Validating measurement system

JAXA validated their system by measuring actual sonic booms from supersonic aircraft at the Northern European Aerospace Test range in Sweden in September 2009. The objectives were to verify the measurement system and identify appropriate transducers and setups during five flyovers and three flight conditions. Sonic booms were measured indoors and outdoors along with vibration along doors and walls in a building at the site. Measurements were also made from a weather balloon suspended at 1000 m.

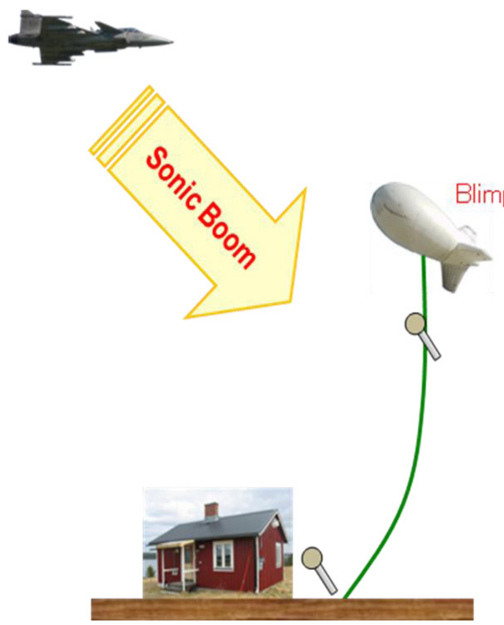

Figure 3: Test site measurements.

2.3 Indoor measurement system

JAXA chose an NI PXI system with a variety of modules to meet their requirements. the NI PXI-4472B dynamic signal acquisition (DSA) module was used to acquire vibro-acoustic data from the microphones and accelerometers due to its high resolution and wide dynamic range, low cut-off frequency (0.5 Hz for AC coupling) for recording infrasound, and software-configurable AC/DC coupling and integrated electronic piezoelectric (IEPE) conditioning. The NI PXI-6682 timing and synchronization module provided synchronization via GPS. An NI 8353 controller provides high-speed data streaming via a RAID 0 as well as the high capacity needed for recording 16 channels for up to one hour.

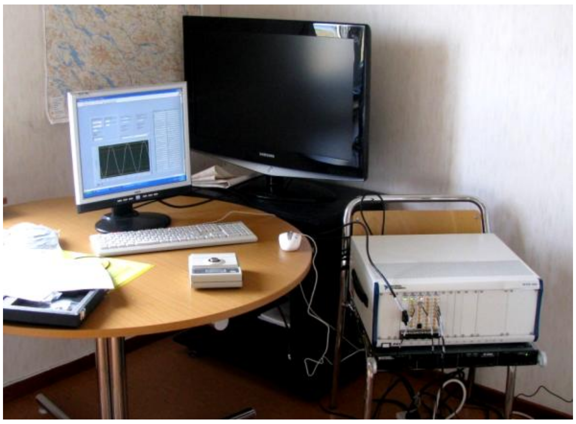

Figure 4: Instrumentation system used for indoor measurements.

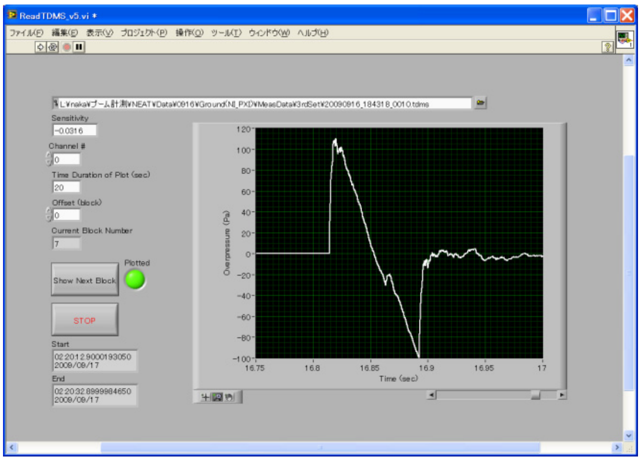

Figure 5: Instrumentation graphical user interface of outdoor recorded sonic boom.

For the tests, the aircraft flew at a maximum altitude of 14 km (approximately 46,000 ft) and a minimum of 6 km (approximately 20,000 ft). The overpressure of the sonic boom heard inside the test building was about one-fourth of that heard outside. Recent research shows that the sonic boom from current aircraft heard inside a building can cause significant annoyance because of the rattling noise and building vibration.

