JOURNAL OF AIRCRAFT
Vol. 33, No. 1, January–February 1996

Boom Event Analyzer Recorder: Unmanned Sonic Boom Monitor

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A series of automatic sonic boom monitors has been developed for unattended field use. These monitors are referred to as the boom event analyzer recorders (BEAR). The BEAR captures the full waveform of sonic booms while excluding other acoustic events. The signatures are stored in a digital format for easy retrieval and analysis. The first units, developed in 1986, were battery powered and operated up to 10 days in the field and stored 100 normal duration sonic booms. In 1992, a second version was developed. An upgraded version developed in 1992 included auxiliary solar power, improved power management, remote communication link via cellular phones, increased memory storage, direct data retrieval to laptop computer, enhanced user interface, autocalibration, power history data, and summary report of stored signatures. These BEAR systems have been used successfully in several sonic boom field studies. This article summarizes the data collection algorithms, the operation procedures, data storage and retrieval routines, and the hardware and software of the BEAR systems in order to understand how the U.S. Air Force currently measures sonic booms.

Introduction

THE U.S. Air Force is required to monitor and describe the sonic boom exposures in military operating areas (MOA) associated with air combat maneuvering intercepts (ACMI) operations to assess the environmental impact of such operations. This required analysis is developed into an environmental impact statement (EIS) that must be technically accurate and legally defensible to comply with the national environmental protection act (NEPA). To satisfy NEPA, the boom event analyzer recorder (BEAR) was developed to provide the U.S. Air Force with a readily portable, unmanned sonic boom recording system. The BEAR was designed to detect and record full sonic boom pressure-time signatures while rejecting unwanted noise events produced by subsonic aircraft, ground vehicles, gunfire, wind, and other sources. The recorder can discern a sonic boom from the normal background noise and store it digitally for later analysis. NASA Johnson Space Flight Center has designed a remote sonic boom monitoring system that uses analog circuitry to collect sonic boom signatures.[1] This NASA system utilizes a simple level-triggered detection algorithm and lacks the capability for long-term unmanned operation.

Currently, two versions of the BEAR are used for U.S. Air Force sonic boom monitoring and measuring studies. The original version was developed in 1986 and the boom capture algorithm was verified in a 1987 field test. An updated version that incorporated new features to enhance field usability was developed in 1992. The original BEAR units were field tested in a comparison measurement study with the analog, manned sonic boom recorder systems of NASA that were used in the extensive National Sonic Boom Program conducted in the 1960s.[2] A comparison plot between the BEAR and the NASA system sonic boom recordings is provided in Fig. 1. In this figure, the recorded boom was generated by an F-4 flying at Mach number of 1.15 at 5200 ft above ground level and was measured directly under the flight track. The boom signatures recorded by the BEARs agree with the recordings of the NASA systems that had frequency response down to dc. Also, the units were successfully utilized in 1987 to collect reference sonic boom signatures from eight different military supersonic aircraft.[3] From 1989 to the present, the BEARs have been used to monitor the sonic boom environment in several supersonic operating areas: the Barry Goldwater Air Force Range, the White Sands Missile Range, and the Nellis Air Force Base Supersonic Range.[4,5] In 1991, NATO used the BEARs to measure sonic booms during their joint acoustic propagation experiment conducted at White Sands Missile Range.[6]

The early studies revealed several hardware and operational deficiencies that have been corrected in the new design. These deficiencies included thermal drift on the microphone, battery RAM failure, cable connectors, and gel cell battery deterioration. These efforts have demonstrated that the boom-capturing algorithm is successful in recording sonic booms while screening out most nonboom events. These field studies have shown that the BEARs are reliable for monitoring of sonic booms.[3] This article describes the basic hardware and software utilized by both versions of the BEAR and the improvements incorporated in the newer units so that the reader may understand the current system used by the U.S. Air Force to measure sonic booms.

Hardware

The BEAR units are comprised of a microphone with a built-in preamplifier, a constant current microphone power source, an analog-to-digital (A/D) converter, a microprocessor, memory storage in RAM, communication interface, and internal and external power capabilities. The newer BEARs include solar power capabilities, modem communication, and cellular phone hookup. Figure 2 provides a basic concept diagram illustrating the components of the BEAR system. Each unit weighs approximately 20 lb without the external components and is the size of a large briefcase. Thus, the units are easily transportable for remote deployment.

