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Contents

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ABSTRACT

For validating "low-boom" supersonic aircraft design concepts and techniques in flight tests, sonic booms must be measured accurately. This paper discusses the systems and methods for accurate sonic boom measurement both on and above the ground. Requirements and issues for sonic boom measurement systems are considered and possible solutions are shown with the measurement systems and methods the authors have developed as examples. For the aerial measurement, the system and method for recording sonic booms at multiple altitudes up to about 1000 m above the ground by using a tethered blimp have been developed. The sonic boom data measured in the recent flight tests demonstrated the validity of the systems and methods for aerial and ground-based sonic boom measurement.

Keywords: supersonic flight, sonic boom, aerial measurement, ground-based measurement

Nomenclature

Symbol	Unit	Description
p_{ideal}	Pa	acoustic pressure of sonic boom
p_{hp}	Pa	acoustic pressure of sonic boom with a high-pass filter applied
p_{lp}	Pa	acoustic pressure of sonic boom with a low-pass filter applied
Δp	psf	shock amplitude
psf		pound-force per square foot. 1 psf ≒ 47.88 Pa.
τ	s	shock rise time
t_c	s-psf	time constant parameter

1. INTRODUCTION

Sonic boom mitigation is one of the most important and challenging issues in the research and development of the next-generation supersonic transport, and the "low-boom" aircraft design concepts and techniques have been actively researched in these days. Based on the theoretical and numerical investigation and on the wind tunnel test results, it is believed that such low-boom technologies can reduce sonic booms to the levels acceptable to the public. For further validation of the low-boom technologies, measurement is valuable especially for validation of the shaping

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of sonic boom waveforms after propagating a long distance in the actual atmosphere having non-uniform meteorological conditions along the propagation path.

This paper discusses the systems and methods for accurate sonic boom measurement. Consideration taken while developing an aerial and ground-based sonic boom measurement system, and the data recorded in the recent flight tests with the system are referred as necessary. The developed system is called Boom Measurement System (BMS). BMS has been used in the flight tests including ABBA Tests[1-3], a series of tests whose main purpose was to check the prototype measurement systems, and the D-SEND#1 Test[4, 5], the first phase of the D-SEND Project whose main objective is to validate JAXA's unique low-boom aircraft design concept.

A fair number of sonic boom measurements have been conducted thus far (Refs. 6-14, for example), and the levels of measurement accuracy in these tests seem sufficient. However, to the best of the authors knowledge, specifications and configurations of the systems and detailed measurement methods have not been discussed in a comprehensive manner. This paper revisits these topics.

In addition to the ground-based measurement, the aerial measurement is discussed in this paper. Aerial measurement is important for validating the low-boom technologies by comparing the measured data to the predicted ones. The key of the low-boom technology is shaping the sonic boom waveforms observed on the ground. However, the sonic boom waveforms on and near the ground are generally distorted by atmospheric turbulence in the planetary boundary layer, which is typically below the altitude of 1 to 2 km, as schematically depicted in Fig. 1-1. Therefore, to validate the low-boom design concepts and techniques, capturing the "clean" sonic boom signatures before distorted by turbulence is essential. Most of the measurements in the past were, however, performed on and very close to the ground surface. Only a limited number of aerial measurements have been made so far[11-14], and it seems there is room for improvement on the aerial measurement system and technologies. For example, aerial measurement at multiple altitudes is useful for investigating sonic boom waveform distortion, but has not been accomplished. The matters and solutions of aerial measurement are discussed in this paper with the case of BMS as an example.

2. SYSTEM SPECIFICATIONS

A sonic boom measurement system must meet several specification requirements. These requirements are derived mainly from two aspects: accuracy for acoustic measurement and operation in the field tests. The requirements for accurate acoustic measurement are common in many sonic

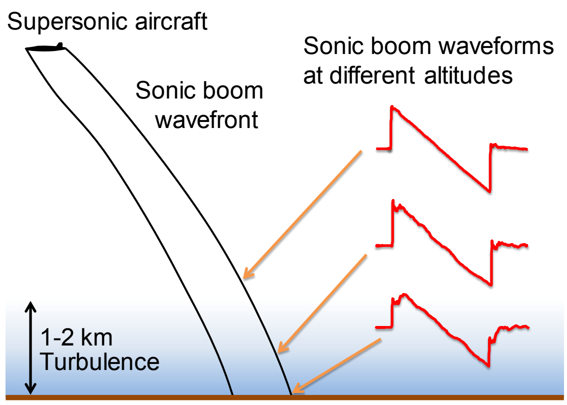


Fig. 1-1 Distortion of sonic boom signature due to atmospheric turbulence.

boom measurements. In contrast, the requirements originated from operational points of view vary depending on the nature and procedure of the tests. In the following subsections, the requirements from these two aspects are reviewed.

2.1. Accuracy for Acoustic Measurement

For recording sonic boom signatures with a sufficient level of accuracy, higher specifications than usual noise measurements are required, as sonic booms have some unique acoustic characteristics. As the most critical specification, the frequency response of the system is discussed below. Although the precise requirements depend on the sonic boom waveforms to be measured, the concept and criteria for determining the specifications can be applied to most of the cases.

2.1.1. Low-Frequency Limit

The low-frequency response is one of the most important specifications of a sonic boom measurement system, since most acoustic energy in the entire signature of a sonic boom is distributed in the infrasonic region[15]. Therefore, the measurement system is required to have a flat frequency response down to this range. In general, sonic booms with a longer duration have spectral peak at a lower frequency, and the duration of the sonic boom signature grows with the length of the supersonic aircraft or projectile. Therefore, a lower cutoff frequency is required to measure a sonic boom created by a larger supersonic aircraft or projectile.

The low-frequency response requirements are discussed below for two example sonic boom signatures with 0.1 s of duration. This is a typical duration of a sonic boom created by a military fighter aircraft, and the longest duration assumed to be measured in the ABBA and D-SEND tests.

The first example is an N-wave. The effects of the low-frequency response characteristics of a measurement system can be evaluated by applying high-pass filters to the sonic boom waveforms. The waveforms before and after applying the high-pass filters with different cutoff frequencies are shown in Fig. 2-1. The signature deforms more with the cutoff frequency. The level of deformation can be estimated, for example, by

$$err = \max|p_{hp} - p_{ideal}|/\max|p_{ideal}| \qquad (1)$$

where p_{ideal} is the acoustic pressure of the original, non-distorted waveform and p_{hp} is that of the high-pass filtered waveform. The error defined by Eq. (1) is plotted in Fig. 2-2 as a function of the cutoff frequency. From such a plot, the low-frequency response requirement can be determined for an arbitrary level of accuracy. For example, if the error needs to be smaller than 5 %, the cutoff frequency of the measurement system must be lower than 0.34 Hz in this example case.

