Measuring Safety

Techniques for Diagnosis of Structural Health

National Institute of
Advanced Industrial Science
and Technology
AIST

Reliability of Structures Improved through Measuring Techniques

Structural health monitoring to support safety and security

The time of mass production and mass consumption has come to an end, and the measure of affluence has changed from material to spiritual. In this context, the structural health monitoring technique plays a more important role as a technique that supports safety and security, the basis of the spiritual aspect of life.

Just like the nerve network that protects a human being from disease and injury, structural health monitoring is a technique for self-monitoring the integrity of structures by equipping them with a network of sensors that can detect cracks and other kinds of damage.

This paper introduces our efforts in developing a structural health monitoring system, focusing on the ultrasonic visualization method which is anticipated as a new technique for detecting structural damage.

Changing from “listening to” to “seeing” ultrasonic waves

The currently used ultrasonic flaw detection method is the pulse-echo method which detects any defect echo on the surface of the specimen through manual scanning with a piezoelectric sensor. This method is a so-called “audio” technique, but with this method it is difficult to identify defect echoes in areas where many echoes are present, such as in a welded joint, and even professional inspectors may overlook or incorrectly identify certain defects.

If we can check for defect echoes by visually observing the propagation of ultrasonic waves, it will be easier to identify the signal waves coming from defects, which will in turn reduce the problems of overlooking or misidentifying defects.

Furthermore, it will be possible for us to extract a great deal of information related to damage—information of the kind that could not be obtained from one-dimensional signal waveforms—by analyzing the moving images of ultrasonic propagation. The ultrasonic visualization method is anticipated as a new measurement technique that has the potential to dramatically improve the reliability of flaw inspections.

Using laser to visualize the ultrasonic waves that propagate through three-dimensional objects

The visualization of ultrasonic propagation has been attempted using, for example, the photoelasticity method and the reception-probe scanning method. However, these methods have been applicable only to transparent objects and flat surfaces. It has been virtually impossible to visualize ultrasonic waves propagating through actual, three-dimensional structures. The computer simulation method has been attempted as well, but it is applicable only to simple shaped objects, and, even then, with such limited simulation, it is impossible to detect defects in actual structures.

We have developed a method that generates thermal-excitation ultrasonic waves on a specimen through pulsed laser scanning, and detects the propagation signals via a reception transducer attached at a fixed point. The images of ultrasonic waves propagated from the fixed point are reconstructed using the reciprocity principle of the sound propagation (Figure 1 left).

The advantage of this method is that the pulsed laser can be directed to any point virtually ignoring the incidence angle and focal length of the laser. Needless to say, the laser beam provides non-contact scanning, with which we can visualize any object—no matter how complicated its shape—and measure the moving images of ultrasonic waves propagating through such objects as a drill blade (Figure 1 right). This method

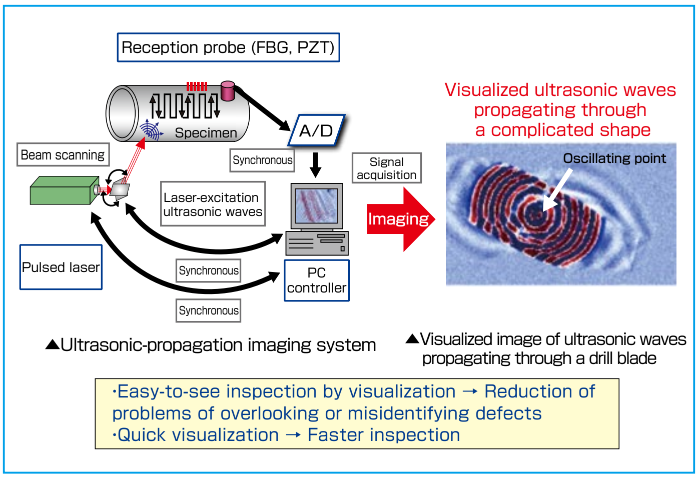

Figure 1. Development of in-situ measurement technique for visualizing ultrasonic propagation using laser

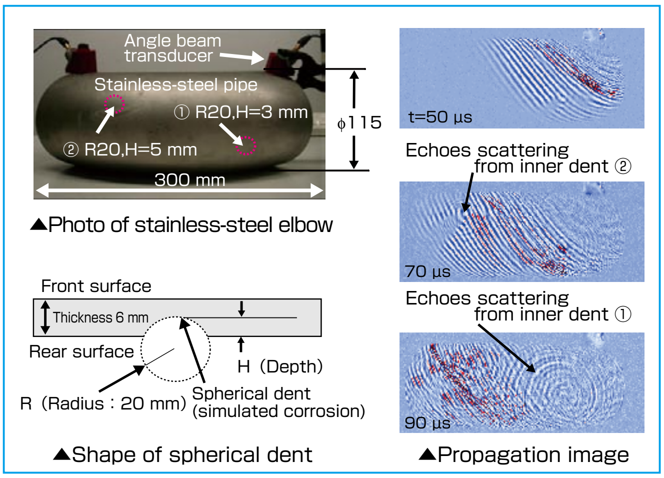

Figure 2. Visualization of the ultrasonic waves propagating through a stainless-steel elbow having simulated corrosion

