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Overview of the Japanese Smart Materials Demonstrator Program and Structures System Project

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Abstract—The Japanese Smart Materials and Structures System Project started in 1998 as a five-year program funded by the Ministry of Economy, Trade and Industry (METI) and supported by the New Energy and Industrial Technology Development Organization (NEDO). This project was primarily conducted by the Academic Institutions Centered Program, a collaborative research and development project among universities, industries, and national laboratories. Initially, this project consisted of four research groups: structural health monitoring, smart manufacturing, active/adaptive structures, and actuator material/devices. Two years later, two demonstrator programs were added in order to integrate the developed sensor and actuator elements into the smart structure system and to verify the research and development results of the four research groups. The application target of these demonstrators was the airplane, and two demonstrators whose shapes simulated the fuselage of a small commercial airplane (for example, Boeing B737) were established. The first demonstrator integrated the following six innovative techniques: (1) impact monitoring using embedded, small diameter optical fiber sensors newly developed in this program, (2) impact monitoring using integrated acoustic emission (AE) systems, (3) whole-field strain mapping using the BOTDR/FBG integrated system, (4) damage suppression using embedded shape memory alloy (SMA) films, (5) maximum and cyclic strain sensing using smart composite patches, and (6) smart manufacturing using the integrated sensing system. The second demonstrator was for suppressing vibration and acoustic noise generated in a composite cylindrical structure. In this program, high-performance PZT actuators/sensors (developed in this project) were also installed. All tests and evaluations were completed. This paper outlines the demonstrator programs.

Keywords: Smart materials and structures; composite structures; damage detection; damage suppression; noise and vibration reduction.

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1. INTRODUCTION

The ‘R&D for Smart Materials and Structures System’, a five-year project supported by the New Energy and Industrial Technology Development Organization (NEDO), Japan, was initiated in late 1998. The project is an Academic Institutions Centered Program of collaborative research and development among universities, industries and national laboratories. Initially, it consisted of four sub-themes: (1) Structural Health Monitoring, (2) Smart Manufacturing, (3) Active and Adaptive Structures, and (4) Actuator Materials and Devices. In early 2000, the Concept Demonstrator Program was added to the project. This program has two goals: evaluating to what extent research and development sub-themes have attained their targets and establishing common basic technologies for a future ‘Smart Structure System’.