The second example is a flat-top signature, which is one of the typical "low-boom" waveforms. A flat-

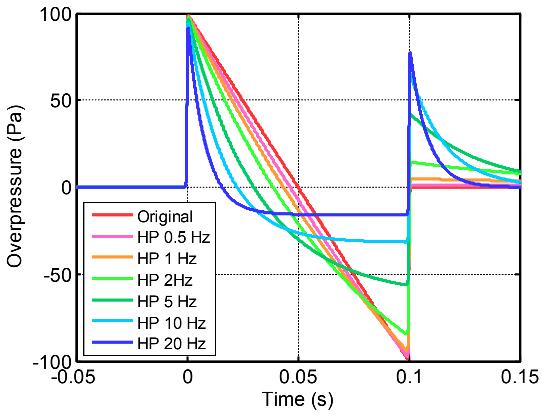


Fig. 2-1 N-wave signatures with high-pass filters with different cutoff frequencies.

top signature is a good practice for investigating the effects of the low-frequency response, since it has more energy at lower frequency region than an N-wave. The acoustic energy in the flat portion of the waveforms is concentrated at 0 Hz. With the same procedure applied to the previous example, the relationship between the cutoff frequency and deformation can be found. The deformed signatures and errors are plotted in Fig. 2-3 and Fig. 2-4, respectively. If it is assumed that the desired level of error estimated by Eq. (1) is smaller than 5 %, then Fig. 2-4 indicates that the cutoff frequency needs to be 0.2 Hz or lower for the flat-top waveform considered here. The waveforms before and after applying the high-pass filter with 0.2 Hz of cutoff frequency is shown in Fig. 2-5. The two waveforms are quite similar, supporting that the choice of the cutoff frequency criterion is reasonable.

The level of error depends on the detailed sonic boom signatures as demonstrated in the examples above. Among various shapes of signatures, a flat-top signature is one of the examples for which the low-frequency response of the system is extremely influential. Therefore, 0.2 Hz or a similar value could be a reference for the low-frequency requirement for measuring sonic booms having 0.1 s of duration. For measuring sonic booms with longer duration, a lower cutoff frequency might be necessary, especially for the low-boom signatures.

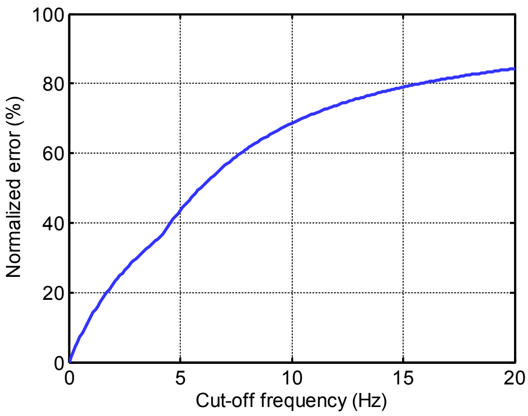


Fig. 2-2 Error of N-wave signatures due to low-frequency characteristics of measurement system.

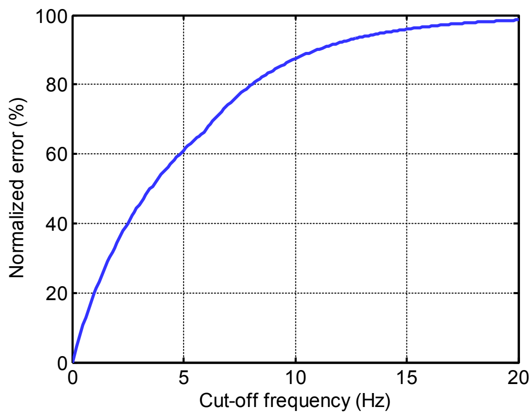


Fig. 2-4 Error of flat-top signatures due to low-frequency characteristics of measurement system.

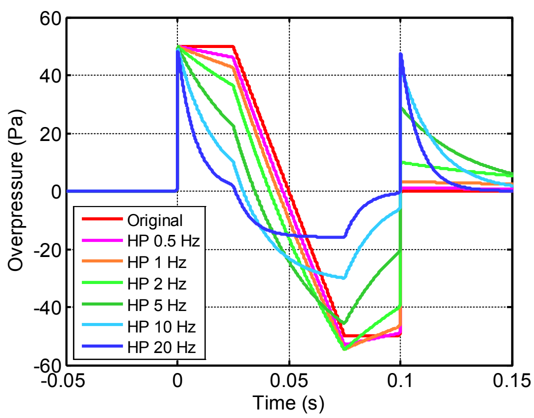


Fig. 2-3 Flat-top signatures with high-pass filters with different cutoff frequencies.

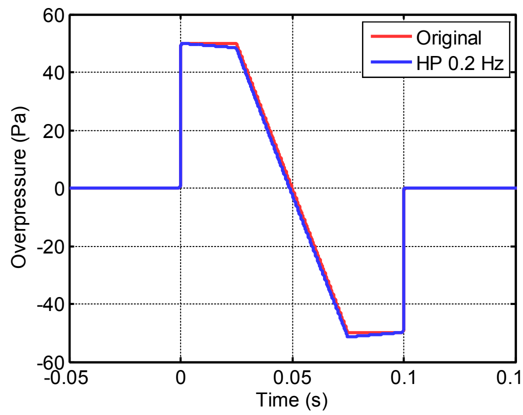


Fig. 2-5 Flat-top signatures with and without applying a high-pass filter with cutoff frequency of 0.2 Hz.

Even in such a case, a similar procedure to one taken above can be applied to estimate the precise requirement.

2.1.2. High-Frequency Limit

The high-frequency response is also important for accurate sonic boom recording since it affects the capability of capturing the detailed shock structures in sonic boom waveforms. The effects of the high-frequency response can be considered by applying low-pass filters with different cutoff frequencies. In order to estimate the requirement for the high-frequency limit, an N-wave with short rise time is examined below.

Although sonic booms are originated from shocks with discontinuous pressure jumps, sonic booms observed on or near the ground have continuous pressure profiles with finite (i.e. larger than zero) rise time. Sonic boom signatures considered here also should have a finite rise time as with actual sonic booms. From the pressure jump of a shock, the continuous pressure structure in an N-wave sonic boom signature can be approximated by

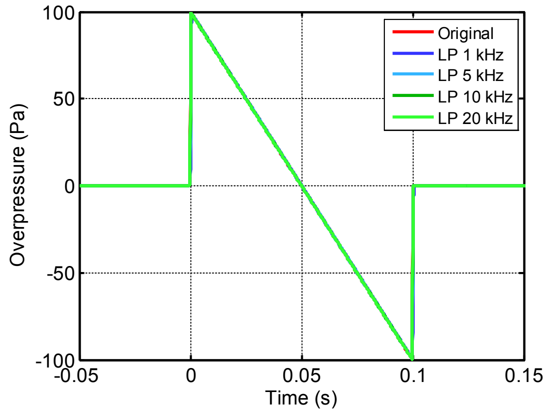
$$p(t) = \frac{\Delta p}{2}\left[1 + \tanh\left(\frac{2}{\tau}t\right)\right] \qquad (2)$$

where p [psf] is the acoustic pressure, Δp [psf] is the shock amplitude, τ [s] is the rise time, and t [s] is time[16]. The pressure unit psf is pound-force per square foot, and 1 psf is about 47.88 Pa. The rise time is inversely related to the shock amplitude as

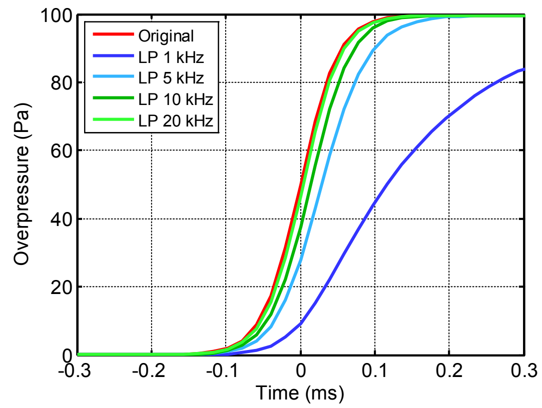
$$\tau \text{ [s]} = \frac{t_c \text{ [s-psf]}}{\Delta p \text{ [psf]}}$$

Although the time constant t_c is usually set at 0.001 s-psf[17], it is set at 0.0002 s-psf here to consider an extreme case. In this case, the resulting rise time is about 0.1 ms for 2 psf shock amplitude. The shock amplitude of 2 psf is typical for sonic booms created by the Concorde. Sonic booms created by aircraft smaller than the Concorde or aircraft with the low-boom design applied have smaller shock amplitudes, and hence longer rise times. Thus, the rise time of 0.1 ms considered here is close to the shortest limit encountered in usual sonic boom measurements including ABBA Tests and D-SEND.