Microphone Requirement

Sonic booms most commonly have an N-wave pressure signature. Variations from N-waves occur because of aircraft maneuvers and atmospheric effects, as illustrated in Fig. 3, but

Presented as Paper 93-4431 at the AIAA 15th Aeroacoustics Conference, Long Beach, CA, Oct. 25–27, 1993; received Dec. 30, 1993; revision received Aug. 30, 1995; accepted for publication Aug. 30, 1995.

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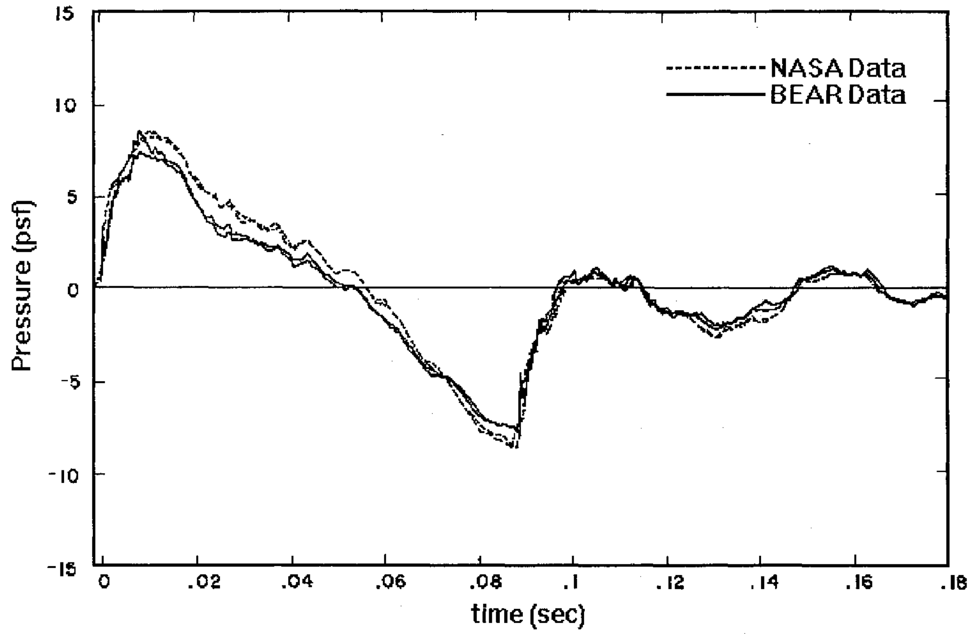

Fig. 1 Comparison plot of sonic boom signatures recorded by the BEAR units and NASA's recording system.

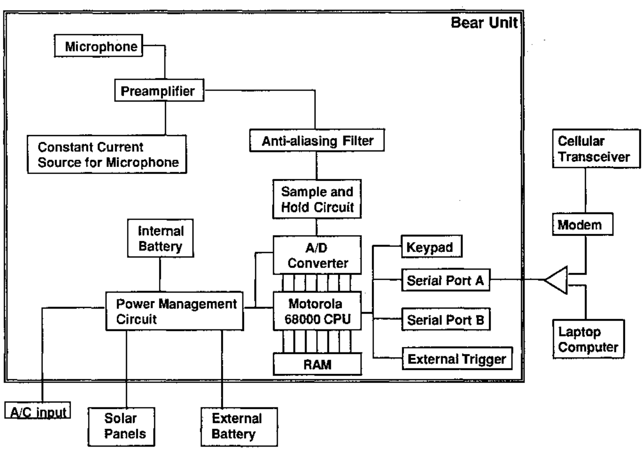

Fig. 2 Concept diagram of the BEAR unit.