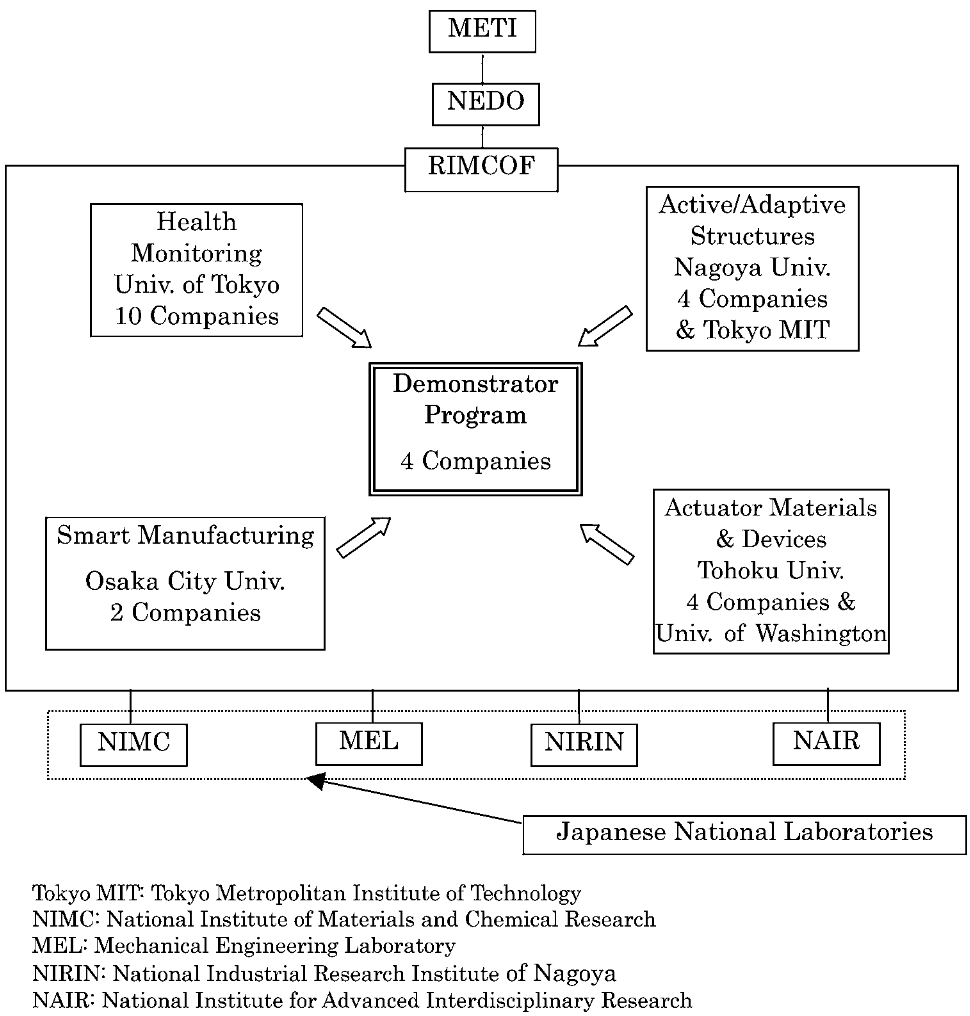


Figure 1. Organization of the project.

The Demonstrator Program was focused on an aircraft fuselage of composite structures and was designed to integrate several research and development results. Two demonstrators were produced: one was aimed at damage detection and damage suppression, and the other was aimed at noise and vibration reduction.

The NEDO 'R&D for Smart Materials and Structures' project in Japan was the forerunner of the Academic Institution Centered Program, which has conducted collaborative research and development among universities, industries and national laboratories in Japan. Six universities, seventeen companies, and four national laboratories took part in the project. RIMCOF (R&D Institute of Metals and Composites for Future Industries) was the management office of the project. The project included the above four sub-themes and the Demonstrator Program. Four sub-themes were primarily basic element-level research and development, and the Demonstrator Program was application-oriented. The organization of the project is shown in Fig. 1.

The Demonstrator Program was designed to integrate the research and development results of four sub-themes. Therefore, we started the preliminary design of the concept demonstrator two years after the research and development of the four sub-themes began.

2. SELECTION OF DEMONSTRATION THEMES

Before starting the preliminary design, we discussed what themes were appropriate for the purpose of the Demonstrator Program. We first asked participating members to submit demonstration theme proposals. Over thirteen proposals were submitted. We subsequently selected demonstration themes in accordance with the following criteria.

(1) Is the theme an advanced technology?

(2) Do users need the theme for future fuselage structures of an aircraft?

(3) Is it possible to show results of the developed research and development on the demonstrator?

(4) Is it appropriate for the schedule of the project?

Seven themes were then selected. They were classified into the followings categories as shown in Table 1.

They were also divided into two groups:

(1) Damage Detection and Suppression $\Longleftrightarrow$ Demonstration Theme #1–#6 and

(2) Noise and Vibration Reduction $\Longleftrightarrow$ Demonstration Theme #7.

3. CONCEPTS OF DEMONSTRATORS

As previously stated, the demonstrator is focused on the aircraft fuselage. Although it is desirable to test a full size fuselage for the actual demonstration, it is expensive and time-consuming in design and production. Moreover, it needs a large area and many test and measurement facilities. Nonetheless, it is difficult for a small demonstrator to simulate the primary physical parameters of the full-scale fuselage due to the minimum gauge size of materials and standard parts (bolts, nuts, rivets, etc.). Stress and strain are key parameters for demonstration themes #1 to #6 of Table 1 (Damage Detection and Suppression), and natural frequencies are key parameters for #7 (Noise and Vibration Reduction). As a result of the trade-offs in the study, we decided on a diameter of 1.5 m (approximately 1/3-scale size of a small class jetliner).

