Development of a high cycle vibration fatigue diagnostic system with non-contact vibration sensing

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Nuclear power plants have a large number of pipes. Of these small-diameter pipe branches in particular are often damaged due to high-cycle fatigue. In order to ensure the reliability of a plant it is important to detect the fatigues in pipe branches at an early stage and to develop the technology to predict and diagnose the advancement of fatigue. Further, in order to carry out the diagnosis of the piping system effectively during operation, non-contact evaluation is useful. Hence, we have developed a "high-cycle fatigue diagnostic system with non-contact vibration sensing," where the vibration of the pipe branch is measured using a non-contact sensor. Since the contents of the developed sensor technology has already been reported [1], this paper mainly describes the newly developed high-cycle fatigue diagnostic system.

Keywords High cycle vibration, fatigue, laser vibrometer, pipe branch, diagnosis

1. Introduction

A nuclear power plant is mainly composed of rotating equipment, piping systems, heat exchange equipment, valves and so on. The piping system is a major part of this. In order to improve plant productivity and to carry out rational control, it is extremely necessary to develop a system capable of easily monitoring and diagnosing a piping system which is distributed over a wide area. The survey of past anomalous cases in piping systems shows that small-diameter pipe branches have a higher rate of damage which is caused by high-cycle vibration fatigue. These pipe branches mostly exist in radioactive areas like loop rooms and as it is difficult to access them to monitor their vibration during operation, we have built a new system for these pipe branches.

Most of the existing fatigue diagnostic systems for piping system use contact sensors [2-6]. However, non-contact sensors are more effective for operational measurement. Hence, the newly developed system adopts the applied technology of lasers and optical fibers in the sensing system, with the sensor head made smaller in size and more resistive to the environment. In the fatigue diagnostic system, an analytical model based on the simulated vibration characteristics of the pipe branch was built by computer. On the basis of the vibration data obtained from the sensing system, the stress and fatigue of a pipe branch are evaluated and diagnosed through the analytical model.

This paper describes the newly developed high-cycle fatigue diagnostic system for small-diameter pipe branches The development project was undertaken by the Japan Power Engineering and Inspection Corporation (JAPEIC) under the consignment of the Ministry of International Trade and Industry (MITI).

2. Outline of System and Sensing System

2.1 System configuration

The configuration of the high-cycle fatigue diagnostic system is shown in Fig. 1. The system is composed of a sensing system and an evaluation and diagnostic system. The sensing system is composed of a sensor head and a signal processing unit. The vibration signal of the pipe branch detected by the sensing system is transmitted to the diagnostic system through an optical fiber cable for analytical evaluation and diagnosis.

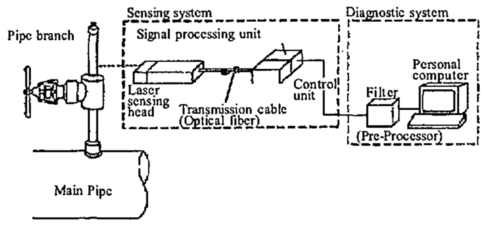


Fig.1 Overview of the whole diagnostic system

2.2 Sensing system

2.2.1 Out-of-plane vibration measurement section (Out-of-plane vibrometer)

(1) Principle of measurement

The newly developed system measures the in-plane and out-of-plane vibrations of the pipe branch in order to improve evaluation accuracy and adopts a Doppler vibrometer for out-of-plane vibration.

(2) Applicability to pipe branches

Because of the plant layout it is often difficult for the pipe branch vibration direction to coincide with the laser direction of a Doppler vibrometer (laser inclination angle 0°) during vibrational measurement, so that an angle of inclination has to be allowed to some extent.
Therefore, before verifying the practical performance of the system, we clarified the application limits of the sensing system through the simultaneous measurement of in-plane and out-of-plane vibration. Figure 2 shows an outline of the test of the out-of-plane vibrometer. A model of a pipe branch was used in the test, with the measuring distance between the sensing system and the pipe branch taken as 5 m, which is necessary in practice. The dominant frequency component of the pipe branch (sinusoidal wave 50 Hz) superposed on the random wave was used as the input wave, with the sensing performance evaluated by the criterion of whether the dominant component, the sinusoidal wave, was detectable or not. The results of the frequency analysis of the input wave (test model acceleration) and the detected wave per laser inclination angle are given in Fig. 3.

According to the result in Fig. 3, the dominant component, the sinusoidal wave, was detectable up to the inclination angle of 25°, so that the application limit of the out-of-plane vibrometer was set to 25° or under.

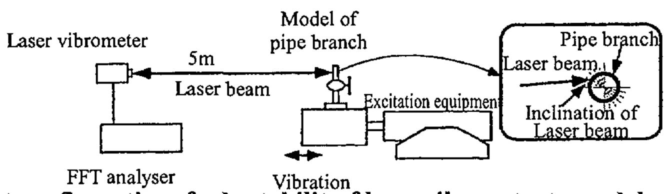


Fig.2 Test configuration of adaptability of laser vibrometer to model of pipe branch