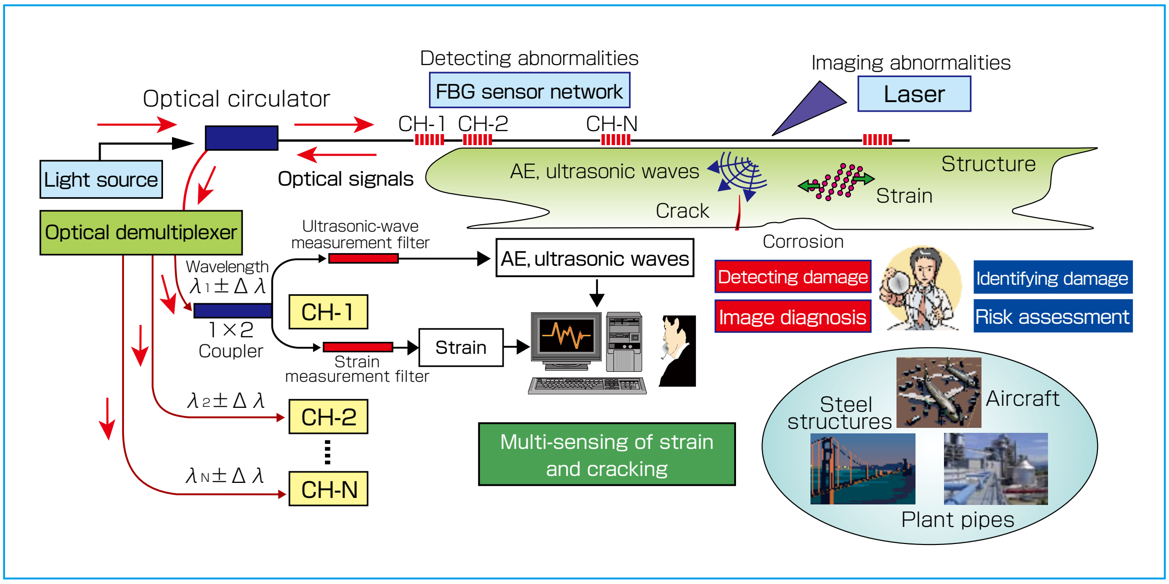

Figure 3. Concept of structural nerve network using FBG optical fibers

will facilitate the inspection of pipe elbows, welded joints, narrow areas and other parts that have conventionally been hard to inspect. Our prototype system has not reached the practical level as it took about one hour to measure a moving image (200 x 200 dots, 500 frames). However, we are currently working to realize a portable device for field use that offers a measurement speed 10 to 100 times as fast as the prototype system.

Ultrasonic propagation images for an elbow with inner defects

An example of applying this imaging method to the flaw inspection of a steel pipe is described below. As shown in Figure 2 left, we machined spherical dents (a curvature radius of 20 mm and a depth of 5 mm, and a curvature radius of 20 mm and a depth of 3 mm, respectively) at two points on the inner surface of a stainless-steel elbow (outer diameter 115 mm, wall thickness 6 mm), in order to simulate corrosion. We then visualized the ultrasonic waves propagating from an angle beam transducer (nominal frequency of 1 MHz and an incidence angle of 45 °) attached at the top-right part of the elbow. From the measured image Figure 2 right, we can observe the echoes as they scatter in a radial manner, like a water ring, from the two points corresponding to the dents on the inner surface.

We also machined a slit crack 1 mm deep and 5 mm long on an aluminum plate of a thickness of 80 mm, and confirmed that the echoes scattering from the back surface slit could be visualized on the surface. These results indicate that the technique is effective in a nondestructive inspection of structures.

Concept of the structural nerve network using optical fibers

As shown in Figure 3, our goal is to realize a structural nerve network by combining FBG (Fiber Bragg grating) optical-fiber sensors and the ultrasonic visualization technique. The FBG sensors for detecting strain have already been commercialized, and we are developing FBG sensors that can also detect ultrasonic waves. Optical fibers are flexible and extremely thin, and several dozen FBG sensor channels can be allotted to a single fiber. This makes it possible to wrap the sensors around a structure as a human nerve network does around a human body. The FBG sensors will monitor strain and ultrasonic waves. If they detect an abnormality, they will measure an ultrasonic image through the remote laser scanning of the abnormal point, then estimate the scale of damage and the associated risk. It is our dream to develop an expert-level flaw detection system which serves as a nerve network as well as a diagnostic device.

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Diagnosing the Degradation of Power Stations and Plants

Age-related degradation associated with old equipment

In recent years, accidents have occurred in succession at power stations and chemical plants. Aging equipment is considered a major factor in these accidents.

When damage occurs in equipment and structures due to aging, it can cause severe human suffering and economic loss. Currently, the time-management type of maintenance and control is being used, in which equipment is periodically brought to a stop and left to cool for the purpose of inspection, repair and maintenance.

However, if we can achieve a high-temperature monitoring system for plants in operation, we will be able to predict damage and avoid severe suffering and loss.

The vibration AE measurement diagnosis technique is expected to be useful in the prevention of accidents. This technique monitors the status of a plant by detecting the abnormal vibration and the acoustic emission (AE) of minute, elastic waves, which are generated by inner breakage of materials within the plant.

The vibration AE sensor generally uses a piezoelectric substance based on lead zirconate titanate (PZT) as a detecting material. Piezoelectric substances are the materials that generate an electric charge on the surface under stress. The stress can be measured by measuring the electric charge. This material is used in the form of a sintered body; therefore, it has the problem of brittle to impact and the loss of piezoelectricity at temperatures (Curie point) as low as 300 °C. The use of this material at a high temperature requires a waveguide or a cooler, which makes it more difficult to take precise measurements. To monitor the status of equipment operating at a high temperature, such as a power plant, there is a strong demand for the development of a high-heat-resistant vibration AE measurement technique that can be operated at 300 °C or higher.