It is impossible for the 1/3-scale demonstrator to simulate both parameters of stress/strain and natural frequencies simultaneously. Moreover, it is difficult to complete all the demonstration tests within the limited time period using only one demonstrator. Consequently we produced two demonstrators. One is aimed at damage detection and suppression, (#1 through #6 of Table 1). The other one is aimed at noise and vibration reduction (#7 of Table 1).

The demonstrator structures are primarily made of composites, but some parts that are not influential in physical parameters are made of aluminum alloys and steel to reduce development cost. To simulate an aircraft fuselage, an internal pressure and an external bending moment are applied for the Damage Detection and Suppression Demonstrator. In contrast, the Noise and Vibration Reduction Demonstrator is

Table 1.
Demonstration themes

#	Demonstration categories	Demonstration themes
1	Real time detection of impact damage	Optical fiber sensors embedded into CFRP laminated structures
2		Integrated acoustic emission sensor network systems
3	Damage detection	Strain distribution measurement in wide area using distributed BOTDR[a] sensors
4		Damage detection by electric conductivity change in smart patch (carbon fiber composite sheets)
5	Damage suppression	Damage suppression system using embedded SMA (Shape Memory Alloy) foils
6	Smart manufacturing	Smart manufacturing of low cost integrated panel by RTM (Resin Transfer Molding)
7	Noise and vibration reduction	Noise and vibration reduction technology in aircraft internal cabin

[a] Brillouin Optical Time Domain Reflectometry.

excited by external speakers and/or shakers without a bending moment and internal pressure. Figures 2 and 3 illustrate the two demonstrators.

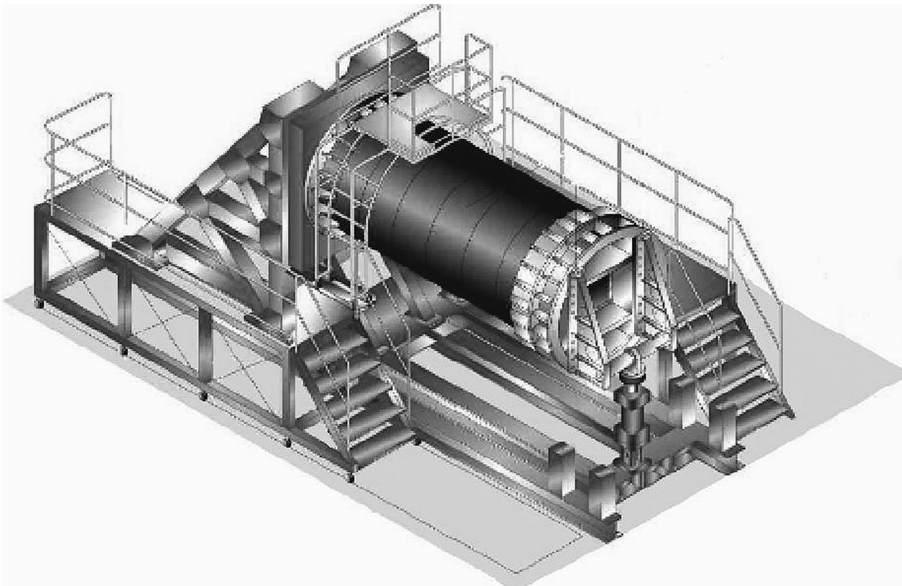


Figure 2. Image of Damage Detection and Suppression Demonstrator.

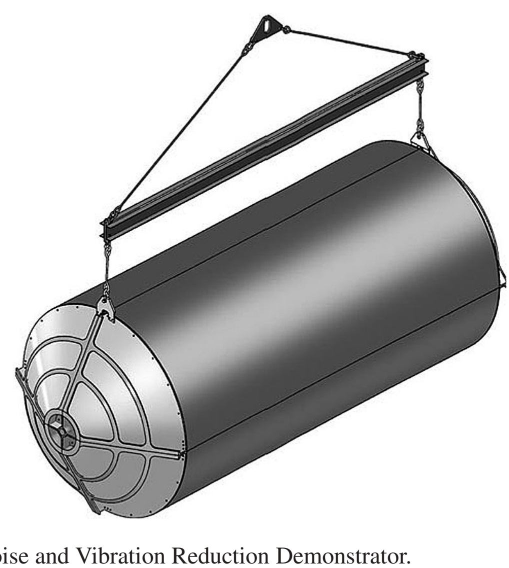


Figure 3. Image of Noise and Vibration Reduction Demonstrator.