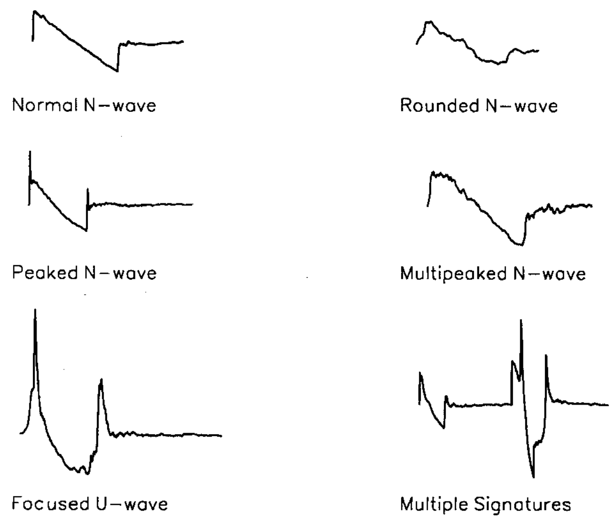

Fig. 3 Variety of sonic boom signatures recorded in the field.

the basic pattern is two shock waves separated by a low-frequency transition. The duration of sonic booms from typical military aircraft ranges from 70 to 300 ms. Shock wave amplitude ranges from a few tenths to a few tens of pounds per square foot (about 5 to over 1000 Pa). The core requirement for the BEAR system is the ability to record sounds in this amplitude and frequency range.

An upper amplitude limit of 77 psf (3700 Pa), 165 dB re 20 μPa, was selected. This is adequate for virtually all booms that have been measured and with a system dynamic range of 80 dB would allow meaningful recording of booms below 0.1 psf (4.8 Pa), 107 dB.

The frequency content of a sonic boom is etablished by the rise time of the shock waves (upper frequency) and the duration of the expansion (lower frequency). Frequency analysis of a variety of sonic booms indicated that energy above 2 kHz is not significant. To capture accurately the expansion portion of an N-wave requires a low-frequency response approaching dc. A practical limitation to achieving this amplitude and frequency response is the low frequency of the measurement microphone. In the original design stage, there were significant practical benefits (cost and availability) to a low-frequency limit of 0.5 Hz. The new design improved the low-frequency limit to 0.1 Hz. Figure 4 shows the distortion of an ideal N-wave subject to a 0.5-Hz low-frequency cutoff. While there is some distortion, the boom is still clearly recognizable. Peak pressure, subjective noise metrics, and spectral content above 0.5 Hz are not comprised by this cutoff.

Microphone Configuration

A PCB, Inc., piezoelectric microphone (model no. 106850) meets the previously mentioned requirements and was selected. This microphone has a built-in preamplifier that is sealed with the microphone to improve its durability under extreme environmental conditions typical of U.S. Air Force supersonic areas (0–65°C). The microphone is placed in an inverted mount that holds the microphone diaphragm 7 mm above a 10-mm-thick, 400-mm-diam steel plate. The 7-mm separation allows the microphone to measure the pressure doubling of the acoustic signal. All pressure time histories are recorded and displayed as the pressure-doubled signals following the standard practice for sonic boom analysis. The inverted mount configuration is a more convenient arrangement for remote field placement and, over the frequency range of interest, provides measurements identical to a flush-mounted microphone.[2,7] The low profile of the inverted mount also reduces the wind noise in the microphone system. A porous foam

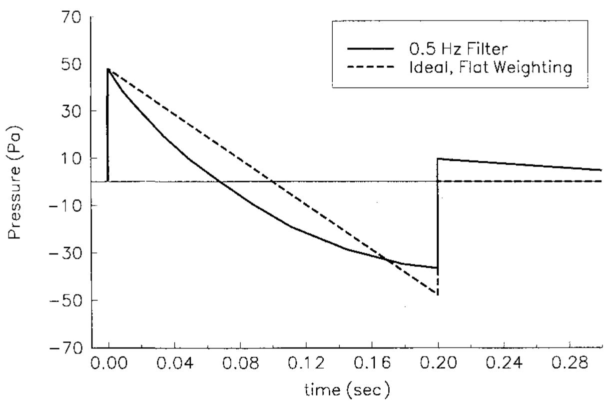

Fig. 4 Effect of 0.5-Hz low-frequency cutoff on sonic boom signature.

windscreen is placed around the microphone and mount, and a larger cone-shaped cloth windscreen is placed around the reflecting plate for additional wind noise reduction. These windscreens also protect the microphone from rain and light snow. A fibrous material is placed over the conical windscreen to act as a sunscreen to reduce the heat buildup inside the conical windscreen. This sunscreen was required to reduce extreme temperature increases (up to 100°C) that cause thermal drift of the PCB microphone.