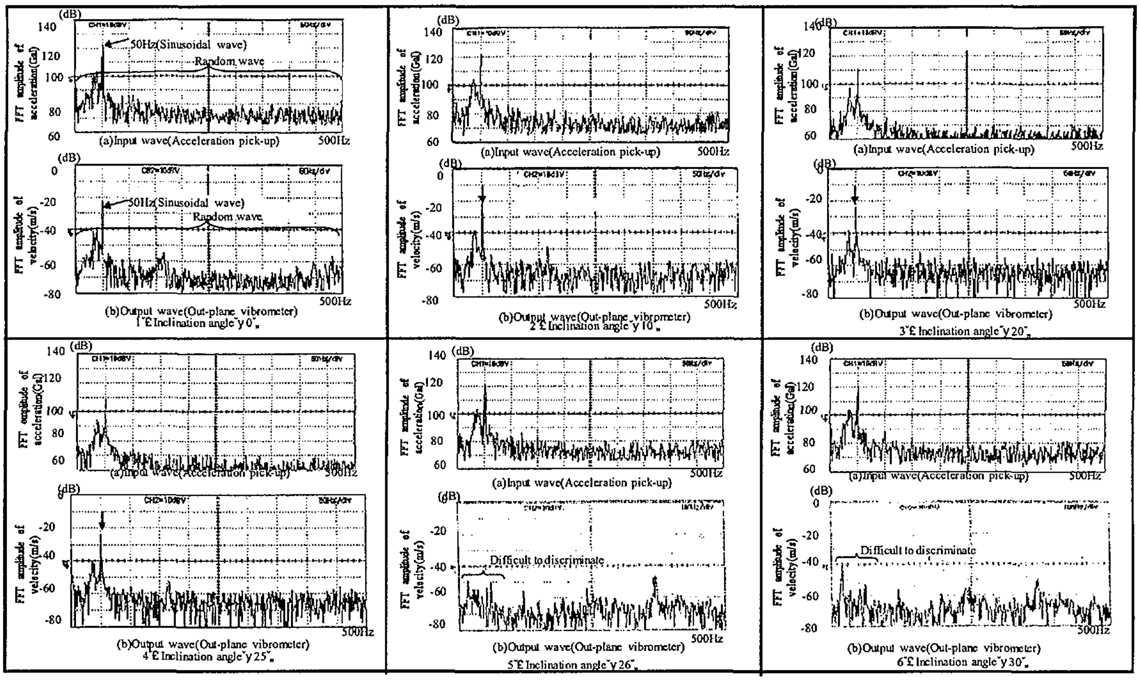


Fig.3 Test results of the out-of-plane vibrometer for inclination of pipe branch

2.2.2 In-plane vibration measurement section (In-plane vibrometer)

(1) Principle of measurement

We studied the Doppler system and the speckle system for measuring the pipe branch vibration in the in-plane direction and found that the former needed a mirror to measure the vibration in the in-plane direction (direction vertical to the laser). As a result, the vibrometer is larger than that of the speckle system, thus we adopted the speckle system to make the equipment compact.

The principle of the speckle system is shown in Fig. 4, and the configuration of the system shown in Fig. 5. 'Speckle' refers to irregular spot patterns formed in the reflected light when a laser beam is irradiated to the surface of an object, which is attributed to the interference of the light reflected irregularly on the rough surface. When the surface of a pipe branch moves, the speckle strength varies in proportion to the velocity of the plane. The vibrational velocity can be calculated by detecting the variation (change) in the speckle strength.

(2) Applicability to pipe branches

We also clarified the application limits of the in-plane vibration measurement in the speckle system. The measuring distance between the sensing system and the pipe branch was set to the practical distance requirement of 5 m, while the dominant frequency component (sinusoidal wave 50 Hz) superposed on the random wave was used as the input wave. The criterion of the evaluation was whether the sinusoidal wave was detectable or not. The results of the frequency analysis of the input wave (test model acceleration) and the detected wave per laser inclination angle are given in Fig. 6.

According to the results in Fig. 6, the dominant component of the sinusoidal wave was detectable up to an incident angle of 15°, so that the application limit of the in-plane vibrometer was set to 15° or under.

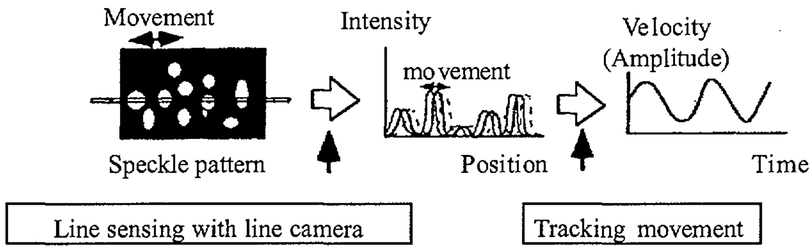


Fig.4˘y˘y Principle of laser in-plane vibrometer with laser speckle method and motion tracking