4. DAMAGE DETECTION AND SUPPRESSION DEMONSTRATOR

4.1. Demonstrator design

Preliminary design of the Damage Detection and Damage Suppression Demonstrator is summarized below and in Fig. 4.

4.1.1. Materials and size. The demonstrator was constructed of composite materials to form a cylinder simulating an aircraft fuselage with a length of 3 m and diameter of 1.5 m. The skin and stringer used a carbon fiber reinforcement composite material. The aluminum alloys used for the frames consist primarily of 2024 and 7075 materials. The support and loading jigs at both ends are made of steel.

4.1.2. Structure. A build-up structure with composite skin-stringer panels and aluminum alloy frames. Four panels form the cylinder, and the support and loading jigs at both ends are divided into four, corresponding to the panels. The bulkhead panel can be freely removed or mounted, allowing a fastener joint to be connected to the loading jig section.

4.1.3. Arrangement. The frame (stringer) has a pitch of about 500 mm (150 to 200 mm). Internally, the test model has a working floor inside of the fuselage for test preparations. The upper panel is divided lengthwise into three parts at STA1000 (STA1000 means the position which is 1000 mm from the left end of the CFRP fuselage structure, as shown in Fig. 4) and STA2000. The skin between STA1000 and STA 2000 was integrated with small-diameter optical fiber newly developed in

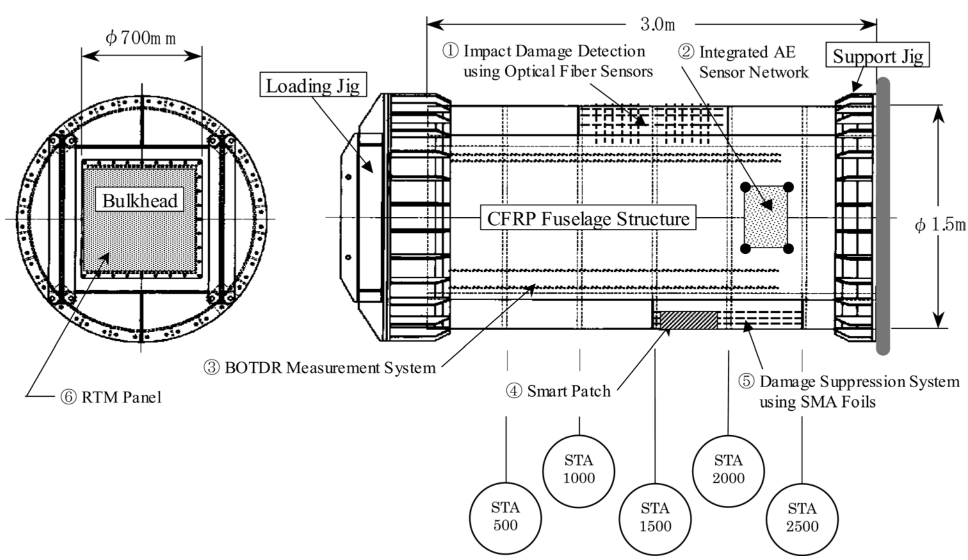


Figure 4. Damage Detection and Suppression Demonstrator.

the present project for impact damage detection. The skin and stringer of the upper panel were co-cured.

The side panels were not divided lengthwise, and skin and stringer were co-cured. On STA500 to 2500 of the external panel and between layers of the skin and stringer, optical fibers were embedded as a BOTDR sensor for wide-area strain distribution measurement.