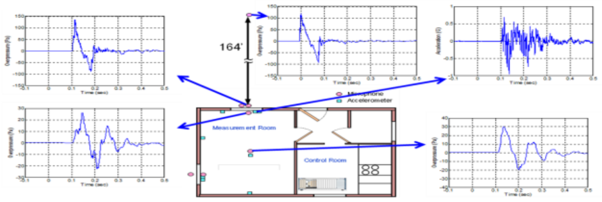

Figure 6: Indoor measurements.

With over-land supersonic flight, the sonic boom will also be heard indoors. The sound of a sonic boom inside a building should be lower than outside. Looking at the results of the sonic boom measurement test performed by JAXA in 2009, the acoustic pressure is significantly reduced indoors as compared to outdoors. Also, the waveform observed indoors has no rapid acoustic pressure increase as seen in the outdoor N-wave, and has a gentle slope. Secondary noises, such as the rattling of windows induced by vibration of the building's walls and windows due to the abrupt acoustic pressure increase and low-frequency component of sonic booms, affect human perception of the noise. The psychological effects caused by a sonic boom can be larger indoors. It is believed that, as metrics to be used in international standards for sonic boom noise, it is necessary to investigate how to also assess these indoor effects. JAXA has developed a sonic boom simulator and is performing assessment testing on trial subjects using files recording with their measurement system.

2.4 Outdoor measurement system

A blimp or weather balloon equipped with infrasonic microphones was held at an altitude of 1 km in order to avoid the influence of the turbulence near the ground, and some other infrasonic microphones are also installed at several points between the blimp and the ground to measure the effect of the turbulence to the sonic boom signature.

A lightweight system was used for the aerial measurements, which were distributed at altitudes up to 1,000 m by using the tethered blimp to avoid the effects of atmospheric turbulence. This system is based on stand-alone computers controlled via wireless LAN distributed aloft with an NI-9234 dynamic signal acquisition 4-channel module for making high-accuracy audio frequency measurements.

Figure 7: Outdoor measurement systems.

2.5 Infrasonic microphones

Modern measurement microphones based on condenser design have vent holes to equalize atmospheric pressure changes. This acts like a high pass filter that cuts off below 3 – 5 Hz. The lower limiting frequency of a condenser microphone is acoustically controlled by the internal volume of the microphone and air equalization vent which ensures that small atmospheric variations are equalized while fast sound pressure variations are not equalized because we want to measure them. A good measurement microphone should equalize as fast as possible in order to cut off unwanted pressure variations which surround us in many ways. Wind turbulence - door slam - floor movements etc. The normal cut off for many high quality measurement microphones is 3 - 5 Hz. For infrasound it should be 0.1 - 0.5 Hz.

Pre-polarized microphones offer significant advantages over polarized in cost, weight and power consumption making them useful for portable field measurements as used here. The low frequency response of a microphone system is given by the electrical cut-off of the preamplifier and the acoustical cut-off of the microphone capsule. These newer microphones have stiffer diaphragms which lower the mechanical cut off

A GRAS ½″ Free-field Microphone System, Infrasound Type 40AZ-S1 is supplied with a special adaptor which has the effect of reducing the lower cut-off frequency of the preamplifier and was used in these tests. It also has the effect of reducing the microphone's sensitivity and increasing the thermal noise. For the microphone capsule capacity of the GRAS Type 40AZ (20 pF), the high input impedance of Type 26CG (40 GΩ) leads to a low-frequency 3-dB limit f L = 0.2 Hz. This was used with this instrumentation system.

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Figure 8: Infrasonic microphone used.

3 Drop Test Measurements

The D-SEND project is composed of D-SEND #1 and D-SEND #2 drop tests. In the D-SEND #1 drop test, two different axisymmetric bodies were dropped and the sonic booms were measured and compared with each other. In the D-SEND #2 drop test, an experimental supersonic airplane model (unmanned aircraft with no engine and capable of autonomous flight) based on JAXA's proprietary low sonic boom design technology will be dropped and the sonic boom measured. This is planned in the summer of 2013. The sonic booms are measured and recorded by the microphone system that is tied to a line between the ground and the blimp (altitude=1km).

3.1 D-SEND #1 Test

In D-SEND #1, two test bodies were dropped consecutively at a 20 second intervals from an altitude of 30 km. The test bodies were the NWM (N-Wave Model), which generates the pressure signature of an N wave, and the LBM (Low-Boom Model), which generates the pressure signature of a low-boom wave.