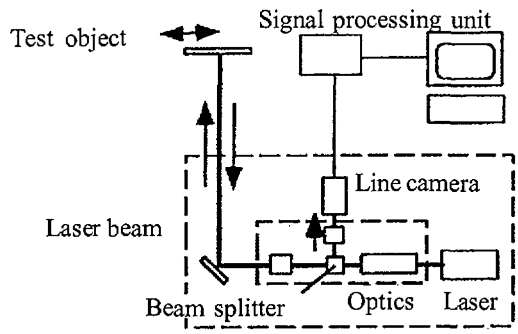


Fig.5˘y˘y Configuration of laser in-plane vibrometer

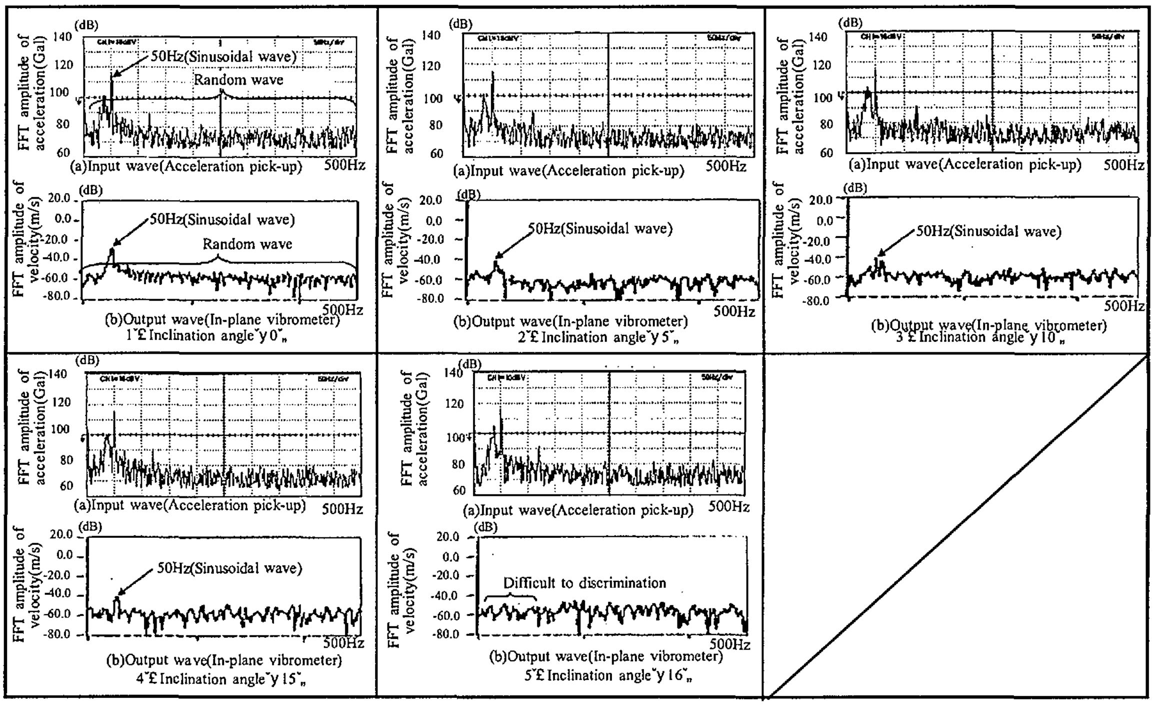


Fig.6 Test results of the in-plane vibrometer for inclination of pipe branch

3. Diagnostic System

3.1 Structure of diagnostic section

The diagnostic system flow is shown in Fig. 7. The diagnostic system is composed of a vibration detection section and an analysis and evaluation section.

The vibration detection section gathers (records) and analyzes the data regarding the branch pipe vibration velocity. The analysis and evaluation section is divided mainly into two parts: the model setting section and the stress and fatigue evaluation section. In the model setting section the relationship between the stress and the velocity response (frequency response character istic)is calculated by making an analytical model of the pipe branch. In the stress and fatigue evaluation section, on the other hand, the stress is estimated and the fatigue is evaluated on the basis of the velocity data (frequency analysis result) obtained by the vibration detection section.

3.1.1 Vibration detection section

The vibration detection section collects the observed record (velocity data) of the pipe branch from the non-contact sensor. The obtained velocity data then undergoes frequency analysis before being stored as a database .

3.1.2 Analysis and evaluation section

This section prepares the analytical model used for response analysis and fatigue evaluation. The prepared model is then used for the frequency analysis to obtain the vibration frequency and vibration mode. The vibration mode is further used to calculate the transferfunctions of stress and response .

In the stress and fatigue evaluation section, the stress is estimated on the basis of the frequency analysis of the pipe velocity response which was gathered and analyzed in the vibration detection section, and the frequency transferfunction of stress and response calculated by the model setting section. The stress is then used to evaluate and diagnose of the fatigue of the pipe branch.

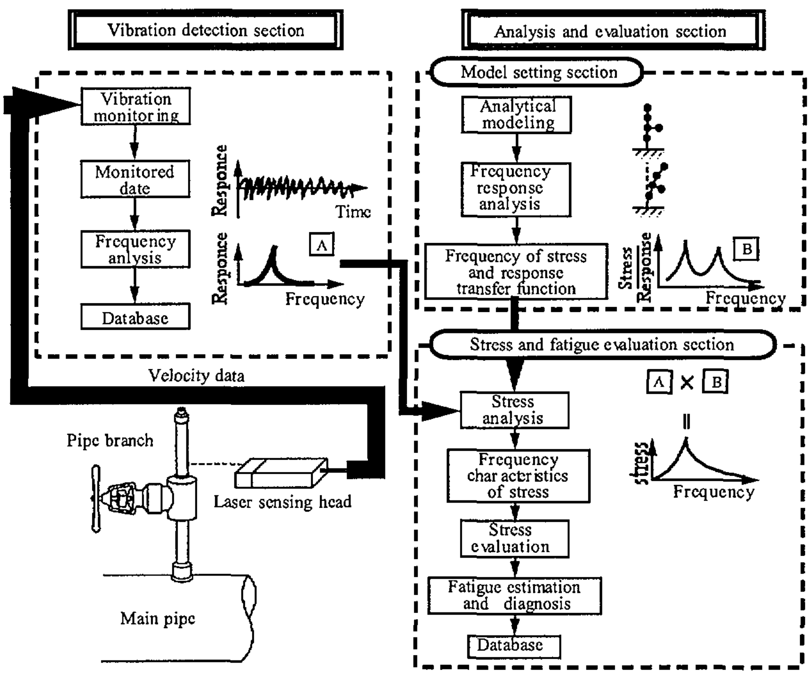


Fig.7 The diagnostic system flow

3.2 Diagnostic algorithm

3.2.1 Estimation of stress

(1) Stress/response frequency characteristic J ( )

Figure 7 shows the flow of procedures for estimating the stress of the pipe branch from the vibration velocity of the pipe measured by using the non-contact vibration measuring method. The stress is obtained in the following manner.

Supposing the stress/response frequency characteristic J ( ) in Fig. 7 is a known value, the stress generated on the branch pipe can be obtained from the measured frequency response (velocity) by the following equation.

(") ˇ¹ v(")ˇ~J(")

ˇyˇyˇyˇ¹ v(")ˇ~H(")ˇ—G(")ˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇy (1)

where: ( ): frequency characteristic of the stress (t) [Fourier transformation]

v ( ): frequency characteristic of the vibration response measured data V (t) of the pipe branch [Fourier transformation]

J ( ): transferfunction of the stress and response

H ( ): transferfunction of the stress

G ( ): transferfunction of the response

In other words, the stress of the pipe branch can be estimated from the frequency response (velocity) of the pipe branch measured in the manner given below.

First, an analytical model for the pipe branch is prepared, and the frequency response transfer function G ( ) and the stress transferfunction H ( ) when excitation force was applied to the main pipe is obtained.