The bottom panel was divided lengthwise into three parts at STA1500 and STA2500. Shape memory alloy foil was embedded in the external panel on the STA1500 to 2500 starboard for damage suppression. To reduce the production risk, the skin and stringer were assembled with secondary bonding. It is likely that with the top panel, connections along the length of the panels were made with butt joints, and the joint with the side panels were made with lap joints allowing one to pull out the electric heating terminals.

Part of the pressure bulkhead at the load side had a removable structure, and the RTM forming panel was attached for the pressure test.

4.2. Verification themes of the Demonstrator

The verification themes shown in Table 1 are outlined below, and the verification positions of each demonstration are illustrated in Fig. 4.

① Real-time detection of impact damage using optical fiber sensors embedded into CFRP laminated structures.

Detection of any impact damage and identification of its location are demonstrated using a small-diameter optical fiber sensor embedded in the upper panel. The detection and identification were verified in the impact test phase.

② Real-time detection of impact damage using integrated acoustic emission sensor network systems.

The occurrence time, location and magnitude of the impact load are identified using the AE sensor mounted on the side panel. They were verified in the impact test phase.

③ Strain distribution measurement in wide area using distributed BOTDR sensors.

Using an optical fiber embedded in the inside of the side panel, damage location and its magnitude are identified from the wide range strain distribution measured. They were performed in the static test phase.

④ Damage detection by electric conductivity change in smart patch (carbon-fiber composite sheets).

Two types of smart patches, carbon-fiber fracture and conductive-particle dispersion, were mounted at the bottom panel of the demonstrator, and the smart patches memorized the applied maximum strain both in cyclic loading and static test phases.

⑤ Damage suppression system using embedded shape memory alloy (SMA) foils.

In order to verify that the shape memory alloy foils embedded in the bottom panel can suppress damage and its growth, the evaluation was performed in the cyclic loading test phase. They were verified by comparing occurrence times at which damage, such as transverse cracks, occur at the observation section and depending on whether the SMA foil is present.

⑥ Smart manufacturing of low cost integrated panels by Resin-Transfer Molding (RTM).

An optical fiber sensor, used for monitoring the manufacturing on the bulkhead panel with RTM process, was verified to measure strains in the pressure test phase.

4.3. Test

The Damage Detection and Suppression Demonstration test was conducted at Mitubishi Heavy Industries, Ltd., from October to December of 2002. Figure 5 shows the set-up of the Damage Detection and Suppression Demonstrator. The Demonstrator was mounted to the test frame in the cantilever mode, and the fuselage bending load and internal pressure were applied.

Shear load (20 tons maximum) was applied to the free end of the demonstrator as a bending load, a pressure load (0.75 atm maximum) was applied to the internal of the demonstrator, and various impact loads (50 J maximum) were applied. The test was performed in the following order: (1) pressure test, (2) cyclic loading test, (3) static test, and (4) impact test. During the pressure test, an internal pressure was applied within the test model. In the cyclic loading test, the bending load was gradually increased in a quasi-static condition. In the impact test, various levels of impact load were applied. A visual inspection was performed before and after each test. The test sequence is shown in Fig. 6. The results of each demonstration theme are summarized in Table 2. All six demonstration themes were successfully verified at the structural level.

Figure 5. Set-up of Damage Detection and Suppression Demonstrator (Mitubishi Heavy Industries, Ltd.).

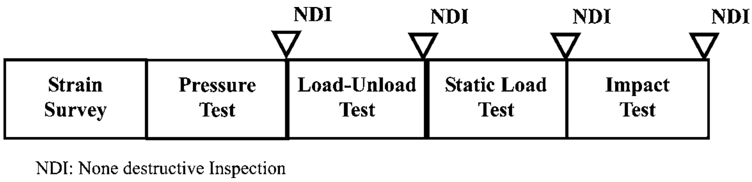


Figure 6. Sequence of the Damage Detection and Suppression Demonstrator test.