For this N-wave, low-pass filters with different cutoff frequencies are applied. The resulting waveforms are plotted in Fig. 2-6. The overall signatures do not change significantly (Fig. 2-6 (a)), while the shock rise time is affected by the



(a) Overview



(b) Zoomed view of front shock

Fig. 2-6 N-wave signatures with low-pass filters with different cutoff frequencies.

higher cutoff frequency (Fig. 2-6 (b)). The error due to the imperfect high-frequency response is estimated by Eq. (1) with interchanging p_{hp} by p_{lp}, the pressure after low-pass filters. The result is plotted in Fig. 2-7. For this specific waveform, the error is less than 5 % for the cutoff frequencies higher than 18 kHz.

The frequency components between 1 and 4 kHz, which are contained in the shock parts, are considered to be influential to human response to sonic booms, as the human auditory system is sensitive in this frequency region. The A-weighted sound exposure level (ASEL), which is highly correlated with the loudness of sonic booms[18], is calculated for the low-pass filtered N-waves, and plotted in Fig. 2-8. The red broken line in this figure indicates the ASEL of the original signature without low-pass filtering. The change in ASEL due to the low-pass filters are 0.2 dB for the cutoff frequency of 5 kHz, and smaller than 0.01 dB for 18 kHz. Therefore, no significant deterioration in terms of both waveform and human perception will occur if the cutoff frequency is higher than 18 kHz.

Based on the considerations above, 18 kHz could be a reference criterion for the higher limit of the frequency range of a measurement system. On the other hand, the higher end of the human auditory system is about 20 kHz, and hence many microphones and acoustic measurement devices have such limit. Thus, it is probably practical to choose measurement devices having the higher limit of 20 kHz or higher. For high-frequency limit of 20 kHz, the signal is discretized with the sampling rate of 40 kHz or higher, or the sampling interval of 0.025 ms or shorter. Therefore, even for a shock with 0.1-ms thickness, four or more sampling points can be captured inside the shock thickness. With this number of samples, the structure of the shock can be reasonably represented.

2.2. Operation in Field Tests

As operational requirements in field tests, operation time duration and system weight are discussed below. These were two main factors considered when developing BMS. Not only for the ABBA and D-SEND tests, operation time must be considered also for most field tests. On the other hand, the weight constraint is more specific to the aerial measurement with a blimp system, which was used in the ABBA and D-SEND tests.

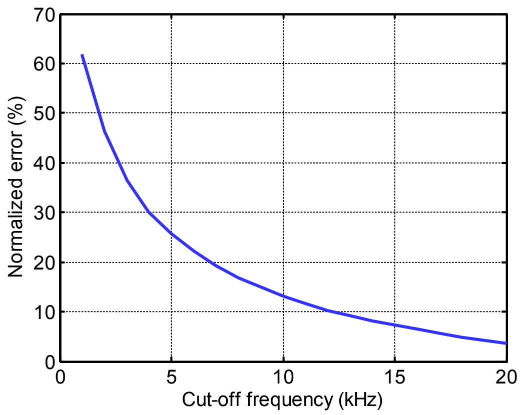


Fig. 2-7 Error of N-wave signatures due to high-frequency characteristics of measurement system.

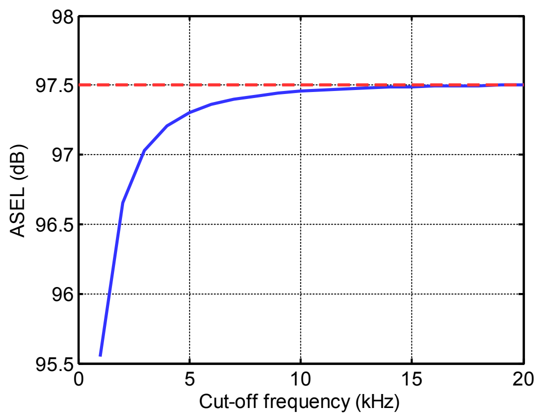


Fig. 2-8 Change of ASEL as function of higher cutoff frequency.

2.2.1. Operation Time Duration

The operation time must cover the installation and measurement phases. The specific time duration required in each of these phases depends on the time schedule and procedure of the measurement test.

In the aerial measurement with BMS, the installation phase requires a relatively long duration, since the blimp needs to be raised up slowly to avoid burst due to quick pressure change. It takes about 2 hours for the blimp to reach 1000 m of altitude. In the case of D-SEND#1, the duration of the measurement phase was also fairly long. For a safety reason, no operator was allowed to stay at the measurement sites during the measurement in D-SEND#1, in which the test bodies freefell supersonically from a stratospheric balloon. Therefore, the measurement phase needed to include the time for the test bodies to arrive the right location for drop from the stratospheric balloon, after the operators had evacuated from the measurement sites. The final requirement of the operation time (the total of the installation and measurement phases) for D-SEND#1 was 10 hours. This could be one of the longest durations required for a sonic boom measurement test.

2.2.2. System Weight

The main restriction for the blimp-based, multi-altitude aerial measurement as with BMS is the weight. The weight limit is mainly determined by the effective buoyancy of the blimp (the difference between the buoyant force and the gravity force of the blimp and tether). The major specifications of the blimp used in BMS are summarized in Table 2-1. In order to keep the blimp at 1000 m above the ground even under a moderate wind condition of 15 m/s, the total weight of the measurement devices needed to be lighter than 25 kg. This weight requirement needed to be met after incorporating all of the devices, not only the devices for recording acoustic data, but also ones for recording three-dimensional positions of microphones, the time code, and atmospheric conditions such as temperature and humidity. The weight of batteries also needed to be included. On the other hand, the weight of the tether was excluded from the requirement.

Table 2-1 Specifications of blimp used in BMS

Manufacturer	Aerostar
Type	TIF-6500
Length	15 m
Max. diameter	5 m
Volume	130 m^3

3. ACOUSTIC MEASUREMENT DEVICES

While an acoustic measurement system can consist of different combinations of devices, a system with microphones and an analog-to-digital converter (ADC) is considered in this paper. Such a system was used in BMS. The output signal from a microphone is converted into a digital format by an ADC and stored electronically. The specifications of the microphones and ADC's required for sonic boom measurement are discussed in this section.

3.1. Microphones

Basic process of selecting microphones for sonic boom measurement is the same as general acoustic measurement. The microphones must meet the requirements for the frequency and pressure ranges. However, care must be taken in selecting microphones since the required low-

Table 3-1 Low-frequency microphone units

Manufac.	Type	Low-freq.	High-freq.	Max. Level	Polarization
Brüel & Kjær	4193-C-004*	0.1 Hz	20 kHz	151 dB	200 V (Externally polarized)
GRAS	40AN-S1	0.09 Hz	20 kHz	150 dB	200 V (Externally polarized)
GRAS	40AZ-S1	0.09 Hz	20 kHz	150 dB	0 V (Prepolarized)

* Two different types with different preamplifier connector types but with same specs. exist.

frequency cutoff is much lower than usual noise measurements. There are currently several types of commercially available condenser microphone units that can measure acoustic signals down to about 0.1 Hz. In these microphone units, low-frequency adaptors are used to increase the effective input capacitance of the preamplifier to attain lower cutoff. It should be noticed that the low-frequency adaptor reduces the sensitivity at the same time. In some cases, therefore, gain control may be necessary to achieve the desired level of signal to noise ratio or resolution.