Next, the stress and response transfer function J ( ) in the model setting section is prepared in advance by using the obtained stress transfer function H ( ) and the frequency response transfer function G ( ).

Then, the pipe branch response v (t) is recorded in the vibration detection section and its Fourier transformation v ( ) obtained.

Then, the stress and fatigue evaluation section, the stress frequency characteristic ( ) can be calculated from the product of the pipe branch response V ( ) and stress/response transferfunction J ( ).

Finally, the fatigue can be obtained from the response level and frequency using the frequency characteristic ( ) of the stress .

(2) Response transferfunction G ( )

The transferfunction Gij_r between the excitation force acting on point i and the displacement of j point in r th mode are obtained on the basis of the results of the frequency analysis. The transferfunction Gij_r can be expressed as follows.

$$Gij_r(\ ) = \frac{AirAjr}{Kr} \frac{1}{1\ \ (\ /\ _r)^2 + j2\ _r\ /\ _r} \text{ˇyˇyˇyˇyˇyˇyˇyˇyˇyˇy} \quad (2)$$

where; r = Mode number

i = Excitation force joint

j = Displacement response joint

$_r$ = r th natural circular frequency

$_r$ = r th damping ratio ($_r$ = 0.01)

j^2 = -1 = Complex number

Air = r th gener alzed coordinate amplitude at joint i
K_r = { Ar }^{T}[K]{ Ar }= r th modal stiffness
{Ar} = r th gener alzed coordinate
{K} = Stiffness matrix

The phase between r th mode excitation force and the response can be expressed in the following manner.

$\tan\{Gij_r(\ )\} = \mathrm{Im}\{Gij_r(\ )\}/\mathrm{Re}\{Gij_r(\ )\}$ (3)

Here, the application point i of the excitation force is regarded as the joint of the concentrated mass of the valve.

Hence ,the frequency response at each point can be obtained per r th vibration mode .

Further, the transfer function Gij( ) can be obtained by adding up the transf erfunctions from 1 – n th mode .

$$Gij(\ ) = \sum_{r=1}^{n} \{Gij_r(\ )\}$$ ˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇy (4)

where: n = Highest mode number

(3) Stress transf erfunction H ( )

The frequency response of the stress for r th mode can be obtained from the transf erfunction Gij_r( ) and phase tan{Gij_r( )} by the analytical model.

The transf erfunction H ( ) can then be obtained by piling the stress transf erfunction Hr ( ) of each mode;

$$H(\ ) = \sum_{r=1}^{n} \{H_r(\ )\}$$ ˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇy (5)

Hence , the response and stress transf erfunction J ( ) at the measur ing point (j = m) can be obtained from the ratio H ( ) / Gij ( ) between the response transf erfunction Gij ( ) and the stress transf erfunction H ( ) in the following manner.

$$J(\ ) = \frac{H(\ )}{Gij(\ )}$$ ˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇy (6)

where: r: Joint of the value
j: Point of measurement

3.2.2 Estimation of fatigue damage

On the basis of the obtained stress frequency char acteristics, the fatigue damage can be calculated from the plant oper aton data and from the stress level and frequency by using Miner 's equation for fatigue damage , given below.

$$= \sum_{i=1}^{m} \frac{n_i}{N_i}$$ ˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇyˇy (7)

where: n_i: number of stress amplitude $_i$ (i = 1 - m)
N_i: allowable repeat number for stress amplitude $_i$ (i = 1 - m)

The ASME curve and data from the National Research Institute of Mater ialsare used as the S-N cur ve used for the calculation of the fatigue damage [8, 9]. Further, the stress is compared with the fatigue limit at the time of evaluation, and if the stress exceeds the fatigue limit, the diagnosis is done on the basis of the fatigue damage . (Judged as "damaged "at 1)

3.3 Diagnostic system input/output

3.3.1 Input data

(1) Model setting section

In this section the setting of analytical model is carried out to diagnose the measured data. The pipe branch is modeled as a beam element, with the boundary conditions of the main pipe modeled by using a rotary spring. In the presence of a support, the support stiffness is modeled with the spring element. The required input data and information for model sitting are given below, with the input data screen examples shown in Fig. 8.

Input data; General elements of model (plant data)

・Type of pipe branch (L-type/I-type)

・Pipe branch dimensions (length, diameter, thickness, etc.)

・Pipe branch material constants (Young's modulus of elasticity and Poisson's ratio)

・Valve general elements (weight and centroid position)

・Support general elements (material, shape, dimensions, etc.)

Measurement Information

・Measuring position on the model

・Sensor position

(2) Stress/fatigue evaluation section

In this section the plant operating data and material data are needed to estimate the fatigue damage, with the input data required for the analysis given below.

Input data: plant data

・The pump operating data (start and stop date/time) in the piping system where the pipe branch is to be installed and the material data

・S-N curve of the pipe branch material

3.3.2 Output result

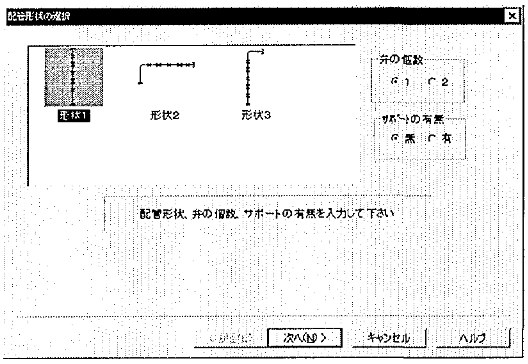
The evaluation results are output in the stress/fatigue evaluation section in the following manner, with the examples of output data screen shown in Fig. 9.