We have developed a high-heat-resistant vibration AE sensor device based on our own thin-film forming method, and with this, we are now developing a status monitoring system for high-temperature equipment operatable at 500 °C or higher.

Developing the high-heat-resistant piezoelectric device

We need sensor materials that are resistant to high temperatures to measure at high temperatures. We focused on aluminum nitride (AlN), which can maintain piezoelectricity even at high temperatures. AlN has the piezoelectric constant d_{33} of 5.6 pm/V and a melting point of 2790 °C, and even at 1200 °C it will not lose its piezoelectricity. This means that AlN is promising as a detecting material for high-heat-resistant pressure and vibration sensors that needs no cooling.

However, unlike ordinary piezoelectric substances, AlN does not allow the direction of polarization to be controlled after it is made. Consequently, the polycrystalline AlN sintered body shows no piezoelectricity. This has prevented AlN from coming into practical use as a piezoelectric substance.

Using a high-frequency magnetron sputtering device, we have successfully formed highly oriented AlN thin films, and the prospects are good for putting AlN into practical use. We are also working to reduce the cost using semiconductor processes.

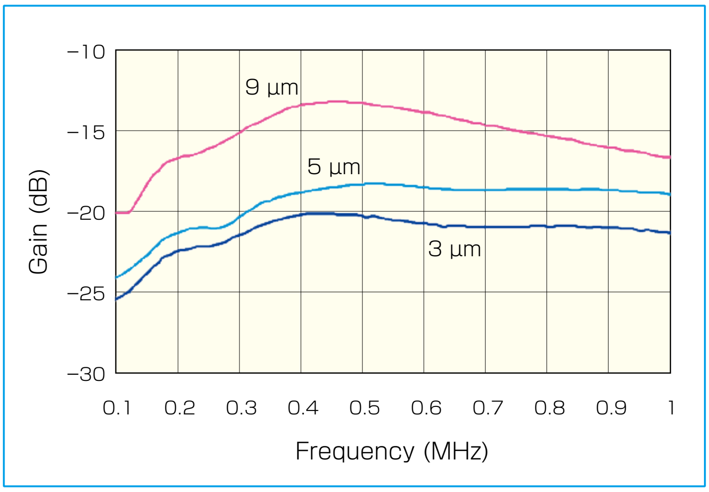

Figure 1. Improvement in sensitivity by thickening aluminum nitride (AlN) thin-film device

Figure 2. High-heat-resistant vibration AE sensor made of aluminum nitride (AlN)

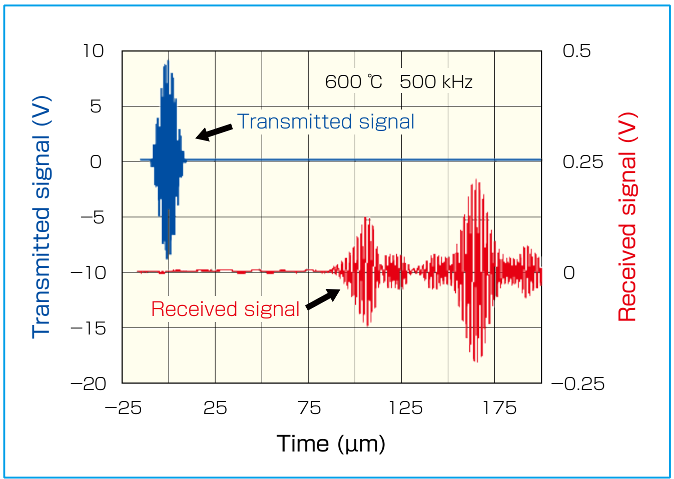

Figure 3. Signal response at a high temperature (600 ℃)

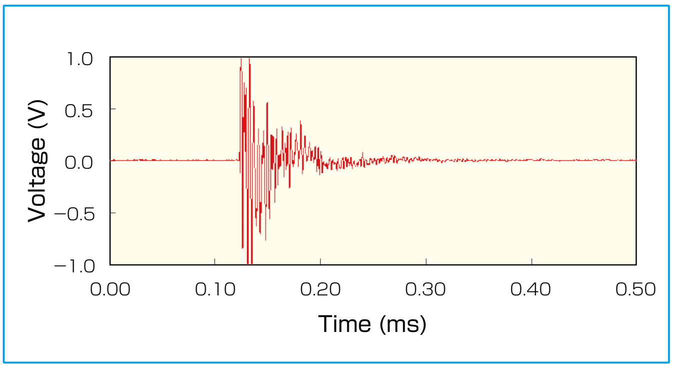

Figure 4. AE signal generated by breakage of a ceramic plate at a high temperature

Developing a high-heat-resistant vibration AE sensor

Subsequent to our development of the AlN thin-film device, we prototyped and characterized a vibration AE sensor using this device. Figure 1 shows the response of the vibration AE sensor to the vibration frequencies for the AlN thin-film device having different thicknesses. It shows that this is a promising vibration AE sensor as it has a flat response in a broad band of 1 MHz or more. It also shows that the sensitivity improves with increasing thickness of the AlN thin-film device.

We have prototyped a high-heat-resistant vibration AE sensor (Figure 2) and are now characterizing it at high temperatures. The sensor has a case made of a heat-resistance metal, Inconel, a receiving surface made of an alumina plate, and a heat-resistant coaxial cable.

We installed this high-heat-resistant vibration AE sensor in an electric furnace, transmitted pseudo AE waves from the outside of the furnace through a waveguide, and measured the response of the sensor at a high temperature. Figure 3 shows the waveforms of the transmitted signal when a 500-kHz tone burst wave was applied at 600 °C, along with the received signal measured by the vibration AE sensor. We confirmed that the signal could be detected even at a temperature of 600 °C and that the sensor showed no deterioration in performance after it was cooled from 600 °C. Figure 4 shows the AE signal generated by the breakage of a ceramic plate to exemplify observation of the AE wave generated by the breakage of a substance at a high temperature.