A/D Converter

The signal from the microphone is fed through a 2000-Hz antialiasing filter into a sample and hold circuit that is used to stabilize the signal for digitizing by the A/D converter. The BEAR has a full 16-bit A/D converter that samples the microphone output at a 8-kHz sampling rate. This 16-bit A/D converter is set to record a maximum peak overpressure of 165 dB re 20 μPa (77 psf, or 3600 Pa). Although the true dynamic range for a 16-bit A/D converter is 96 dB, the usable dynamic range is reduced to 80 dB because of poor resolution at the lowest bits. For a resolution of less than 1 dB, the usable threshold is 95 dB (0.02 psf, 1.1 Pa). The dynamic range can be adjusted to higher or lower maximum levels, but the output data would need to be adjusted accordingly.

Microprocessor and Memory Storage

For the BEAR to screen for sonic boom (as described later) without missing any data points, analysis must take place during the 125 μs between sampling intervals. Additionally, the system must provide for user-input of detection algorithm parameters (allowing flexibility to collect other impulsive events), input of supporting data (test identification, setting time and date, etc.), and special operating modes (manual recording, field calibration, and power-up self test). This requires a high-speed general-purpose processor, so the Motorola 68000 processor was selected. At the time of original development, this processor was the fastest available chip that could handle the signature processing requirements. In the new BEAR design, the microprocessor performs many additional tasks such as power management, data summary, and control of external cellular communication. Memory in the original BEARs consisted of RAM packaged into two removeable modules with a total memory of 512 kbytes. Using two bytes per datum this memory size is capable of storing 100 sonic boom signatures of 250-ms duration plus individual header information. The new design provides an internal RAM with 1 Mbyte. Seven hundred kbytes is used for signal storage, and the remaining memory is used for event summary tables, battery voltage logs, and an event evaluation parameters change file.

Interface

The original BEAR design utilized removeable RAM modules that would be removed for off-line processing. Data were downloaded from the RAM modules via a data retrieval unit (DRU) connected via an RS-232 serial communication to a self-standing microcomputer. This arrangement minimized downtime in the field and also reduced old BEAR costs and power requirements since download capability is separate. The new BEARs (with built-in RAM) have a RS-232 serial port, and replicate the capabilities of the DRU. This slightly increases downtime during service (a few minutes is required for data transfer), but generally simplifies servicing and data handling. This improvement was made possible by the decrease in cost and power requirements of serial communication chips and by the availability of laptop computers.

The serial ports of the new design allow 9600-Bd communication with a microcomputer via a direct or modem connection, any Hayes compatible modem or a cellular transceiver modem. The cellular transceiver used with the new BEARs is a Motorola Cellular Connection Transceiver with cellular connection interface that allows access to digital modems. The modem used for cellular communications is Microcom's MicroPorte™ 4232bis with fax. The modem uses a V.32bis/V.42/V42bis protocol and has MNP class 10 capability that offers dynamic shifting of the band rates for communication over telephone lines. The BEAR uses two control lines to send power control signals to the cellular modem through the serial port. This configuration uses a nonstandard Db 9, RS-232 serial cable for the power control lines.

Power

The BEARs require approximately 7 W of power at 12 V to operate. The original BEAR design had three internal 10 A-h and three external 100 A-h gel cell rechargeable batteries linked in parallel to provide seven days of power for remote deployment. Solar panels were added to increase the duration of field deployment and to reduce the number of batteries required. The solar panels are 30-W, multicrystal, photovoltaic panels that are connected to the external batteries through a charge controller to prevent overcharging. With this arrangement, one full solar day provides enough power to operate the units for about four days under normal conditions. A timer to turn the units on and off on a daily basis has been added in the new design. This feature provides better power management by shutting down the units when no supersonic activity is anticipated. As stated previously, the low-temperature operational limit is 0°C and is determined by reduced battery capacity at freezing temperatures. At these temperatures, the BEAR will operate properly as long as power is supplied. Thus, remote deployment during cold weather is hindered by reduced battery capacity.