Output data

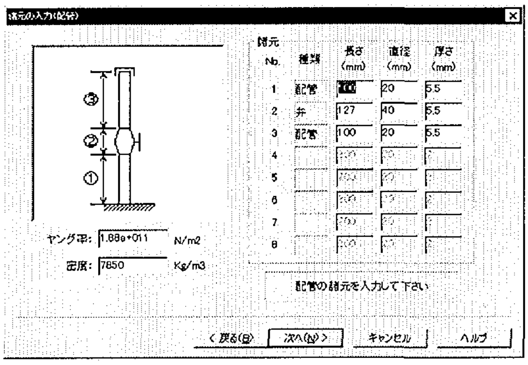
・Comparison between stress and allowable stress (fatigue limit) in each pipe branch

・Fatigue damage

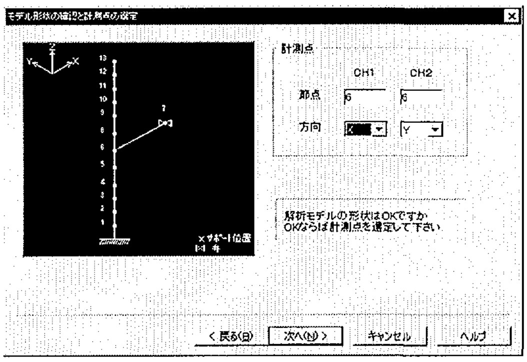
・Evaluation result of remaining life



1) Selection of pipe branch shape

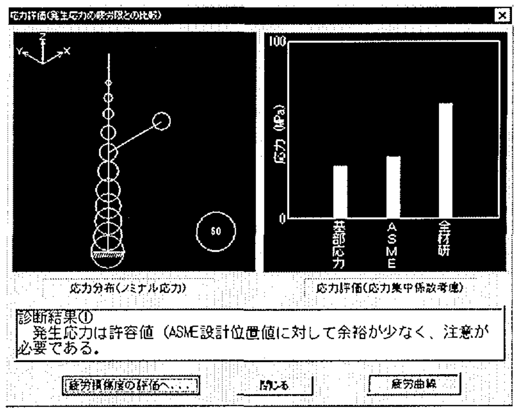


2) Input of stractural and material data

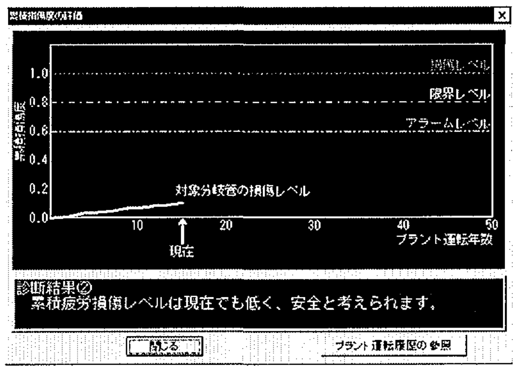


3) Analytical model

Fig.8ˇy Inputdatascreen examples of the diagnostic system



1) Results of stress analysis



2) Estimation results of fatigue

Fig.9ˇy Estimation results screen examples of the diagnostic system

4. Verification Test

4.1 Selection of concerned branch pipe and test model

In order to study the applicability of the high-cycle fatigue diagnostic system to actual equipment, a verification test was conducted using a shaking table. When deciding the test conditions ,the access conditions to the pipe branch in the sensing system were studied using the three-dimensional CAD data from a pipe branch in the loop room of a PWR-type plant.

The monorail shown in Fig. 10 was assumed to be the means of transportation to the sensing system. The route was selected so that the distance between the sensing system and the pipe branch was less than 5 m and the laser inclination angle to the branch pipe was less than ± 15°, the angle confirmed through the test of the sensing system. The results of the investigation of the access to the pipe branch are given in Table 1.

From Table 1, there are three types of pipe branch shape as shown in Fig. 11, and the distance between the pipe and the rail was found to be less than 5 m, substantially enabling the measurement. Most of the laser inclination angles enable measurement at less than ± 15°, except for some points where the inclination angle is 15 - 25°. As for measurement at inclination angles exceeding 15°, a verification test was conducted for confirmation.

From the above results, the pipe branches were classified into 9 types on the basis of the structural parameters given below. However, four representative types were used for the verification test, with the test model shown in Fig. 12.

Structural parameters:

①Diameter of main pipe

②Pipe branch pipe shape

③Number of valves

④Valve installation direction

⑤Joint type, etc.