Table 2.
Summary of test results of the Damage Detection and Damage Suppression Demonstrator test

#	Demonstration themes	Summary of test results
1	Real time detection of impact damage using optical fiber sensors embedded into CFRP	Optical fiber sensors embedded at the upper panel can identify impact damage and its location
2	Real time detection of impact damage using integrated AE sensors network	Magnitude and location of the impact load can be detected within 1 cm accuracy
3	Strain distribution measurement in wide area using distributed BOTDR sensors	Wide range strain distribution can be measured within 100 micro strain accuracy
4	Damage detection by electric conductivity change in smart patch (Carbon fiber composite sheets)	Maximum strain by electric conductivity change using carbon fiber composite sheets can be measured within 5000 micro strain
5	Damage suppression system using embedded SMA foils in CFRP laminates	Shape memory alloy foils embedded at the bottom panel can suppress the occurrence and growth of damages
6	Smart manufacturing of low cost integrated panel by RTM (Resin Transfer Molding)	Optical fiber sensor, used for monitoring the manufacturing with RTM process on the bulkhead panel, is useful to measure strains in the pressure test phase

5. NOISE AND VIBRATION REDUCTION DEMONSTRATOR

Acoustic absorption materials have good noise reduction features in the high frequency range, but thick absorption layers are needed in the low frequency range to significantly reduce the noise level. Therefore, it is practical to use active noise control in the low-frequency range and acoustic absorption materials in the high-frequency range. In the Noise and Vibration Reduction Demonstrator, the target frequency range is below 500 Hz.

The demonstrator is the same size as the Damage Detection and Suppression Demonstrator described in 'Concepts of Demonstrators'. Skin panel thickness, dimensions of stringers and frames, spaces between the stringers and the frames of the Noise and Vibration Reduction Demonstrator differ from those in the Damage Detection and Suppression Demonstrator due to differences in key parameters. In this demonstrator, natural frequencies are the key parameters to be simulated. All the natural frequencies of the demonstrator cannot represent those of the assumed jet liner. Therefore, our policies in the setting of natural frequencies are as follows.

(1) To approximate the natural frequencies of one bay area enclosed by stringers and frames.

(2) To simulate the order of structural vibration natural frequencies and acoustic vibration natural frequencies.

The dimensions of stringers and frames, their spacing and end cap shapes were designed in accordance with the above policies. High-performance PZT actuators that were developed by the ‘Actuator Materials and Devices’ group were used.

The conventional way to reduce the noise in an aircraft cabin is to install sound-absorbing material. Sound-absorbing material effectively reduces noise in the high-frequency range, but not in the low-frequency range. Therefore, noise reduction with structure vibration control has been studied in research organizations worldwide. At present, however, verified noise reduction methods only apply to specific frequencies in a narrow band. Therefore, in this test, we manufactured a test model presuming an aircraft fuselage with $1/3$ the size of a small commercial jet liner. Applying the cabin noise reduction technologies developed in the ‘active/adaptive structure technology development’ to the above test model, we demonstrated noise vibration reduction in a wide range of low frequencies for the active/adaptive structure.

The Noise and vibration Reduction Demonstrator is outlined below.

5.1. Test objectives

The two objectives in this test are:

– Increase the attenuation factor by 20% or more and
– Decrease the noise level by 3 dB or more.

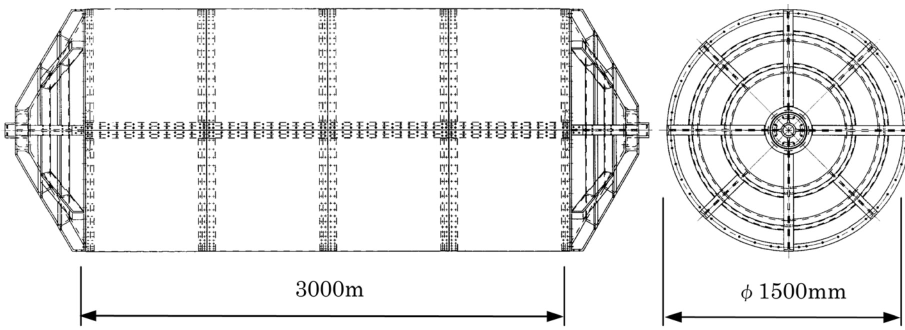
5.2. Test model

The test model is shown in Fig. 7. Using software such as NASTRAN/MATLAB, we performed acoustic vibration analysis and control simulation to determine the number and arrangement of the PZT actuators that were optimal for noise and vibration reduction. We also designed the applicable control rules.