It has been demonstrated that vibration AE measurements can be achieved at high temperatures of 500 °C and higher. There are many issues to be considered, such as sensitivity, frequency characteristics and oxidation resistance. However, if a status monitoring system for equipment operating at high temperatures is realized through the use of this high-heat-resistant vibration AE sensor, it will allow for the safer operation of plants and other facilities.

We seek to promote the standardization of developed elements and devices by making additional improvements, and to develop a diagnostic measurement system for plant pipes and gas turbines and thus contribute to energy savings and to a safe, secure society. If we can succeed in measuring ultrasonic waves at high temperatures, we will be able to detect the occurrence of defects in pipes using the ultrasonic guided wave method (which transmits ultrasonic waves in the axial direction of a pipe and checks for defects over a wide area) and thereby contribute to safer plant operations.

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Safety Assessment on Structural Materials for Hydrogen Energy

Hydrogen gas as a fuel for automobiles

Vehicles powered by fuel cells use hydrogen as a fuel. Automobile manufacturers are developing them as clean cars without carbon dioxide emission which harms the global environment.

The major method for storing this fuel is a high-pressure hydrogen storage method, which stores pressurized hydrogen in order to increase the driving distance of a fuel cell vehicle. Today, the high-pressure hydrogen storage containers of the 35 MPa class are used in fuel cell vehicles experimentally driven on public roads. However, when high-pressure hydrogen gas contacts with metallic materials, it causes hydrogen gas embrittlement, and this has become a serious problem.

Developing a material testing device under a high-pressure hydrogen atmosphere

We have developed a testing device that is specifically designed to conduct high-precision material tests under a working high-pressure hydrogen atmosphere of 105 MPa (see the photo below).

A hydrogen gas embrittlement material testing device is generally designed to apply a load to a test piece within a pressure chamber through a rod-like tensile part from an external material testing machine. The tensile part goes through the pressure vessel wall, so that increasing the inner pressure of the pressure vessel generates a load that tries to push the part out of the vessel. This load increases to a non-negligible level under high pressure, and affects the operability of the testing machine and causes errors in the measured load.

Our device, however, has a uniquely designed pressure balancer in the middle of the tensile part. The balancer is connected to the vessel through a tube and the inside pressure of the balancer is kept equal to the inside pressure of the vessel, thus the load applied to the tensile part by the inner pressure of the pressure vessel is cancelled out. This prevents the tensile part from moving before the start of a test force and applying to the test piece.

This device is structured to allow liquid to circulate around the pressure vessel, so that material tests can be conducted at temperatures ranging from room temperature to 100 °C. Compared to a conventional design, our device has the following features:

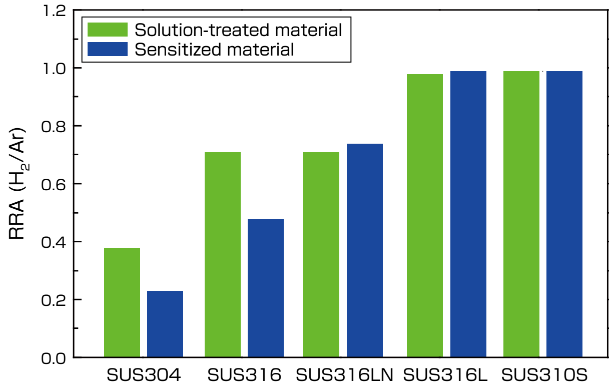
- It is equipped with a pressure balancer that eliminates the influence of the high-pressure hydrogen on the pull force of the tensile part.
- It facilitates accurate measurement of the load applied to a test piece by measuring the friction resistance between the tensile part and the seal part using an external load meter.
- It allows a test piece to be set and removed without disassembling the entire pressure vessel, thus significantly improving the operability.

Hydrogen-gas embrittlement material-testing device

Safety assessment in the high-pressure hydrogen atmosphere

The hydrogen gas embrittlement of metallic materials affects the reduction of area. Therefore, the degree of embrittlement can be quantitatively expressed by the relative reduction of area (RRA) which is calculated by dividing the reduction of area in hydrogen by the reduction of area in argon. The RRA of 1.0 indicates that there is no influence of hydrogen. A smaller RRA indicates more severe hydrogen gas embrittlement.

As candidates for structural materials to be used for high-pressure hydrogen storage, austenitic stainless-steel materials show the RRA in hydrogen at 105 MPa as shown in the graph below. SUS304, SUS316 and SUS316LN each have an RRA as small as 0.4 to 0.7, while SUS316L and SUS310S have the RRA of 1.0. This indicates that hydrogen gas embrittlement is severer for SUS304, SUS316 and SUS316LN, while hydrogen has a smaller influence on SUS316L and SUS310S. Note that SUS304 and SUS316 are more significantly affected by hydrogen when they are heat-treated and sensitized.



Measurement results of candidates for structural materials used in storage

Data on hydrogen gas embrittlement

The results of the tensile tests conducted at AIST on various kinds of metallic materials in a high-pressure hydrogen atmosphere of up to 105 MPa are shown in the table of AIST data on hydrogen gas embrittlement.

Again, the RRA is used to indicate the degree of hydrogen gas embrittlement. Various metallic materials are roughly classified into four categories: Heavy HGE, Moderate HGE, Light HGE and Non-detectable HGE. In the future, we will classify the materials as being "usable," "usable with care" or "unusable."