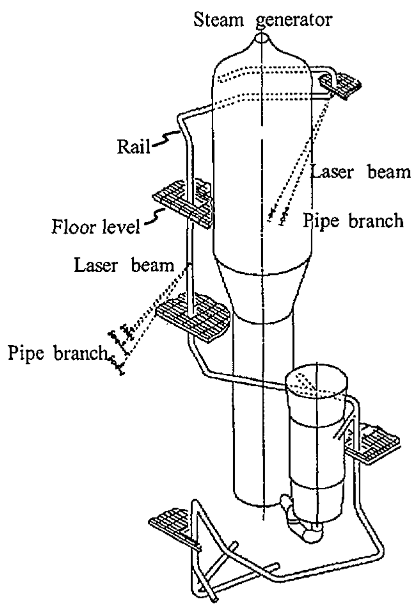


Fig.10 Transportation means of sensing system by monorail in SG room

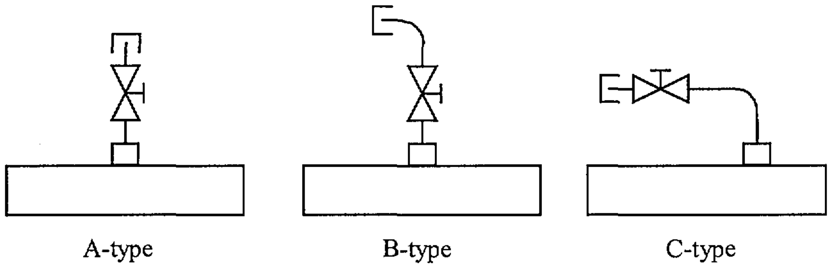


Fig.11 Type of pipe branch

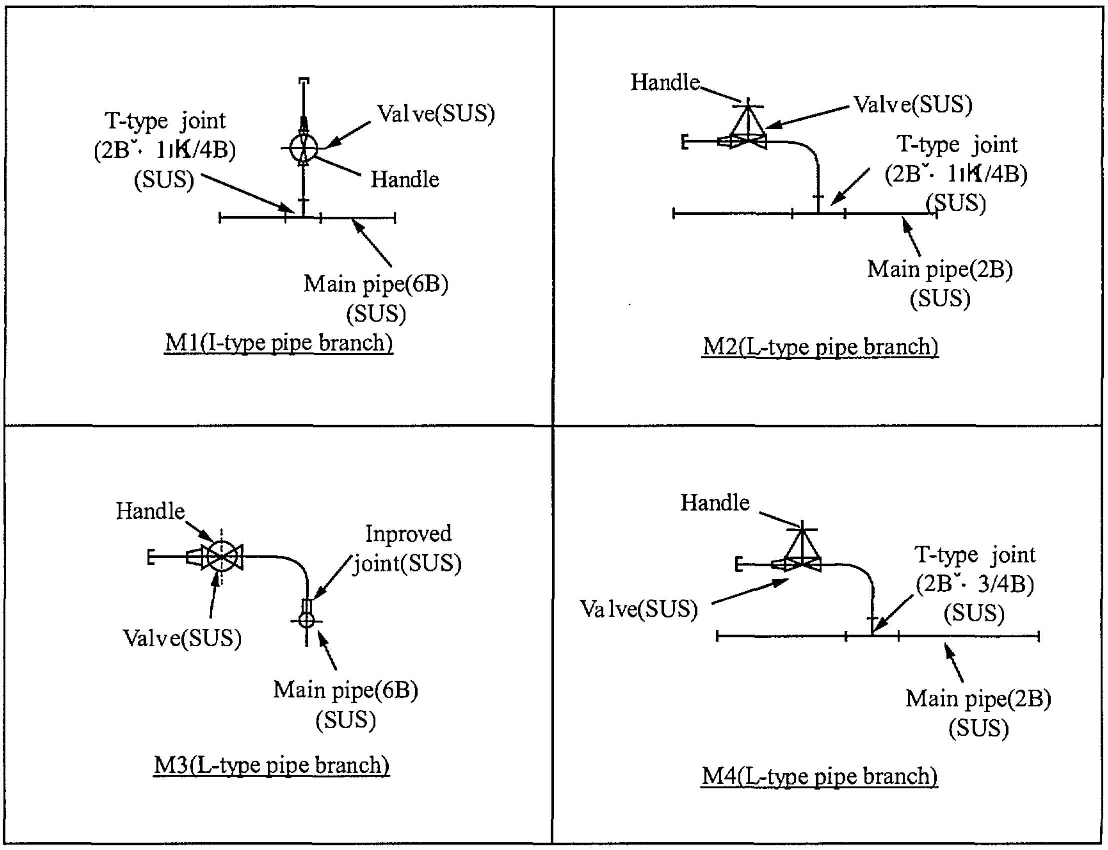


Fig.12 Test model

Table.1 The investigation results of the access to the pipe branch

	Item	Results
Pipe branch	Number	43
	Joint type	Inproved type(3/4B)
	Shape	Fig.11
	Main pipe sides	3/B˘™
Measurement condition	Measurement distance	0.7 5.0
	Inclination beam angle	<˘™ 15˘„˘•<37 15˘™™25˘„ ˘•

4.2 Contentof test

As sho wn in Fig. 13, the pipe branch test model was mounted on the shaking table to conduct the vibration test by means of the input wave based on the simulated main pipe vibration. Figure 14 sho ws the configur ation of the verification test. The stress gener ated on the branch pipe was estimated by means of the diagnostic system using the data measured by the sensing system. The result was compared with the estimated result using the con ventional system with an acceler ation pick-up and the stress measured by a strain gauge in order to verify the diagnostic perform ance of the system. Since the stress is largest on the base pipe branch in view of the stress concentration, a compar ative evaluation was carr ied out on the stress of the base pipe branch. The test conditions are given below.

Test Conditions:

- Input wave: Random wave (simulating the random fluid vibration of the main pipe)
- Sinusoidal wave (simulating the fluid vibration containing a simple frequency component)
- Input direction: one-way
- Sensor inclination angle: 15, 25°