The low-frequency microphone units the authors have surveyed are listed in Table 3-1. All of these microphone units have the frequency range between 0.1 Hz and 20 kHz or wider, satisfying the requirement described in Sec. 2.1. As for the pressure range, these microphone units have the upper limit of the pressure of 150 dB SPL or higher, corresponding to more than 600 Pa. This upper limit seems sufficient for general sonic boom measurements, since the typical maximum overpressure of a sonic boom created by the Concorde was about 100 Pa. The upper limit of 600 Pa was also suitable for D-SEND#1 and ABBA Tests, in which the maximum overpressure was assumed to be about 300 Pa. However, it should be noted that the required specifications need to be satisfied not only by each device but as a whole system, including a microphone, a power supply (if necessary), and an ADC. For instance, even though a microphone unit meets the requirement, inadequate choice of an power supply module could deteriorate the accuracy as a whole system.

Among the microphones satisfying the required specifications, one criterion for selecting a specific type is the polarization method. Condenser microphones can be divided into two types with respect to the polarization methods: externally polarized and prepolarized (IEPE type). Some of the low-frequency microphone units are of the former type, and the others are of the latter. Thus, one can choose the desired type depending on the specific applications or requirements for the measurement. In the case of BMS, prepolarized microphones were chosen mainly because they were suitable for reducing the total weight of the measurement system as described in detail in Sec. 4.1.

3.2. Analog-to-Digital Converter

The frequency and pressure ranges are major criteria also for selecting an ADC, as with general acoustic measurement.

The higher end of the frequency range can be simply judged by the product specifications of each ADC. Currently, many ADC's have upper limit of 20 kHz or higher, suitable for sonic boom measurement.

In terms of the low-frequency response, a DC-coupled ADC is ideal, as it has a flat response down to 0 Hz. However, DC-coupling is not necessarily compatible with some types of microphones. For example, some DC-coupled ADC's cannot be directly connected to prepolarized microphones, since the IEPE power supplying function cannot be used. Another example is a case when the microphone preamplifier whose output signal is DC-biased is directly connected to a DC-coupled ADC. In this case, the DC-offset remains in the digitized data, resulting in possible over range or deterioration of the resolution.

An AC-coupled ADC has the opposite advantages and disadvantages. It can be used with most, if not all, types of microphones, but the low-frequency response is not perfect since AC-coupling acts as a high-pass filter. This drawback may be critical for sonic boom measurement system since many ADC's with AC-coupling have the low-frequency cutoff that is not suitable for sonic boom measurement. A possible solution for this issue is discussed in Sec. 3.3. In BMS, an AC-coupled ADC was selected in order to provide the IEPE power to the prepolarized microphones.

Methods of analog-to-digital conversion were also considered when developing BMS. While many conventional ADC's use successive approximation register (SAR), currently more commercially available ADC's use delta-sigma modulation. Between these two methods, delta-sigma modulation seems preferable for sonic boom measurement. The resolution of a SAR ADC is limited to 16 bit, while that of a delta-sigma ADC can be as high as 24 bit. Higher resolution is desirable for sonic boom measurement, especially for capturing the post-boom noise, whose level is much lower than the peak pressure of the sonic boom[19]. Lower noise level of a delta-sigma ADC is also attractive. Thus, a delta-sigma ADC with 24-bit resolution was chosen for BMS.

In summary, 24-bit, delta-sigma ADC's with 20 kHz or higher high-frequency cutoff are desired for sonic boom measurement. Also, the low-frequency response, including the choice of coupling method, needs to be carefully determined. This can be related to the polarization method of the microphone.

3.3. Response Compensation

Although the measurable range of frequency is limited for each measurement device, the frequency characteristics of a device can be improved to a certain degree by compensating the response. For example, some commercial products compensate the frequency response of a transducer in real time of recording to attain a wider range of frequency.

In BMS, the low-frequency response of the ADC was compensated in real time by applying a digital filter having the amplitude characteristics shown by the green line in Fig. 3-1. When this filter is

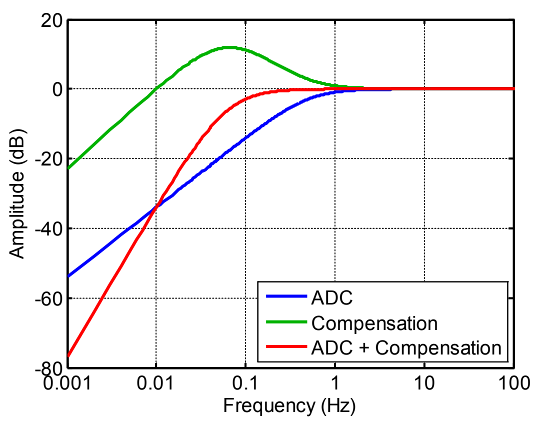


Fig. 3-1 Frequency characteristics of compensation filter

used with the ADC, which has the low-frequency response shown by the blue line in the same figure, the resulting response becomes the red curve. This is the summation of the green and blue lines. By this compensation procedure, the lower cutoff frequency was improved from 0.5 Hz to 0.1 Hz.

4. MEASUREMENT METHODS

4.1. Aerial Measurement

4.1.1. System Overview

As already mentioned, aerial sonic boom measurement is useful for evaluating sonic boom signatures before distorted by atmospheric turbulence in the planetary boundary layer. In this subsection, issues and solutions for aerial sonic boom measurement are discussed. Large part of the consideration here are taken during the development of the aerial sonic boom measurement system in BMS and through the measurements in the D-SEND#1 and ABBA Tests by using the system.

In the aerial measurements performed in the past, a tethered blimp or a sailplane was used to setup a microphone above the ground[11-14]. While both methods have strong and weak points, a system using a tethered blimp was chosen for BMS. The major advantages of using a blimp over a sailplane are: (1) Microphone positions are almost fixed to certain spatial positions during the flight test. (2) More than one microphones can be installed on the tether at multiple altitudes to form a nearly vertically distributed microphone array. To the best of the authors knowledge, only one microphone was installed to the body of the blimp in the past tests[11, 12]. In order to take advantage of the second point to investigate the deformation of sonic boom waveforms in the planetary boundary layer, a system and methods for aerial measurement at multiple altitudes by using a tethered blimp as schematically depicted in Fig. 4-1 have been developed as a part of BMS and used in the D-SEND#1 and ABBA Tests.