Fracture Stage I indicates that the influence of hydrogen is recognized before the yield point. Fracture Stage II means the influence of hydrogen is recognized between the yield point and the maximum tensile strength. Fracture Stage III indicate that the influence of hydrogen is recognized after the maximum tensile strength. FS indicates that the influence of hydrogen is recognized only on the fractural surface, while No represents that there is no influence of hydrogen.

Regarding the fracture mode, GB stands for the intergranular fracture, QC for the quasi-cleavage fracture, BTG for brittle transgranular fracture, C for the cleavage fracture, SM for the fracture associated with strain induced martensitic transformation, and D for the dimple fracture.

AIST data on hydrogen gas embrittlement

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HGE	Material	H_2 (MPa)	RRA H_2/Ar	Fracture stage	Fracture mode
Heavy HGE	SCM440(Q)	70	0.00	I	GB+QC
	SNCM439(Q)	20	0.00	I	GB+QC
	18Ni-Maraging(300)	20	0.00	I	GB
	HastelloyB2	70	0.03	II	GB+(BTG)
	SUS630(H900)	70	0.04	II	*
	SUS630(H1150)	70	0.16	II	*
	26Cr-1Mo	39	0.16	II	QC+C
	SUS631(Wire)	70	0.16	III	QC+(GB)
	SFNCM980S(QT833K)	70	0.17	II	QC+GB
	SUS329J1(A)	39	0.21	II	QC+C
	SUS304(Sen)	105	0.23	II	GB+SM
	SFNCM980D(QT833K)	70	0.25	II	QC+GB
	Inconel 750	70	0.26	II	BTG
	S80C	70	0.27	II	QC+C
	SCM440(N)	70	0.29	II	QC+C
	HastelloyC22	70	0.29	II	GB+(BTG)
	SUH3	39	0.29	III	QC
	Fe-30Cr Alloy(A)	39	0.29	III	QC+C
Moderate HGE	S35C	70	0.30	II	QC+GB
	19Cr-1Mo	39	0.30	III	*
	SNCM630	70	0.32	III	QC
	S55C	70	0.35	III	QC+C
	SUS304L	45	0.37	II	*
	SUS304(Wire/T)	70	0.38	III	SM
	SUS304	105	0.38	II	SM
	Inconel 718	70	0.39	II	BTG
	SUS304	70	0.40	II	SM
	MarM247LCDS(//)	20	0.42	II	BTG
	SCM440(QT873K)	70	0.48	II	QC+C
	SUS316(Sen)	105	0.48	II	SM+GB
	S15C	70	0.50	III	QC+C
	Udimet720	20	0.50	II	BTG
	SUY	70	0.53	III	QC+C
	IN100	20	0.58	II	BTG
	SCM440(A)	70	0.59	II	QC+C
	SWP(Wire)	70	0.60	III	QC
	SUS405	39	0.65	III	QC
	Ni201	70	0.71	III	BTG
	2.25Cr-1Mo(A)	39	0.71	III	QC
	SUS316	105	0.71	III	SM
	SUS316LN	105	0.71	III	SM
	SUS316LN(Sen)	105	0.74	III	SM+GB
Light HGE	Inconel 600	70	0.80	III	BTG
	SUS316(Wire)	70	0.96	III	D+(SM)
	SUS316L	105	0.98	FS	D+(SM)
Undetectable HGE	SUS310S(Sen)	105	0.99	No	D
	A6061-T6	70	0.99	No	D
	Incoloy 800H	70	0.99	No	D
	SUS310S	105	0.99	No	D
	SUH660	70	1.01	No	D
	C3771	70	1.06	No	*

(HGE : Hydrogen Gas Embrittlement, * : Not implemented)

Open facility for assessment of hydrogen gas embrittlement

To help companies develop high-pressure gas equipments, we are now developing an open facility for the assessment of hydrogen gas embrittlement. This facility will provide high-pressure hydrogen gas for the test equipment of companies as part of a funded collaborative research project. We also offer the above-mentioned AIST data on hydrogen gas embrittlement along with other data necessary for designing the equipment, and conduct required tests for the continued improvement of equipment safety.

We are also developing a 210 MPa hydrogen gas embrittlement material testing device at the facility. Based on these experimental results, we will assess the safety of hydrogen storage tanks, accumulators, pipes, valves and other parts of fuel cell-powered vehicles and hydrogen stations. Thus we will contribute to the establishment of technical standards for high-pressure hydrogen storage and the development of techniques to prevent hydrogen embrittlement. We will also aim to assist in standardizing the methods of evaluating hydrogen embrittlement.

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Development of Compact X-Ray Sources for Nondestructive Inspections Using the Accelerator Technology

Need for the compact X-ray sources for nondestructive inspections

Nondestructive X-ray inspection is the means to provide internal images of objects without actual contact, and is used in a wide range of fields such as the baggage checks at airports.

X-ray inspection has also been used for product inspections in the area of industry. To ensure plant safety in factories and power stations, nondestructive X-ray inspections have recently become more important, as evidenced in piping inspections.

Regarding plant piping inspections, it is necessary to choose the appropriate optimal X-ray energy for the size and thickness of pipe being inspected. Moreover, the objects under testing cannot be moved, so the X-ray sources need to be moved during inspection quite often into narrow spaces. Compact, portable X-ray sources with energy of 300 KeV (kilo electron-volts) or lower are commercially available. However, X-ray sources with energy higher than 300 KeV are required for the inspection of thick pipes, particularly in elbows, welded parts and such.