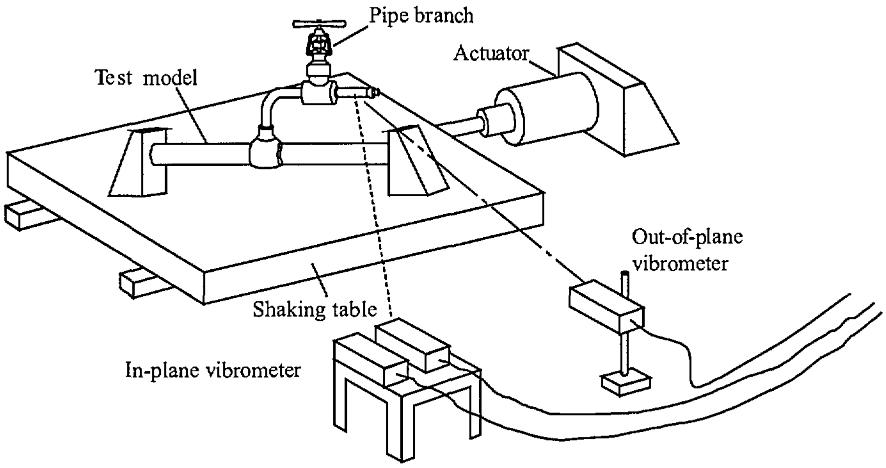


Fig.13 Overview of the verification test

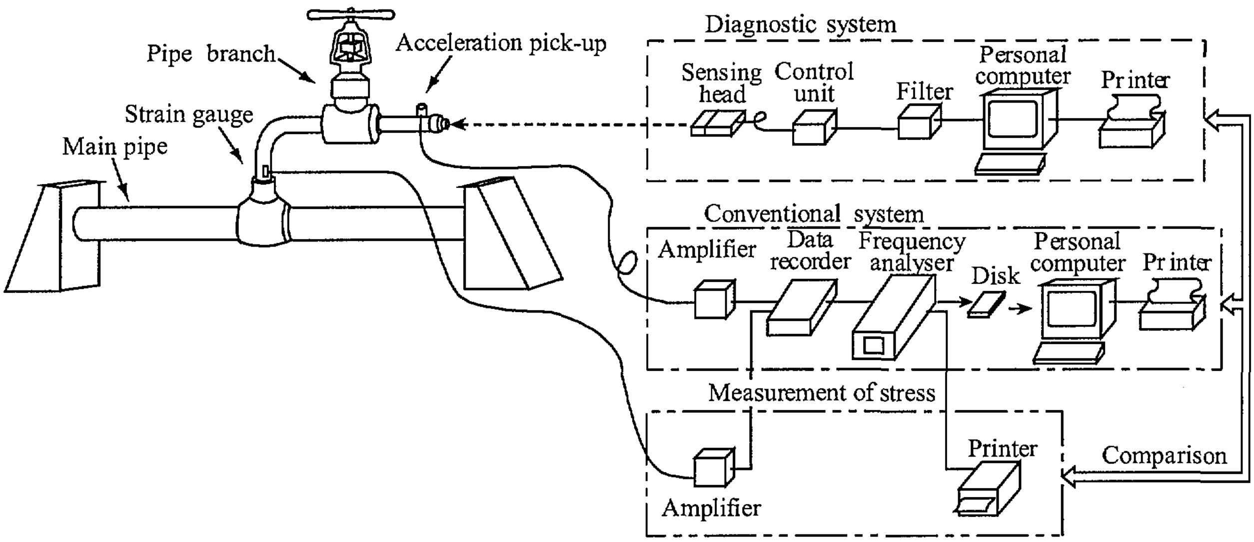


Fig.14 Configuration of the verification test

4.3 Test result

The test results of the M3 model are given below as an example. The M3 model uses an L-type pipe branch with the pipe shaft laid in an orthogonal direction to the main pipe and the valve is installed in the horizontal direction so that the model has comparatively complicated vibrational properties with the torsional vibration being dominant. As for the input vibration, random vibration with a simulated random fluid and a sinusoidal vibration with simulated fluid containing the dominant frequency component (the dominant frequency corresponding to the natural frequency, 72.5 Hz, of the pipe branch) were applied. Further, in-plane and out-of-plane tests were carried out at the sensor inclination angle of 15°, while only an out-of-plane measurement was made at the sensor inclination angle of 25°.

The stress estimated by the new diagnostic system and the measured velocity response are given in Table 2. The stress obtained through the structural analysis software and the stress measured by using strain gauges are also given in the same table. The stress obtained through the structural analysis software is the stress calculated from the analytical model in Fig. 15 on the basis of the acceleration response measured by using the installed accelerometer.

The stresses at the sensor inclination angle of 15° (simultaneous in-plane and out-of-plane measurement) and of 25° (out-of-plane measurement) are given in Fig. 16, while a comparison of the stress measured by the strain gauge and the stresses measured in different ways and at different sensor angles is found in Fig. 17.

From Figs. 16 and 17, compared with the stresses obtained through the conventional direct process using structural analysis software and a strain gauge, the stress estimated by using the newly developed diagnostic system was found to be equivalent. Further, the estimation accuracy in the case of out-of-plane vibration (measuring at an inclination angle of 25°) is almost equivalent to the estimation accuracy in simultaneous in-plane/out-of-plane measurement (measuring at an inclination angle of 15°), so that a substantial estimation can be made through an out-of-plane vibration measurement only, provided that the vibration mode is specified.

