



ISSN 1349-1121
JAXA-RM-14-002E

JAXA Research and Development Memorandum

Functional Enhancement of Multiaxis Vibration Evaluating System and Outline of Overall System

Atsushi KANDA and Kiyoshi SAMATA

September 2014

Japan Aerospace Exploration Agency

Table of Contents

1. Introduction.....	1
2. Outline of System	2
2.1. Outline of MaVES	2
2.1.1. Configuration of system	2
2.1.2. Mechanism of measurement	3
2.2. Outline of MaVES-c	4
3. Details of MaVES	5
3.1. 3D scanning vibrometer.....	5
3.1.1. Configuration of vibrometer	5
3.1.2. Specifications of vibrometer	6
3.1.3. Measurement functions	6
3.1.4. Optical system.....	7
3.1.5. Vibration velocity detection performance.....	8
3.1.6. Functions of PSV software	8
3.2. Sensor positioning control robot.....	10
3.2.1. Configuration of robot.....	10
3.2.2. Specifications of robot	11
3.2.3. Coordinate system of robot.....	12
3.2.4. Functions of robot	12
3.3. Integrated software.....	12
3.3.1. Role of software	12
3.3.2. Functions of integrated software.....	13
3.4. Modal analysis software	13
3.4.1. Configuration of software	13
3.4.2. Functions of modal analysis software.....	13
3.5. Others.....	14
3.5.1. Safety light barrier	14
3.5.2. Scanning head installation jig	16
3.5.3. Robot stand	16
3.5.4. PC and network.....	17
3.5.5. Laser vibrometer	17
3.5.6. Surface plate.....	18
4. Details of MaVES-c.....	19
4.1. 1D scanning vibrometer.....	19
4.1.1. Configuration of vibrometer	19
4.1.2. Specifications of vibrometer	20

4.1.3.	Measurement functions	20
4.1.4.	Optical system.....	21
4.1.5.	Vibration velocity detection performance.....	21
4.1.6.	Functions of PSV software	21
4.2.	Sensor positioning control robot.....	21
4.2.1.	Configuration of robot.....	21
4.2.2.	Specifications of robot	22
4.3.	Others.....	22
4.3.1.	Safety fence.....	22
4.3.2.	Installation of scanning head	23
4.3.3.	Robot stand	23
4.3.4.	Surface plate.....	23
5.	Measurement Methods.....	25
5.1.	Flow of measurement.....	25
5.2.	Measurement preparations	25
5.2.1.	Installation of test piece and measurement equipment	25
5.2.2.	Switching of system.....	25
5.2.3.	Startup of MaVES.....	25
5.3.	Setting of optical system.....	25
5.3.1.	Preference settings of PSV.....	25
5.3.2.	Setting of 2D alignment	26
5.3.3.	Setting of 3D alignment	26
5.3.4.	Calibration of BASE coordinate system	26
5.4.	Teaching of robot position	27
5.5.	Setting of measurement points.....	28
5.6.	Analysis of measurement points	29
5.7.	Setting of measurement conditions	32
5.8.	Execution of automated measurements	32
5.9.	Processing of measurement results	32
6.	Measurement Examples	33
6.1.	Natural mode measurements.....	33
6.1.1.	Test piece	33
6.1.2.	Setting of measurements.....	34
6.1.3.	Robot position.....	34
6.1.4.	Geometries	34
6.1.5.	Measurement conditions	35
6.1.6.	Operational analysis.....	35
6.1.7.	Modal analysis	36

6.2.	Ultrasonic elastic wave transmission measurements	38
6.2.1.	Test piece	38
6.2.2.	Setting of measurements	38
6.2.3.	Geometries	39
6.2.4.	Measurement conditions	39
6.2.5.	Ultrasonic elastic wave transmission	41
7.	Special Training	42
8.	Conclusion	43
References	43

Functional Enhancement of Multiaxis Vibration Evaluating System and Outline of Overall System*

Atsushi KANDA^{*1} and Kiyoshi SAMATA^{*2}

Abstract

The Multiaxis Vibration Evaluating System (MaVES) can automatically measure the three-directional vibration characteristics of objects in a non-contact mode, and analyze modal characteristics and operating deflection shapes. This system consists of three laser Doppler sensors, a six-axis robot, and control software. The MaVES was originally developed in 2010 and was later enhanced in the area of sampling frequency, accuracy of measurement point geometry, and analysis function. In 2013, the MaVES was moved to a new area and secured with safety light barriers during measurements. Additionally, the MaVES-c was developed as a portable version of the MaVES. This paper describes the entire system specifications, functions, measurement procedures, and examples of the MaVES and MaVES-c.