In June 2005, the Laws Concerning the Prevention from Radiation Hazards Due to Radioisotopes and Others were put into effect, and the related government and ministerial ordinances were revised. This enabled us to use the movable X-ray sources with linear accelerators of 4 MeV (mega electron-volts) or lower for nondestructive inspections of bridges and other structures following relatively simple procedures. Furthermore, there is an increasing need for compact, portable X-ray sources with the energy range of 300 KeV to 4 MeV.

We are developing compact X-ray sources for nondestructive inspections within this energy range, based on the know-how and results obtained from our research on high-energy electron-beam generation technology using electron accelerators.

Developing compact electron accelerators

A general low-energy X-ray generator produces X-rays by applying high DC voltages to electron beams and accelerating and directing them toward the target. To increase the energy, it is necessary to increase the size of insulators, which makes it impossible to downsize the X-ray source. To solve this problem, a high-energy electron accelerator supplies high-frequency power to many resonant

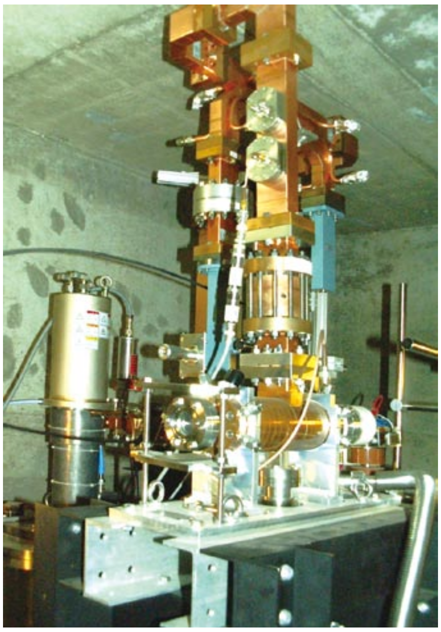

Photo 1. C-band compact electron accelerator system. The cylindrical accelerator tube is seen on the lower front side, and the microwave amplifier tube is seen in the left rear side.

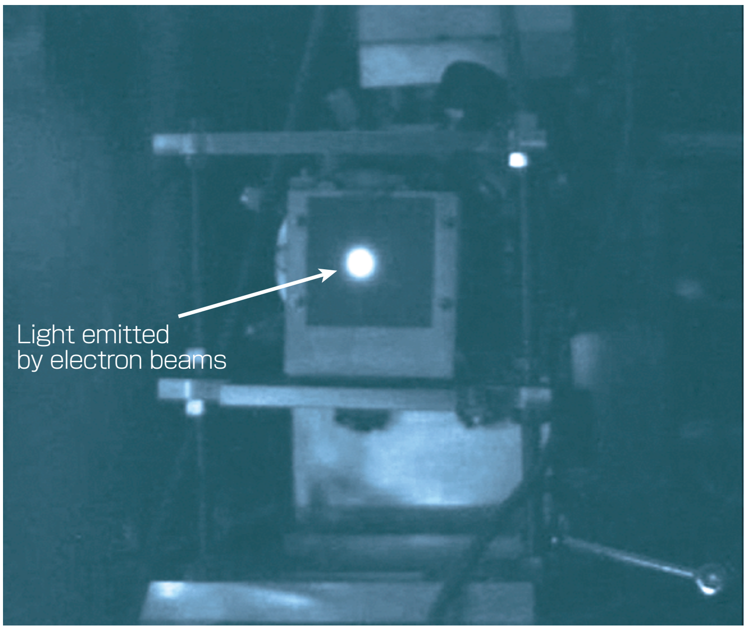

Photo 2. Light emission by electron beams generated by the C-band compact electron accelerator

cavities and uses the periodic electric field generated within those cavities for acceleration. The cavity size is inversely proportional to the resonance frequency. A smaller electron accelerator can be realized by raising the resonance frequency.

However, higher frequencies require greater levels of technology. We have studied the electron accelerator using the microwaves in the S-band (2,856 MHz), and in 2001 we began the study of an electron linear accelerator (LINAC) using the microwaves in the C-band (5,712 MHz) to realize compact electron accelerators that can generate high-energy, high-pulse-rate electron beams. As a result, we have developed the C-band compact electron accelerator system shown in Photo 1.

The electron accelerator depicted in the photo can generate electron beams of 3 MeV or higher. The main unit of the accelerator tube is approximately 35 cm long, and all the components, including the microwave source and the power supply, can be stored within a space of 1 m × 1 m × 1.5 m and can be carried on a dolly. Most commercially available compact electron accelerators use magnetron tubes as microwave sources. However, magnetron tubes oscillate microwaves by themselves. Therefore, it is difficult to synchronize multiple tubes or to change the output, and thus, it is difficult to change the energy.

Contrastingly, the accelerator we have developed employs a microwave amplifier tube (klystron tube) with which we can easily change the output or synchronize multiple tubes in response to various energy levels. Photo 2 shows the light emitted when the electron beams generated by this accelerator enter an alumina plate through a window. We have confirmed that the electron beams can be accelerated as intended.