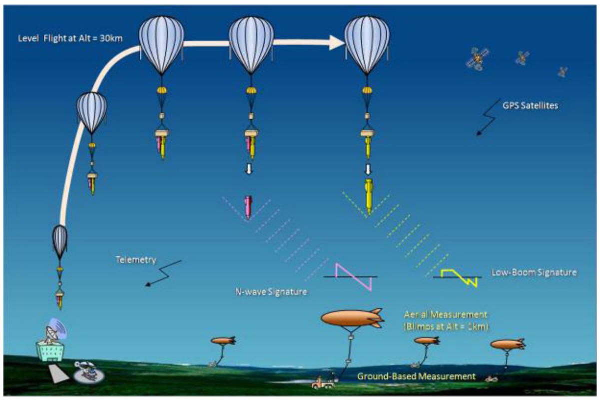

Figure 9: Diagram of drop test #1

Both bodies trace almost the same Mach number history and generate sonic booms forward and perpendicular to the Mach cone angle. The sonic booms are measured by a boom measurement system (BMS) 1 km from the ground. Information such as velocity (speed) and position data of the drop test models are transmitted to the ground by the telemetry system.

Figure 10: N-WAVE and Low-Boom Models being prepared for drop.

Through this test, JAXA demonstrated its low sonic boom axisymmetric design concept technology which reduced the sonic boom by half.

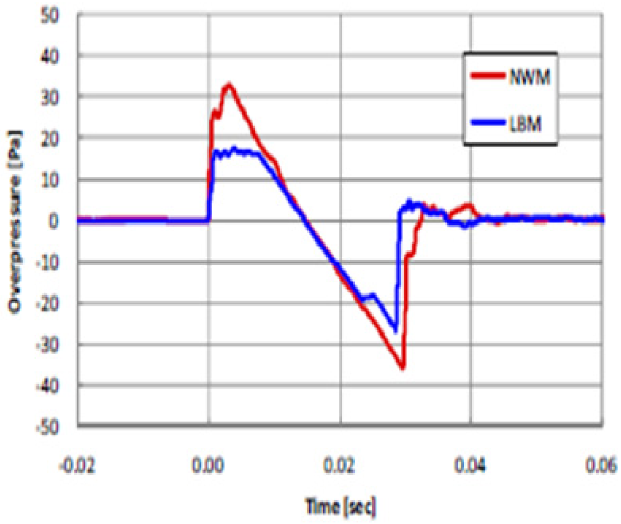

Figure 11: Contrasting sonic boom signatures recorded with NWM and LBM test bodies.

The data obtained from the test is valuable as a reference for the validation of the sonic boom propagation analysis method and is expected to contribute to low-sonic boom studies in the future. JAXA has also established for the first time a new method of demonstrating the low sonic boom design concept in the form of a balloon drop test.

3.2 D-SEND #2

For D-SEND #2, an experimental supersonic airplane (S3CM : S-cube Concept Model) will be used designed using JAXA's proprietary low-boom design technology. The airplane has a shaped boom signature at the front and end of the fuselage.

Figure 12: Experimental supersonic airplane model (unmanned aircraft with no engine and capable of autonomous flight) to be used in D-SEND#2.

The airplane will be dropped from an altitude of 30 km and glides over one of four boom measurement systems at Mach 1.3 and a flight-path angle of 50 degrees. At this flight-path angle, the shaped boom signature generated by the airplane will be projected vertically toward the sonic boom system. The goal is to establish values for low sonic boom design technology and to establish the low-boom wave acquisition technology developed so far.

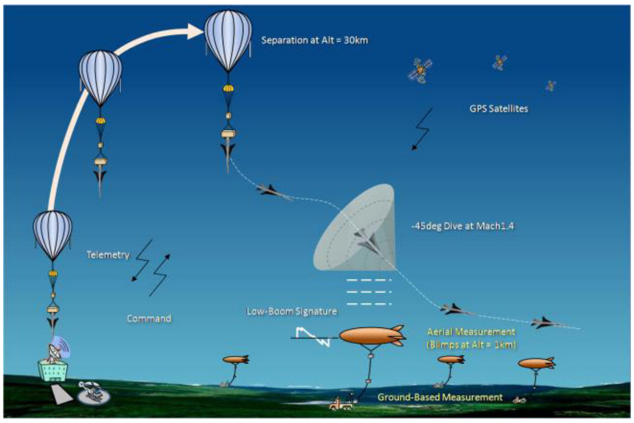

Figure 13: Diagram of D-SEND #2 test planned for 2013.

4 Conclusion

The tests by JAXA in Sweden validated that the measurement system can measure sonic booms and works well with a variety of microphones optimized for infrasound measurements. The ground-based measurement system has been expanded to include an aerial measurement system distributed at altitudes up to 1,000 m to reduce the effects of atmospheric turbulence. JAXA hopes to accelerate the development of civil supersonic aircraft by demonstrating the low-boom design technology in the next planned drop test.

Acknowledgments

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