The cellular transceiver communication arrangement requires an additional 6 W of power to provide remote downloading of data. To conserve power, a user can program the new BEARs to turn the transceiver on and off at preset times to create a window for remote downloading. For example, if the time window is set for 1-h daily window, the power consumption for the cellular modem would be reduced to 1/24th of its power consumption when left on all of the time.

Signal Processing

An event-capturing algorithm[8] allows the BEARs to discern impulsive events like sonic boom from other noise events. This algorithm was developed to screen the microphone signals continuously for sonic boom events. This algorithm includes two timers, five event evaluation parameters, and nine signal values from an event. If the digitized signal exceeds a preset lower trigger level, it is fed to the RAM for event identification analysis by the microprocessor. The timers are then started for determining when to evaluate the signal sent to RAM. When triggered to evaluate, the signal values and the evaluation parameters are then compared to determine if the event is a desired impulsive event. If the event passes the comparison, then the event is saved. This signal processing software is stored in electrically programmable read only memory (EPROM) and is exercised in the 68000 microprocessor. Also, in the new BEAR design, summary information for the good event is stored to a new part of memory.

Capturing Algorithm

The BEAR continuously monitors the noise environment by digitizing and examining the noise signature every 125 μs. When the noise level rises above a set threshold level, the BEAR considers the signal a possible valid event and starts to write the digitized values to the RAM and starts the event timer T_{event}. The BEAR stops writing the signal to memory when the level falls below the threshold level for a set cycle time T_{cycle}, or when the event duration exceeds T_{event}. Once either timer is exceeded, the event is evaluated to determine if it is valid. In this evaluation, the capturing algorithm compares five parameters to the values flagged in the event. The evaluation triggers and parameters are the following:

P_{low} = threshold pressure level
P_{high} = high-pressure level
t_{PP} = minimum positive pulse duration
ΔP_{RT} = rise-time pressure gradient
t_{RT} = rise-time time step for pressure gradient

The event values that are flagged for comparison to the previous parameters are illustrated in Fig. 5 for an idealized N-wave and listed next:

t^*_{Low} = time of initial threshold level crossing
P^*_1 = first local peak pressure
t_1 = time of first local peak pressure
P^*_{MAX} = absolute maximum pressure
t_{MAX} = time of absolute maximum pressure
t_p = time of first downward crossing of P_{Low} after P_{MAX}
P^*_{min} = absolute minimum pressure
$t$min = time of the absolute minimum pressure
t_n = time of last crossing of $-P_{low}$ prior to P_{min}

The * denotes the actual values that are flagged in the memory register. The event time is identified by t_{Low} and is recorded within ± 0.1-s accuracy from an internal real-time clock. With the original BEAR design the time can only be set manually by the user, but the new design allows the time to be set and synched with a laptop computer.

The event is evaluated by checking its peak pressure, positive and negative pulse duration, and the rise-time pressure gradient. The peak pressure check ensures that P_{MAX} is above P_{High}. The positive pulse duration checks that the duration between t_{Low} and of the first downward crossing of P_{Low}, after P_{MAX}, t_p, is greater than the preset minimum duration time t_{PP}. The negative pulse duration check is similar to the positive pulse check, although the preset minimum duration time is one-eighth of t_{PP}. The rise-time gradient check is separated into

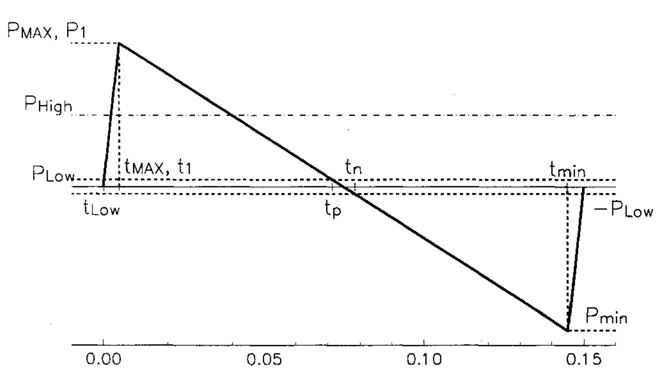

Fig. 5 Idealized N-wave with boom event evaluation parameters.