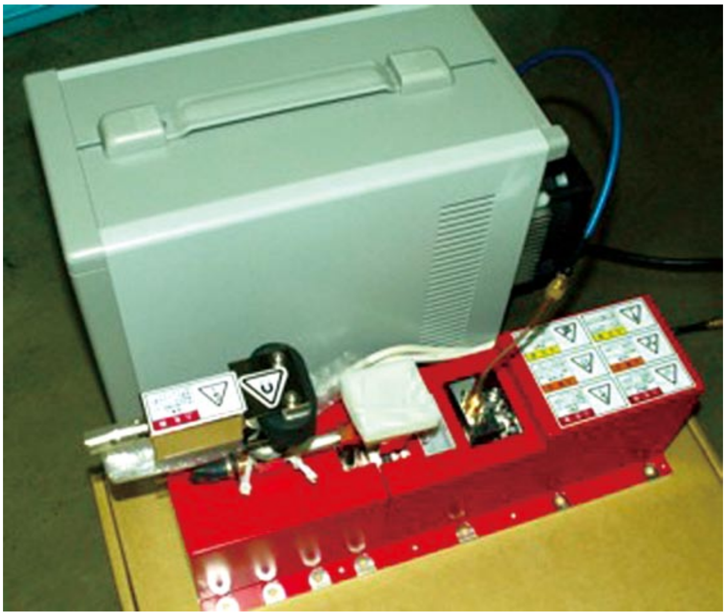

Photo 3. Microwave amplifier tube for X-band accelerator (front) and its driver unit (back)

Developing a portable X-ray generator system

The above-mentioned electron accelerator can be carried on a dolly or similar means, and can generate x-rays of 3 MeV or higher. Therefore, it is suitable for the nondestructive inspection of bridges and other large structures, but it is too large to be used in a narrow space for the inspection of small structures such as the pipes used in factories and power stations.

To solve the problem, we are developing an ultracompact electron accelerator, which can be carried easily by hand, that uses microwaves in the X-band (9.4 GHz to 11.4 GHz) which are of higher frequencies than the microwaves in the C-band. We have already fabricated the main components such as the microwave source, accelerator tube and pulse power supply.

The most important component of this ultracompact electron accelerator is the acceleration microwave generator, and a key aspect of our work is to reduce the size of the generator. We have developed a microwave generator (the microwave amplifier and driver unit included) with a maximum dimension of 35 cm that can be carried easily in one hand (Photo 3).

We are planning to assemble these components into a portable X-ray generation system and carry out experiments involving X-ray nondestructive inspections.

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Monitoring Minor Damage for Enhancing Safety

Structural health monitoring technique for aircraft structural components

To reduce the weight of aircraft and improve their fuel efficiency, light but strong CFRP (Carbon Fiber Reinforced Plastic) is about to be used widely as structural components of next-generation aircraft, where it will substitute aluminum alloy and other metallic materials that are currently being used. Particularly in regard to aircraft, equipment failures and fuselage damage can have a direct and serious impact on human life, and the maintenance and inspection work is very important.

However, most CFRP damages occur in the inner parts and cannot be seen from the surface. Moreover, the damage can be very complicated in shape, thus requiring enormous time, labor and cost of nondestructive inspections during maintenance work.

The structural health monitoring technique is thereby drawing attention. It monitors the occurrence and propagation of damage in real time during operation. If we can immediately become aware of the presence or absence of a damage, its position and its scale, we will be able to conduct inspections very efficiently, and thereby secure aircraft safety and reduce the cost associated with maintenance.

Companies, universities and public research institutes in Japan are promoting joint research and development programs supported mainly by the Ministry of Economy, Trade and Industry.

This article introduces the ultrasonic structural health monitoring technique we are now developing for CRFP structural components of aircrafts.

Detecting any “hot spot” damage

An airfoil consists of a surface layer called the skin and a skin-reinforcing material called the stringer (Photo 1). As is generally the case with metallic structural components, one of the factors that causes damage to the CFRP structural component is a repeated load—or a fatigue load. In the zones of stress concentration close to mechanical joints such as rivets and bolts, innumerable small fissures called ply cracks occur in the skin as a result of fatigue, which eventually develop into harmful delaminations. There are also cases where the interfacial disbond between the bonded skin and the stringer occurs at the edge of the stringer and gradually spreads.

If we can predict the points where damage may occur—otherwise known as hot spots—we can detect the damage by installing piezoelectric devices that can transmit and receive ultrasonic waves at the points and monitor the waveforms of received ultrasonic waves.

However, the ultrasonic waves that propagate through CFRP and other thin plates have several modes, each of which has a different speed depending on the frequency and thickness of the plate. As a result, the detected waveforms become very complex, and generally this makes it difficult to detect flaws in thin plates using ultrasonic waves.

To overcome the problem, piezoelectric devices must be designed and ultrasonic excitation signals must be optimized so that detected waveforms of ultrasonic waves are relatively simple and that subsequent analyses can be performed easily. Figure 1 shows the results of changes in the ultrasonic waveforms with the progress of interfacial disbond between the bonded skin and the stringer. This is done using a pair of optimally designed piezoelectric elements as shown in Photo 1. It can be seen that one simple wave-packet is detected and the arrival time is delayed with the progress of

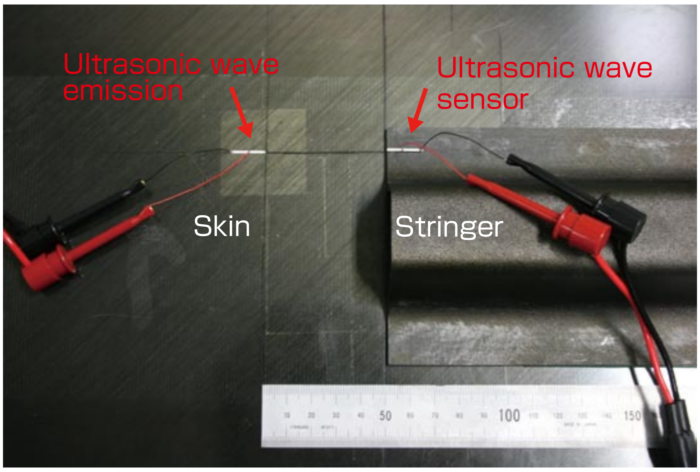

Photo 1. Piezoelectric devices installed on a CFRP skin/stringer structural component