5.3. Noise and vibration reduction test

The outline of the test is illustrated in Fig. 8. This test consists of the three items listed below.

5.3.1. Vibration characteristics acquisition test. The vibration characteristics of the testing structure (natural frequency, vibration mode, and attenuation factor) were derived from the vibration force and vibration acceleration data obtained by applying a vibration load to the test model with a vibration exciter. These vibration characteristics were used to verify and review the PZT actuator arrangement based on the existing control rule design and to tune such control rules.



Shape and basic size	:	Cylinder, ϕ 1.5m × 3.0m(except for the bulkheads)
Structural arrangement	:	Skin/Stringer/Frame
Material of structures	:	Skin→C/EP FRP(P3060B-12) Stringer/Frame/Bulkhead→Al Alloy
Sensor	:	PZT/Accelerometer/Microphone/Strain gauge
Actuator	:	PZT

Figure 7. Noise and Vibration Reduction Demonstrator.

5.3.2. Vibration control test. Using PZT actuators, the vibration load was applied to the test model with the vibration exciter, both when the noise-vibration control system was operating and when it was not operating. Vibration characteristics of the test model (natural frequency, vibration mode, and attenuation factor) were then derived from the vibration force and vibration acceleration data obtained from the test model.

5.3.3. Noise control test. Using PZT actuators in an anechoic room, a noise load was externally applied to the test model from a speaker to obtain the sound pressure level data inside the test model, both when the noise-vibration control system was operating and when it was not operating. The Noise and Vibration Reduction Test was conducted at Kawasaki Heavy Industries, Ltd. from September to December 2002. Figure 9 illustrates the set-up of the Noise and Vibration Reduction Demonstrator. The Demonstrator was set in an anechoic room. The vibration reduction test verified that the vibration attenuation factor was increased by 31%, compared with the target of 20% or more. The noise reduction test verified that the noise level was decreased by 4 dB, compared with the target of 3 dB or more. These results indicate that the objectives of noise and vibration reduction test were successfully attained.

6. CONCLUSIONS

The NEDO ‘R&D for Smart Materials and Structures’ project has finished its five-year project. From the third year, the project was focused on two demonstrators, (1) Damage Detection and Suppression and (2) Noise and Vibration Reduction. Both demonstration tests were finished successfully.