As already mentioned in Sec. 2.2.2, weight reduction is one of the most important requirements for developing an aerial measurement system using a blimp. One effective approach for reducing the weight is omitting the cables connecting the ground and aerial devices. Weight saving by not using wires is significant, especially when one wants to raise the microphones at high altitudes. In BMS, the standalone recording systems were installed to the tether and controlled remotely from the ground via a wireless LAN network as shown in Fig. 4-1. The measured data were stored locally on a laptop PC in each of the standalone systems. The operations for start and stop of recording and monitoring of the system status and data for all of the standalone systems were controlled from

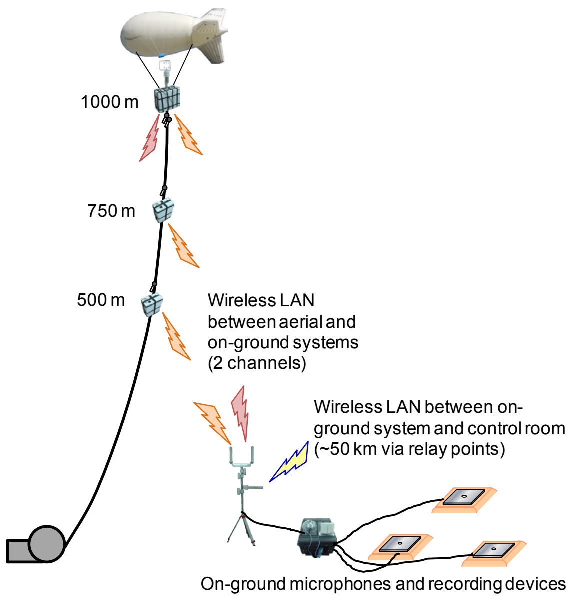


Fig. 4-1 Overview of aerial sonic boom measurement system developed at JAXA.

the ground. In addition, with an adequate network infrastructure, the system can be controlled from anywhere regardless of the physical distance from the measurement sites. In D-SEND#1, the systems were controlled and monitored from the control room located several tens of kilometers away from the measurement sites.

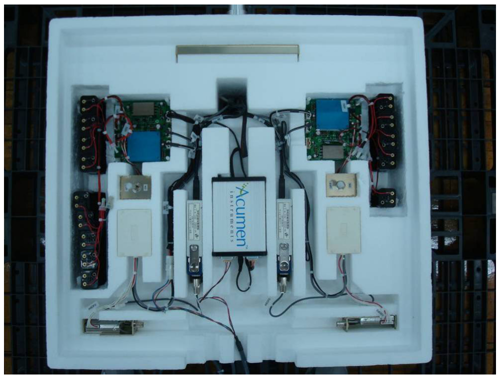
The light weight requirement can be pursued also when selecting the acoustic measurement devices. In BMS, an ADC having an IEPE power supply function was adopted. With such an ADC, no external microphone power supply was needed. The final acoustic measurement system in BMS consisted of GRAS 40AZ-S1 low-frequency prepolarized microphones and National Instruments NI 9234 24-bit, delta-sigma ADC with IEPE power supply.

Another technique for achieving the light weight requirement was to use primary lithium batteries. High energy density of a lithium battery helped reducing the weight of batteries. This was especially beneficial for BMS, because a long operation time was required as stated in Sec. 2.2.1.

The total weight of the final aerial measurement system was about 21 kg, lighter than the required weight of 25 kg. This included four standalone recording systems and an atmospheric measurement system, which was installed right beneath the blimp. Under calmer wind conditions, more standalone systems (i.e. more microphones) can be installed to the tether of the blimp, because the effective buoyancy of the blimp increases under such conditions. In fact, five microphones were installed in the second drop test of D-SEND#1, and six microphones were used in ABBA Test#2-2. In these cases, the total weights of the devices installed to the blimp were about 25 kg and 29 kg, respectively. The highest microphone altitude reached 1000 m above the ground in both of the cases.

4.1.2. System Installation to Blimp

At the highest measurement altitude, the recording system including the ADC, laptop PC, GPS antenna and receiver, atmospheric measurement sensor, and batteries of BMS were stored in a polystyrene foam box as shown in Fig. 4-2, and attached to the payload strings of the blimp as shown in Fig. 4-3 (a). The microphones were attached to the tether by using a square-shaped attachment as shown in Fig. 4-3 (b). The microphones were installed about 10 m below the recording system to reduce the effects of the blimp on the measured



(a) Front side

(b) Rear side

Fig. 4-2 Recording devices at the highest altitude stored in a polystyrene foam box data. In D-SEND#1 and ABBA Test#2-2, two microphones and two independent recording systems were setup at the highest measurement altitude to keep redundancy.

At the lower measurement altitudes, the recording systems and the microphones were installed on the tether as shown in Fig. 4-4. The microphones were setup at about 10 m above the polystyrene foam box containing the recording devices in order to reduce the effects of the reflection from the box and accurately capture the sonic boom waveforms traveling downward.

4.2. Ground Measurement

4.2.1. System Overview

For the ground-based measurement, no restriction applies to the system weight. This means that there are more choices of the devices. However, basically the same hardware and software as for the aerial measurement were used for the ground measurement in BMS. By using the common system, the number of spare hardware to be prepared, and the time and cost for developing software can be saved. Also, the chance of operational error can be reduced.

The main difference between the aerial and ground-based measurement systems in BMS was the microphone installation method. The methods for installing microphones in the ground-based measurement are described in the following subsection.

(a) Recording devices and atmospheric measurement sensor

(b) Microphones installed on the tether

Fig. 4-3 Installation of aerial measurement system to the blimp at the highest altitude

4.2.2. Microphone Settings

When measuring acoustic pressure on the ground surface, the methods of microphone installation need to be appropriately determined.

First, the condition of the ground surface is to be considered. In order to impose a known reflecting factor, it is preferred to install the microphones on reflecting boards as in the previous flight tests for sonic boom measurement[9, 10]. In BMS, an acoustically nearly rigid boundary condition, which

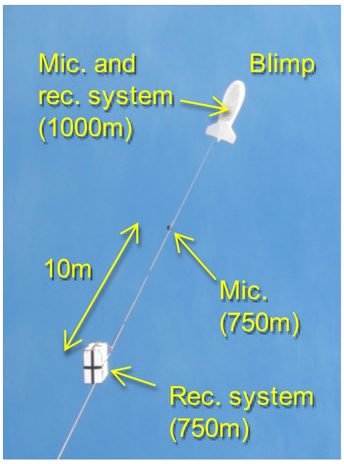


Fig. 4-4 Installation of aerial measurement system to the blimp at lower altitudes

makes the magnitude of the waveforms almost as twice as those above the ground, was imposed by using aluminum boards. The dimensions of the aluminum board were 1 m x 1 m with the thickness of 4 mm. When using a reflecting board, care must be also taken to reduce the vibration of the board. With the pressure change due to sonic booms, the board may vibrate and induce spurious signal from the microphones. To avoid this, sand was installed beneath the reflecting boards as shown in Fig. 4-5. The effects of the sand bank will be discussed in Sec. 5.4.

Second, a microphone installation method needs to be selected. Possible configurations include the flush-mount, inverted, and transverse (laid) setups. These microphone setups are shown in Fig. 4-6. In BMS, the flush-mount setup was chosen as the default configuration, based on the measured data. The details will be discussed later in Sec. 5.5.