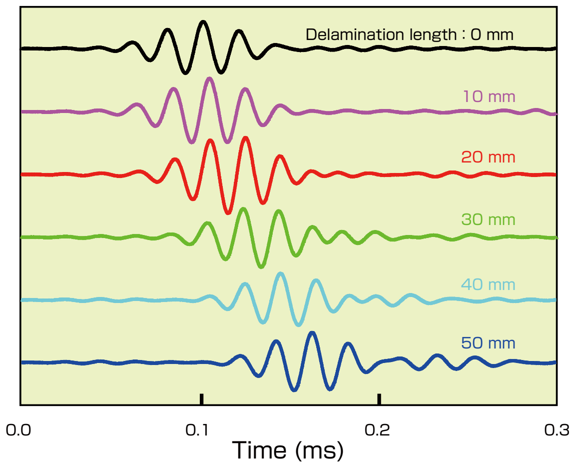

Figure 1. Changes in detected ultrasonic waveforms with the progress of delamination

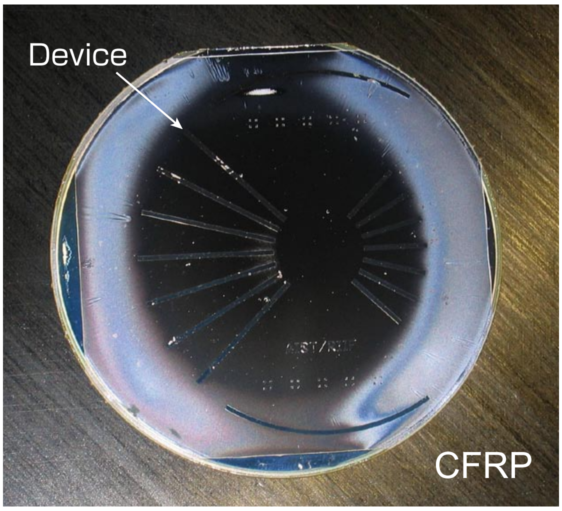

Photo 2. Array sensor composed of directional piezoelectric devices installed on the skin

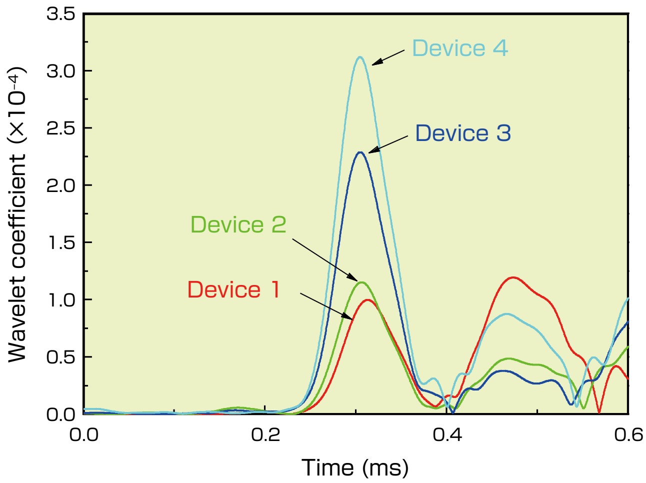

Figure 2. History of wavelet coefficient of the signals detected by each device of the array sensor

disbond.

It has already been proven that, by detecting these changes in the ultrasonic-wave arrival time, we can detect the occurrence of damage. Thus we can also quantitatively evaluate the number of ply cracks and the length of delamination with a certain accuracy.

Identifying the "epicenter" in an aircraft using a new-function ultrasonic sensor

Another important form of damage to aircraft components is the damage under impact load caused by collisions with stones, birds, hailstones and other flying objects during a flight, and by falling tools during maintenance work. It is impossible to predict when and where these impact damages will occur. Thus, based on the same principle of locating the epicenter of an earthquake, there have been attempts to locate the impact points by detecting the ultrasonic waves generated under impact load using ultrasonic sensors installed at multiple points. However, this is not practical as large structures like aircrafts require that sensors be mounted extensively at a large number of points.

We have developed a new wide-area monitoring system that locates a sound source (where an impact or damage occurs) by designing the shape of the piezoelectric devices, adding a new function—directivity—and combining them to form an array sensor. Photo 2 shows an array sensor composed of several long, thin directional piezoelectric devices that have been fabricated by forming a 10 µm thick piezoelectric film on a silicon substrate using microfabrication technology.

Using this array sensor, we detected ultrasonic waves generated under impact load and then extracted the magnitude of certain frequency components by signal processing. The results are shown in Figure 2, indicating that the long-axis direction of the piezoelectric device detecting the maximum strength is the direction of the impact load. With this array sensor, it is also possible to quantitatively determine the direction of the epicenter and its distance from the sensor, with a high degree of accuracy.

Achieving aircraft with the ability to sense "pain"

"It seems that stones have struck the lower part of the fuselage at the coordination (X, Y) during takeoff. But, there is no safety problem. We will continue flying." "Five-centimeter delamination has occurred at the edge of the seventh stringer at the root of the main wing. For caution, please repair it after the flight." To achieve safe-and-secure lightweight aircrafts that are capable of such self-detection and diagnosis, we will promote the creation of new sensors and develop highly-reliable techniques for damage analysis.

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Measuring Safety
Techniques for Diagnosis of Structural Health

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