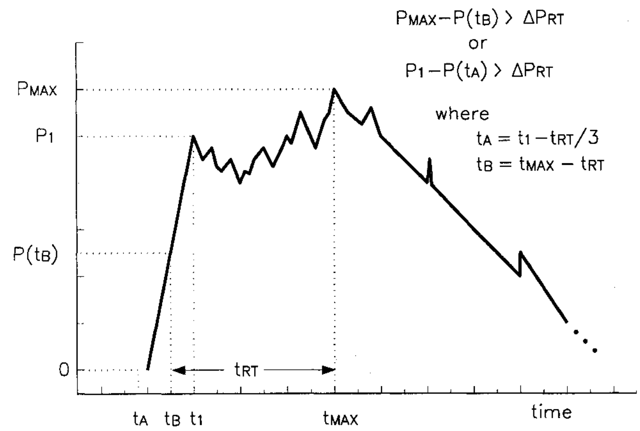

Fig. 6 Diagram of rise-time pressure gradient evaluation check.

a two-step condition to account for the effects of distorted signatures. Figure 6 provides an illustration of the rise-time gradient check. In this figure, the positive pulse of the sonic boom waveform is shown with the relevant evaluation parameters. The first step compares the pressure gradient relative to the maximum pressure to the preset rise-time gradient. The pressure gradient is measured by looking at the pressure difference from the maximum level to a level occurring earlier in the event determined by the preset rise-time time step t_{RT}. If this step fails, then a comparison is made relative to P_1, with a time step of one-third of the rise-time time step. It should be noted that if this earlier pressure occurs before the first theshold crossing t_{Low}, then the event automatically passes this check. For an event to be valid it must satisfy all four of these conditions, which are restated in the following equations:

$$P_{MAX} > P_{High} \tag{1}$$

$$t_p - t_{max} > t_{PP} \tag{2}$$

$$t_{min} - t_n > \tfrac{1}{8} t_{PP} \tag{3}$$

$$P_{MAX} - P(t_{MAX} - t_{RT}) > \Delta P_{RT} \tag{4a}$$

or

$$P_1 - P[t_1 - (t_{RT}/3)] > \Delta P_{RT} \tag{4b}$$

If any of these conditions are not met, the event is considered invalid and is discarded.

The microprocessor evaluates the data by scrolling through digitized data and performing a direct comparison of the digitized A/D values at the appropriate data registers. As an example, the positive pulse duration check is performed by starting at P_{MAX} and checking for $P(t) > P_{Low}$ until $t = t_{MAX} + t_{PP}$. If the previous relation holds over this time duration, then the event passes the positive pulse duration check [Eq. (2)].

Under real-world conditions boom signatures can be significantly different from the N-wave of Fig. 5 because of atmospheric propagation effects, flight-path unsteadiness, and lateral propagation. As a boom propagates through a turbulent atmosphere, the signature can become distorted by possibly increasing the rise time and shortening the positive pulse duration. These distortions cause the signature to be peaked, multipeaked, or rounded N-waves. If the aircraft is maneuvering, the sonic boom energy can be focused on the ground by a convergence of the ray paths. Focusing transforms the boom signature into a U-wave that has an increased peak overpressure with a much shortened positive pulse duration. Moreover, multiple boom signatures will be generated downtrack from the convergence, or superfocus, point. Also, as a boom approaches the lateral cutoff, it is refracted upward and away

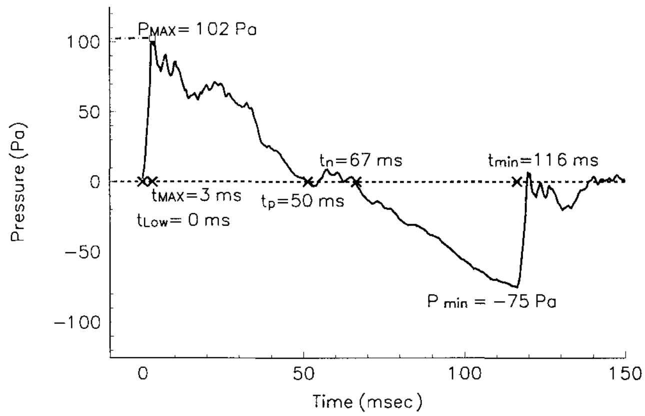

Fig. 7 Actual sonic boom signature captured by the BEAR.