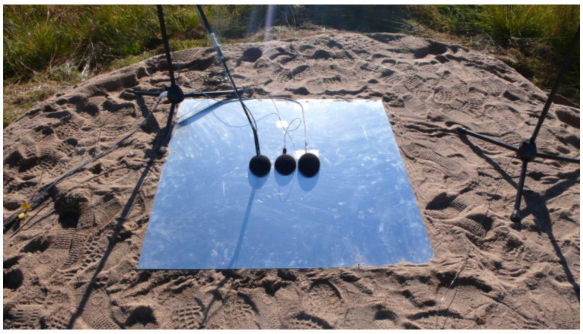


Fig. 4-5 Reflecting board installed on sand

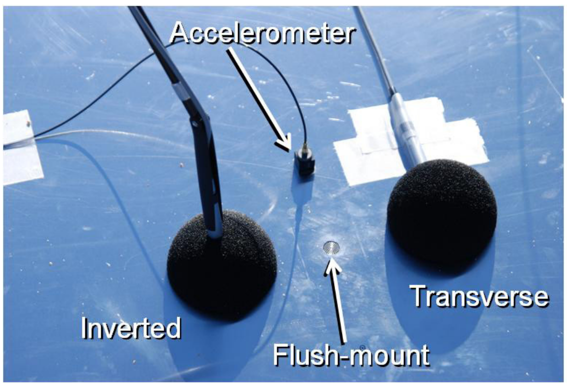


Fig. 4-6 Microphone installation methods in ground-based measurement

5. MEASURED DATA AND DISCUSSION

5.1. Overview

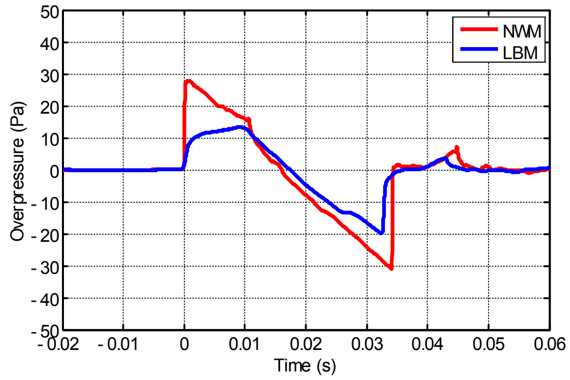
The examples of the sonic boom signatures recorded by using the developed aerial and ground-based sonic boom measurement systems in the first drop test of D-SEND#1[5] are shown in Fig. 5-1. In D-SEND#1, sonic booms created from the two types of differently shaped axisymmetric bodies in supersonic free falls were measured. The two types of the test bodies named N-Wave Model (NWM) and Low-Boom Model (LBM) were designed to produce N-shape and flat-top type low-boom sonic boom signatures, respectively. The maximum overpressure of the low-boom signatures were about a half of those of the N-waves as initially designed.

From the measured data, it was also found that the sonic boom signatures above the ground were not distorted by turbulence so much. The on-ground data were, in contrast, distorted by the atmospheric turbulence and the boom-ground interaction such as reflection and scattering[20]. Therefore, the effectiveness of aerial measurement for validating the low-boom aircraft design technology was demonstrated.

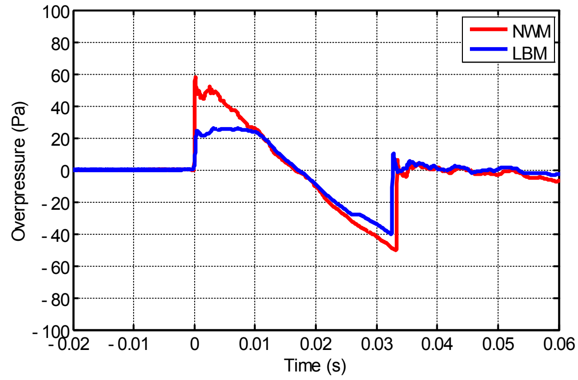
5.2. Effects of Blimp on Sonic Boom Waveforms

Hitherto JAXA has conducted aerial sonic boom measurement in three flight tests, namely ABBA Test#1, ABBA Test#2-2, and D-SEND#1. In some of the flights in these tests, unusual deformations were observed in the aerial sonic boom signatures measured at the highest altitude. The examples of the deformed waveforms are shown in Fig. 5-2. In some cases, spikes occurred about 10 ms after the front and rear shocks (Fig. 5-2 (a) and (b)). In other cases, gradual pressure rises preceding the sonic boom signatures were observed (Fig. 5-2 (c)). Note that the small shocks in the middle of the signatures recorded in ABBA Test#2-2 were due to the aircraft shape, and not distortion. As shown in Fig. 4-3 (b), the microphones at the highest position were installed about 10 m below the blimp, which had the maximum diameter of about 5 m and the length of about 15 m. Therefore, it was suspected that these deformations were due to the interferences of the booms with the blimp.

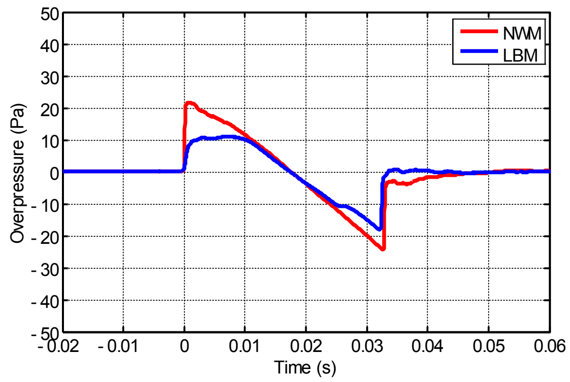
Preliminary numerical analysis was conducted, and the results supported this inference[21]. Examples of calculated waveforms are shown in Fig. 5-3. Although the computation was performed for