Keywords: *robot, laser, vibrometer, modal characteristics, MaVES, MaVES-c*

Outline

The multiaxis vibration evaluating system (MaVES) is capable of conducting non-contact and automated measurements of vibrations of an object in three axis directions, using laser Doppler-type sensors and a six-axial robot. The system can also perform modal and operating deflection shape analyses. Since its development in 2010, functional enhancements such as (a) increase in sampling frequencies, (b) improvement of positional accuracy for measurement points, and (c) additional analysis functions have been implemented in the system. Furthermore, a new measurement area was established and improved, and a safety light barrier was added. The MaVES was relocated to the new area in 2013, and the prototype MaVES-c, a compact, automated, non-

contact multiaxial vibration measurement system was developed with the aim of improving the portability of the MaVES. This paper outlines the specifications and methods of measurement of the MaVES and MaVES-c systems after their functional enhancements, and also provides examples of the measurement methods such as natural mode and ultrasonic elastic wave transmission measurements.

1. Introduction

The Japan Aerospace Exploration Agency developed the automated, non-contact, multiaxial vibration measurement system (MaVES) in March 2010¹⁾. The MaVES is capable of conducting automated, non-contact, three-dimensional (3D)

* 11 June 2014 received

*1: Structures Research Group, Institute of Aeronautical Technology

*2: Airframe Group, System Engineering Office, Engineering Department, JAL Engineering Co., Ltd.

vibrational measurements of objects and automatically obtaining the vibrational characteristics of entire objects by moving laser sensors using a six-axial arm-type robot. A variety of vibrational measurements have been conducted both within and outside the agency since the development of the MaVES and implementation of its functional enhancements (such as the increase in its sampling frequencies, improvement of the positional accuracy of its measurement points, and addition of analysis functions), in response to the increasing demand for measurement over the years. In March 2013, further large-scale expansions were made, with the establishment of a new measurement area and the relocation of the MaVES. A safety light barrier was added to the MaVES (Fig. 1.1) and the prototype compact, automated, non-contact multi-axial vibration measurement system (MaVES-c) (Fig. 1.2) was developed with an aim of improving the portability of the MaVES.

This paper provides an overall outline of the MaVES and MaVES-c systems, including their functional enhancements, specifications, functions, and measurement methods along with measurement examples such as the natural mode and ultrasonic elastic wave transmission measurements.



Fig.1.1 Multi-axial Vibration Evaluating System (MaVES)



Fig.1.2 Compact Multi-axial Vibration Evaluating System (MaVES-c)

2. Outline of System

This section provides the outline of MaVES and the MaVES-c.

2.1. Outline of MaVES

2.1.1. Configuration of system

The MaVES is comprised of a 3D scanning vibrometer, a sensor positioning control robot, integrated software for synchronizing them, modal analysis software, and a safety light barrier (Fig. 2.1), for performing a series of tasks ranging from the measurement of vibration characteristics to analysis. The 3D scanning vibrometer, sensor positioning control robot, and modal analysis software are general-purpose items that can be used independently.

The 3D scanning vibrometer is at the core of the system and is capable of conducting vibration measurements (out-of-plane or in-plane) using lasers in the three axis directions within a timeframe or frequency range. It also comprises built-in PSV software that features pre- and post-process functions that can be used to set measurement points, display measurement data and results of operational analysis, or as a function for performing laser scans over a specified area by controlling the mirror in the sensor section.