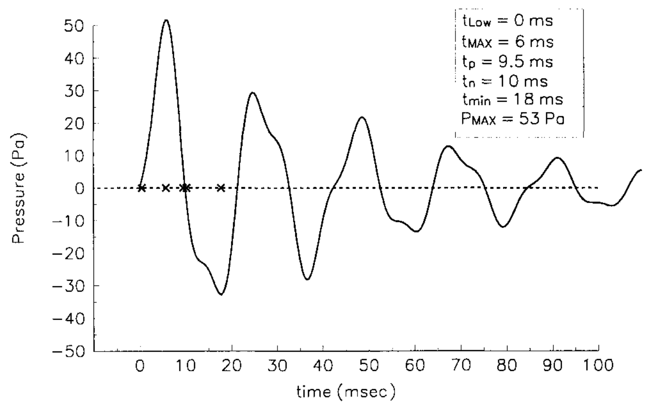

Fig. 8 Rejected nonboom impulse signature.

from the ground. This refraction causes the boom signature to degenerate into a rumble noise on the ground beyond the cutoff. Examples of these signature variations are illustrated in Fig. 3.

To accommodate the wide variety in sonic boom signatures observed in the field, the BEARs use the following default values for the evaluation parameters and timers:

$$P_{\mathrm{Low}} = 100 \text{ dB re } 20\ \mu\mathrm{Pa} \qquad t_{\mathrm{PP}} = 10 \text{ ms}$$
$$P_{\mathrm{High}} = 107 \text{ dB re } 20\ \mu\mathrm{Pa} \qquad t_{\mathrm{RT}} = 35 \text{ ms}$$
$$\Delta P_{\mathrm{RT}} = 6 \text{ dB}$$
$$T_{\mathrm{event}} = 2 \text{ s} \qquad T_{\mathrm{Low}}\, 0.2 \text{ s}$$

These values have been used successfully for several sonic boom measurement programs.[3-6] For multiple booms, the BEAR will capture the booms in one file or separate files, depending on the time separation of the individual signatures. Figure 7 shows a typical sonic boom signature and its evaluation values obtained by the BEAR.

For illustration, Fig. 8 shows an idealized rifle bast signature that would be rejected by the BEAR with the previous default evaluation values. In this figure, the event passes the first condition that $\Delta P_{\mathrm{MAX}} > P_{\mathrm{High}}$, but fails the positive pulse duration check since $t_p - t_{\mathrm{MAX}} = 3.5$ ms $< t_{\mathrm{PP}}$. Although the capturing algorithm was developed primarily for sonic boom, the event evaluation parameters can be changed to capture other types of impulsive events such as gunfire, artillery blasts, and explosions.

Postprocessing

Once a signature has been collected, it is saved in a digital file that includes event information and the pressure time history at 125-μs intervals. The header information includes the time and date of the event, the serial number of the BEAR, and user-specified data such as the site number. The postprocessing program provides an event summary that includes maximum and minimum overpressures, the duration of the event, and the number of data points. The plot routine allows the user to specify the y axis and will drive various printers to produce hard copies, if desired. When the signature is plotted to the screen, the user can zoom in on the signature or scan the pressure time values. The program also provides an ASCII export file that includes the header information along with the time and pressure data formatted in columns. This feature allows the user to export the data files for a more detailed analysis of the signatures.

Concluding Remarks

The BEAR systems provide the U.S. Air Force with the required capability to monitor sonic boom exposures under supersonic operating areas in a cost-effective manner. The system detects and captures the sonic boom waveform and stores it into a digital format for easy analysis. The frequency range of 0.5–2000 Hz for the original design and 0.1–2000 Hz for the new design is sufficient to describe boom exposure generated by military aircraft and the NASA Space Shuttle. The units are compact and transportable for remote monitoring and provide an improvement in acquiring, storing, and retrieving sonic boom data in an immediate and accessible electronic digital file. The units have been successfully employed in several sonic boom measurement and monitoring programs. These field studies have shown that the BEARs are reliable for monitoring sonic booms. Also, the boom data collected by these systems provide researchers with an additional source of data to improve our current knowledge of sonic boom.

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