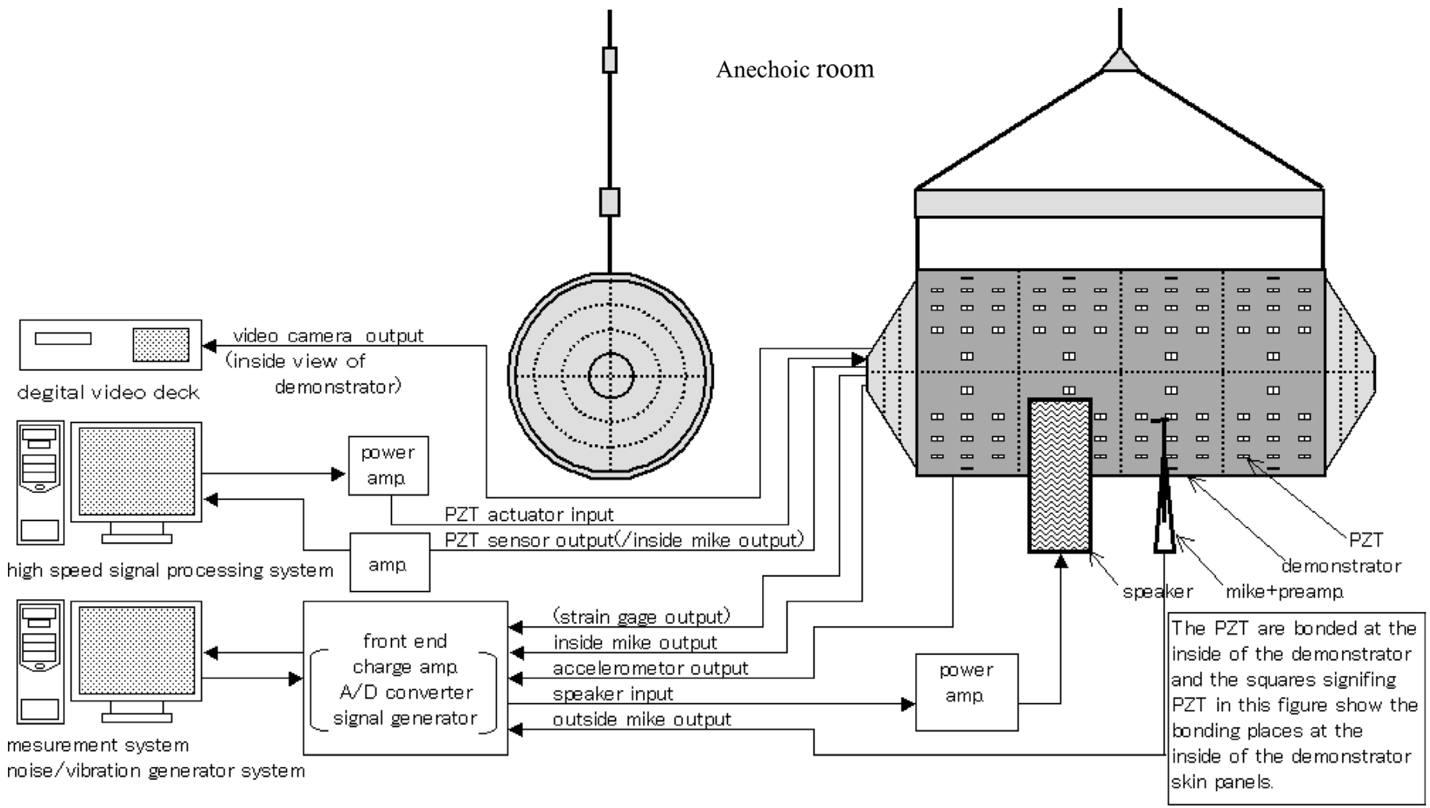


Figure 8. Test configurations of the Noise and Vibration Reduction Demonstrator test.

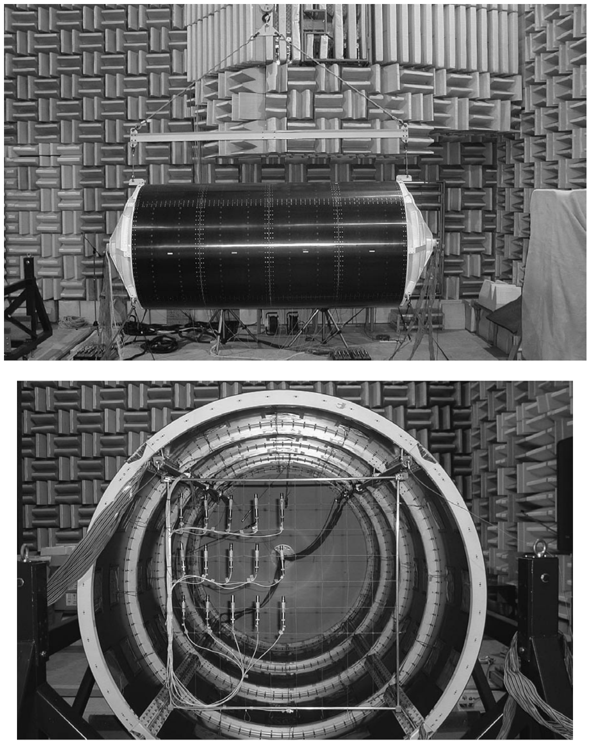


Figure 9. Set-up of the Noise and Vibration Reduction Demonstrator (Kawasaki Heavy Industries, Ltd.).

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