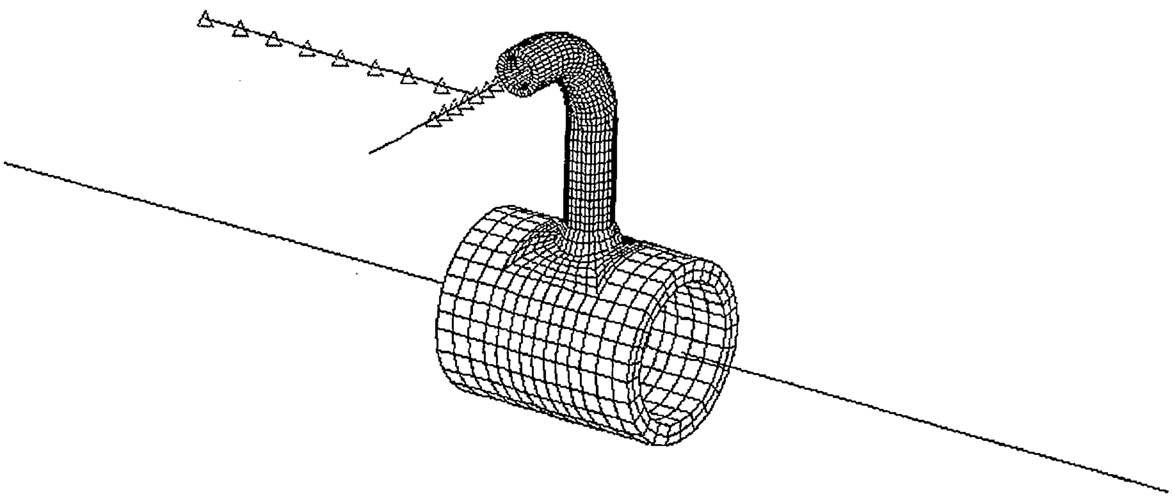
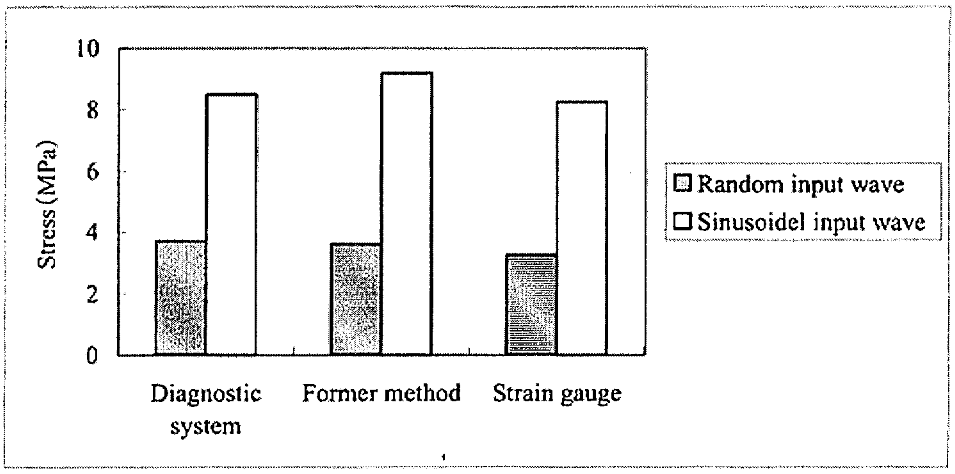
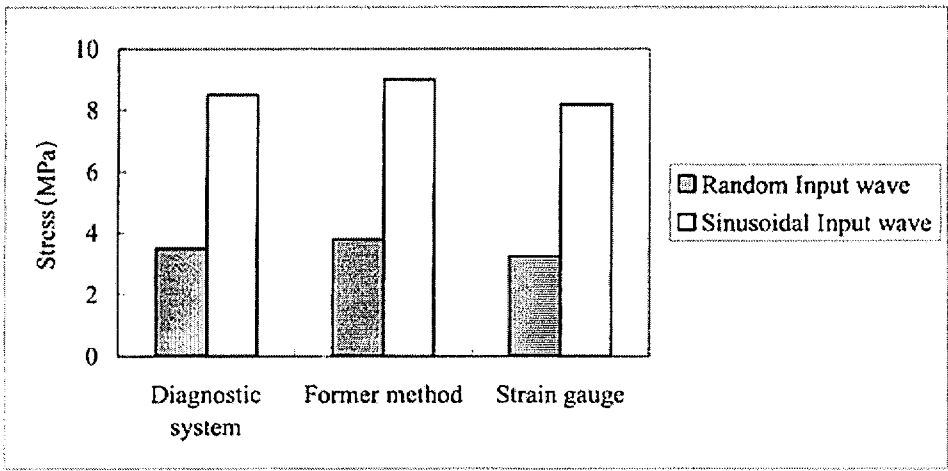


Fig.15 Analytical solid model(M3 model)



1) Estimated stress with in-plane and out-of-plane vibrometer(Inclination angle 15•)



2) Estimated stress with out-of-plane vibrometer(Inclination angle 25•)

Fig.16 Estimated stress of pipe branch by each method

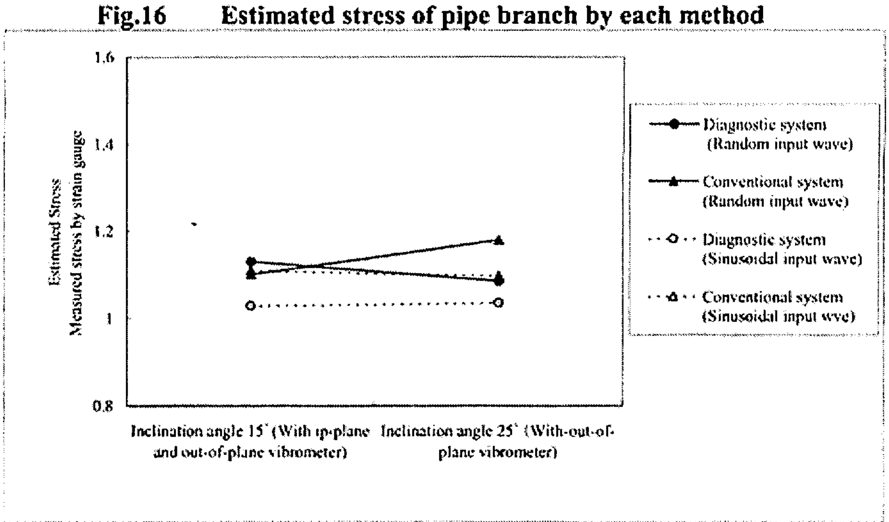


Fig.17 The comparison of measured stress by strain gauge and estimated stress

Table.2 The test result of estimated stress(M3 model)

Case	Input condition		Diagnostic system					Conventional system		Strain gange
	Input wave	Level	Measurement condition		Measured velocity		Estimated stress (MPa)	Measured acceler ation (G)	Estimated stress (MPa)	Measured stress (MPa)
			Distance (m)	Inclination angle („)	Out-of-plane	In-plane				
M3-1	Random wave	0.5	5	15	2.8	0.8	3.7	1.32	3.6	3.27
M3-2	Sinusoidal wave	0.06	5	15	6.4	1.8	8.5	3.38	9.2	8.26
M3-3	Random wave	0.5	5	25	2.5	•	3.5	1.38	3.8	3.22
M3-4	Sinusoidal wave	0.06	5	25	6.0	•	8.5	3.31	9.0	8.20

5. Conclusion

In this development project, the measurement methods and the diagnostic methods needed for the high-cycle fatigue diagnostic system of small-diameter pipe branch were established and the newly developed system was given a verification test to confirm the availability of the system.

It is necessar to miniaturize the sensing section and to develop the transportation equipment such as the rail, shown in Fig. 10 when installing the new system. However, the adoption of the high-cycle fatigue diagnostic system helps to avert the mismatching of pipe branches to shorten the piping system repair time and to rationalize the periodic inspections, significantly contributing to the improvement of the safety and reliability of a plant.

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