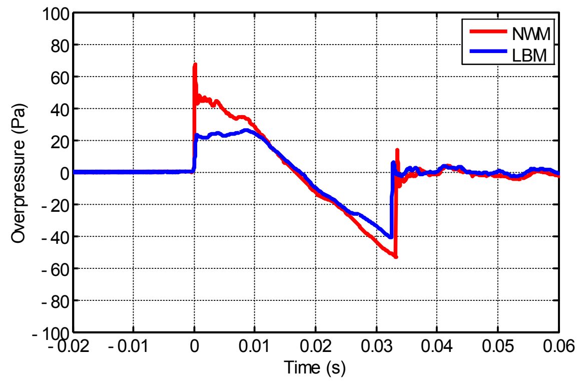
(a) 1000 m



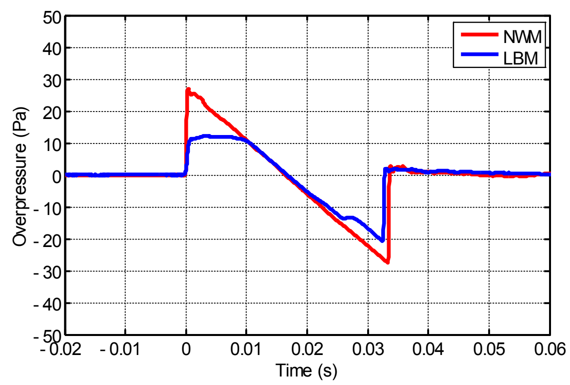
(d) Ground, Ch 1



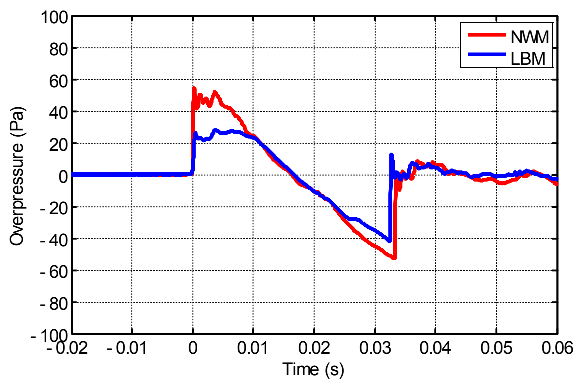
(b) 750 m



(e) Ground, Ch 2



(c) 500 m

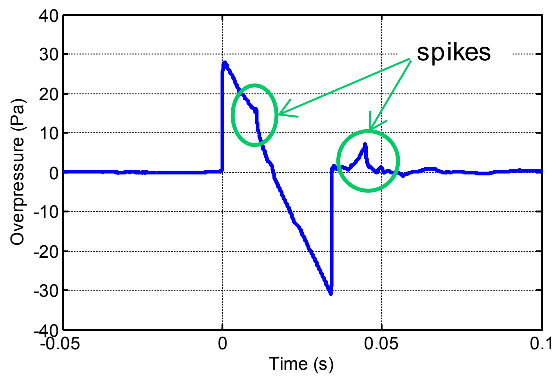


(f) Ground, Ch 3

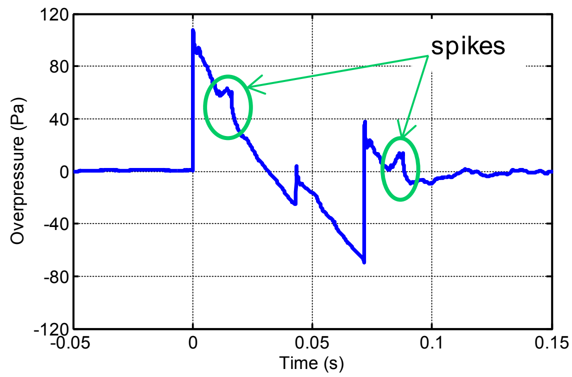
Fig. 5-1 Sonic boom signatures measured in D-SEND#1 1st drop test a two-dimensional problem and hence the results cannot be directly compared to the measured data, the numerical data indicate the qualitative agreement with the measured signatures to a certain degree. Tendency of occurring both the spikes and preceding pressure rises is found in the calculations.

Possible mechanisms of deformation were also implied. For the spikes after the shocks, reflection and diffraction of the boom at the surface of the blimp was considered as the prime cause. For the preceding pressure rise, the wave traveled inside the blimp was considered as a possible reason. The blimp was filled with helium, whose speed of sound is faster than air. The time difference for sound waves traveling for 5 m in air and helium is about 8 ms, which agrees reasonably to the time difference between the preceding pressure rises and the shocks in the measured data shown in Fig. 5-2 (c). Further investigation on more detailed mechanisms of the deformation is currently undertaken.

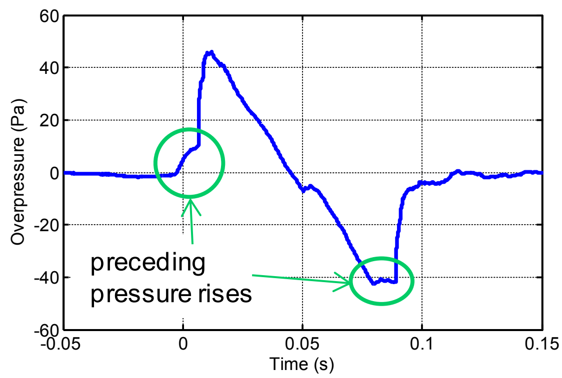
From the measured data, it was concluded that such effects of the blimp can be negligible for a



(a) D-SEND#1 1st drop test (Free fall)

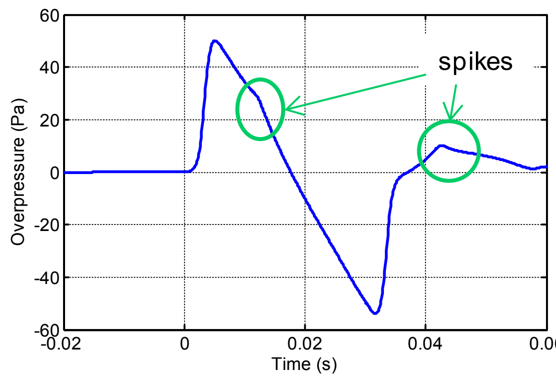


(b) ABBA Test#2-2 Flt.5 (Level flight)

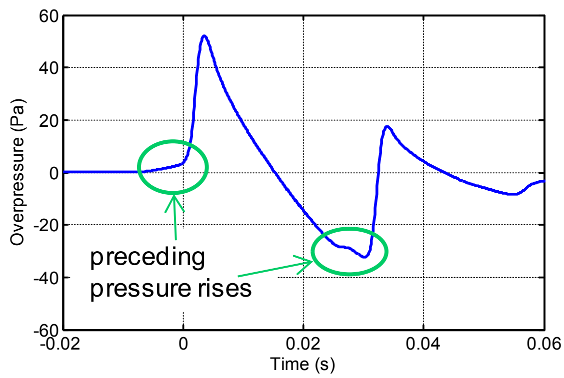


(c) ABBA Test#2-2 Flt.2 (Dive maneuver)

Fig. 5-2 Sonic boom waveforms distorted due to blimp



(a) Distortion with spikes



(b) Distortion with preceding pressure rises

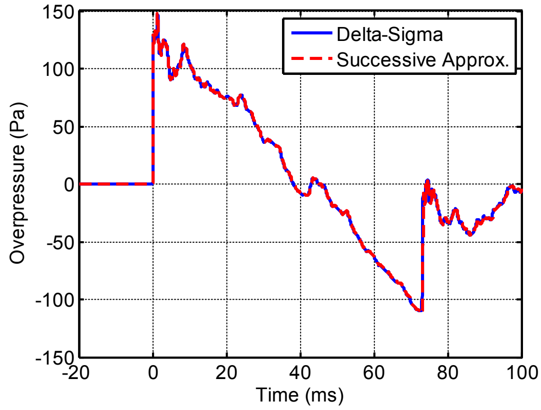
Fig. 5-3 Calculated sonic boom signatures near a blimp microphone location with a sufficient distance away from the blimp. No significant deformation due to the blimp was found in the sonic boom signatures recorded by the microphones installed 250 m below the blimp in all of the flights as found in Fig. 5-1. Preliminary numerical analysis also demonstrated that the effects of the blimp decreased with the distance from the blimp. The pressure disturbance around the blimp spreads nearly cylindrically in the two-dimensional problem solved numerically.

5.3. Effects of ADC Types

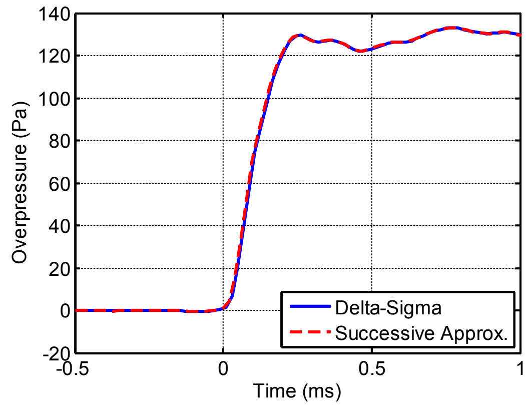
The difference of the ADC type was investigated in ABBA Test#2-2[3]. In this test, sonic boom waveforms captured by the same microphones were converted to the digital data by a 24-bit delta-sigma and a 16-bit successive approximation ADC's. The example waveforms recorded with these different types of ADC's are shown in Fig. 5-4. The two waveforms are almost identical, both in overall signature and shock structure as shown in Fig. 5-4 (a) and (b). The noise level of the data recorded by using the delta-sigma ADC was lower as expected as shown in Fig. 5-4 (c). This result supports the hypothesis that a delta-sigma ADC is preferable to a successive approximation ADC as discussed in Sec. 3.2.

5.4. Vibration of Reflecting Board

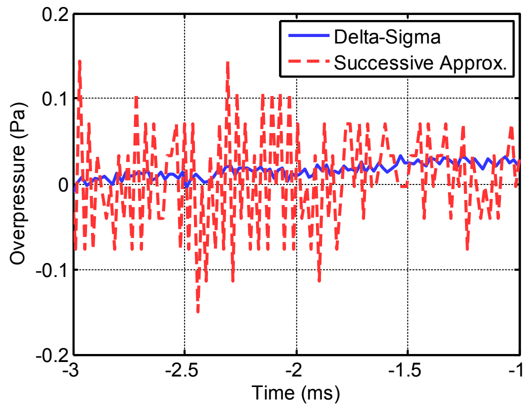
As described in Sec. 4.2.2, the ground boards were installed upon sand bank. In ABBA Test#2-1, the acceleration of the reflecting board setup on the sand bank was measured as shown in Fig. 4-6[2] and the effectiveness of this setting was confirmed. An example of the measured acceleration data is shown in Fig. 5-5 (a). According to the product datasheet of the microphone, the effects of the vibration is about 0.038 Pa/(m/s^2). Therefore, the spurious signal was estimated at about 0.4 Pa as shown in Fig. 5-5 (b). This spurious signal is plotted together with the recorded acoustic data



(a) Overview

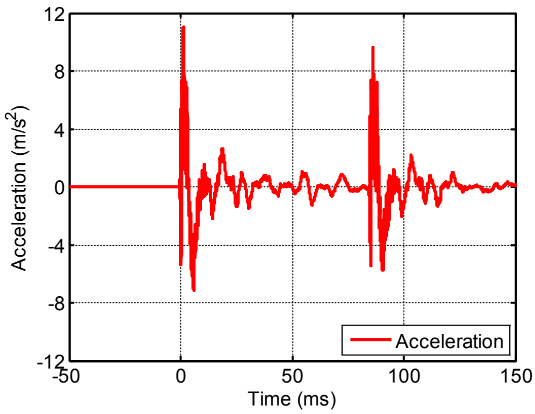


(b) Zoomed view of front shock

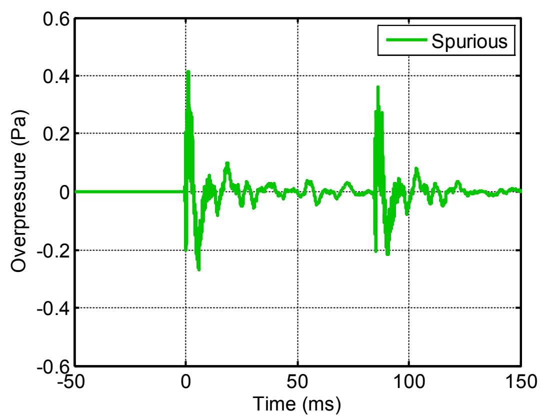


(c) Noise components before sonic boom signature

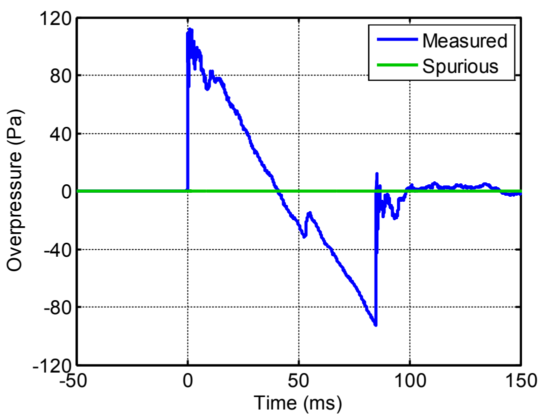
Fig. 5-4 Sonic boom waveforms recorded by using delta-sigma and successive approximation ADC's in Fig. 5-5 (c). From this plot, it can be concluded that the vibration of the plate was damped to a negligible level by the installation method using a sand bank.



(a) Acceleration of reflecting board



(b) Spurious acoustic pressure from microphone

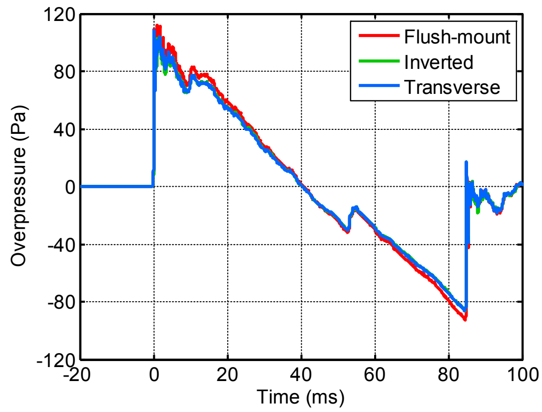


(c) Measured and spurious acoustic pressure

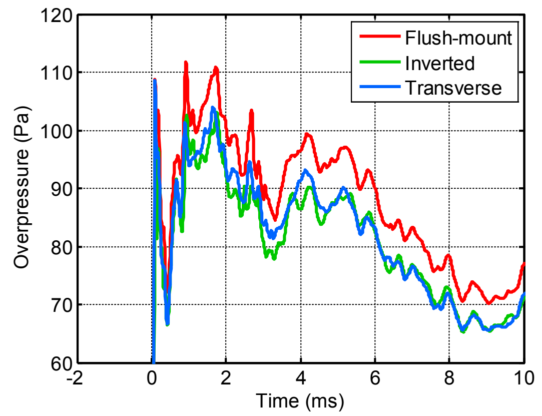
Fig. 5-5 Effects of vibration of a reflecting board

5.5. Effects of Ground Microphone Setups

In ABBA Test#2-1, several installation methods of microphones to the reflecting boards in the ground-based measurement were tested as shown in Fig. 4-5 and Fig. 4-6[2)]. The methods tested were flush-mount, transverse (laid), and vertically inverted setups. The examples of the recorded data are shown in Fig. 5-6. In all of the six flyovers in ABBA Test#2-1, the sonic boom signatures recorded by the microphone with the flush-mount setup had the largest amplitudes. In the transverse and inverted setups, the diaphragms of the microphones were placed about 1 cm above the surface of the reflecting board, resulting in a



(a) Overview



(b) Zoomed view of front shock

Fig. 5-6 Sonic boom waveforms measured by different microphone setups weak response at the frequency corresponding to the distance between the diaphragm and the board. This could be a reason why these two methods led to smaller magnitudes. The directivity of the microphones might also affect the measured data for the transverse and inverted setups. Therefore, the flush-mount setting was selected as the default method of installing the microphones for the measurement on the ground surface in BMS, although the installation procedure was not as straightforward as the other setups.

6. SUMMARY

In this paper, systems and methods for measuring sonic booms both on and above the ground were discussed. In developing a sonic boom measurement system, the frequency response of the system is one of the most important aspects to be considered. In order to capture the sonic boom signature with high accuracy, the frequency range of the sonic boom measurement system is desired to cover between 0.2 Hz and 20 kHz. With an adequate choices of commercially available recording devices and with the appropriate software algorithms, if necessary, this requirement for the frequency range can be satisfied. In the development of the aerial measurement system with a tethered blimp, it is also essential to reduce the weight of the system. With the system the authors have developed as an example, techniques for fulfilling the aerial measurement at multiple altitude up to about 1000 m were discussed. As for the ground-based measurement, the methods of microphone installation were considered, and the flush-mount setup on an acoustically rigid board with adequate vibration damping was considered as an accurate technique. The measured data in the recent flight tests conducted by JAXA indicated that the measurement system and methods are suitable for accurate sonic boom measurement.

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