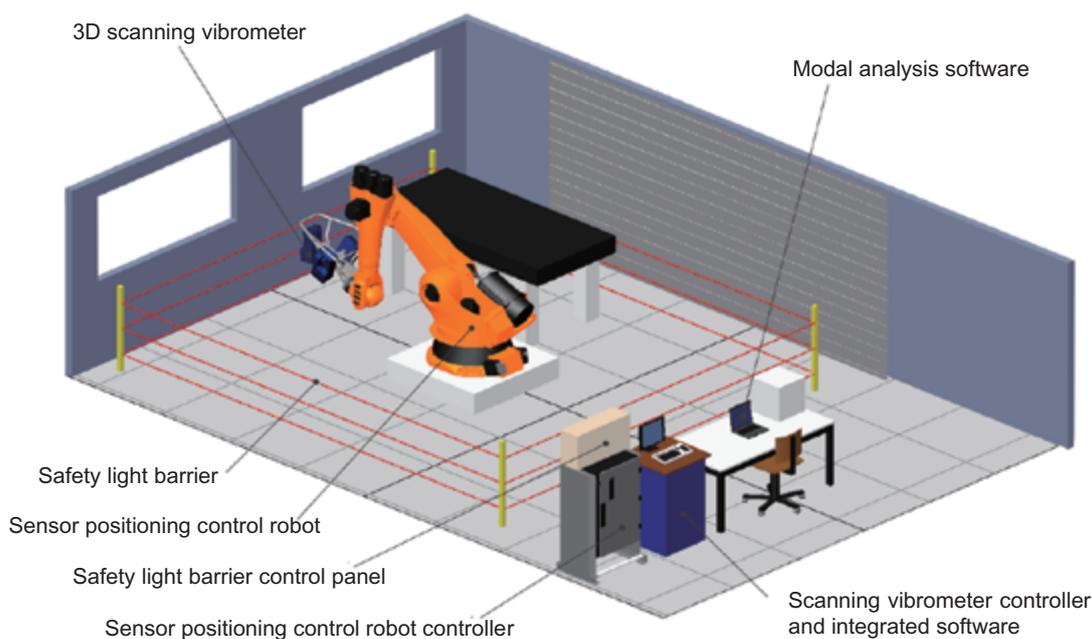


Fig.2.1 Configuration of MaVES

The sensor positioning control robot is an arm-type, six-axial, articulated robot used for determining the position of the sensor of the 3D scanning vibrometer. The sensor can be easily set to a desired position without having to set it up on a tripod or frame, unlike conventional systems.

The integrated software is intended for enabling the automated measurement of vibrations over a broad range of measurement points, by synchronizing the operations of the 3D scanning vibrometer and robot.

The modal analysis software is intended for performing modal analysis using the vibration characteristics data obtained from the 3D scanning vibrometer (along with the sensor positioning control robot and integrated software).

2.1.2. Mechanism of measurement

The vibrometer detects the vibration velocity of the vibrating test piece in the axial direction of lasers using the laser Doppler effect. The MaVES mechanism derives the vibration velocity at the

intersection of the X, Y, and Z axes by calculating the vibration velocity component in each of the three directions using such an arrangement of the three laser sensor units wherein the units are never coaxial with each other.

The vibration velocity can be measured in three axial directions at an arbitrary point using a single measurement. However, measurement at multiple points is possible only by using the scanning function of the laser for sequentially scanning the multiple measurement points and conducting measurements. Laser scanning is actuated by operating the galvanometer mirror built into the sensor. Vibration measurements can be conducted only using the 3D scanning vibrometer and without using the robot and the integrated software for synchronization, provided the target area is located within the operating range of the mirror. Measurements over wider ranges are conducted by operating the robot on which sensors are mounted. Automated measurements at multiple measurement points located across a broad range are possible owing to the existence of the mechanism for

synchronizing the operations of the robot, scanning (using the sensors), and capturing of data.

Furthermore, the measurement points can be set on the screen by displaying their video images using a PC, as a CCD camera is built into each laser sensor. The coordinates of the measurement points can be calculated by (a) measuring the distance from each sensor to the measurement point using the geometry scan unit built into the sensors and (b) using the positional coordinates of the sensors, in turn, calculated from those of the robot.

2.2. Outline of MaVES-c

The MaVES-c is a compact version of the MaVES created for the purpose of enhancing portability. It comprises a one-dimensional (1D) scanning vibrometer, sensor positioning control robot, and safety fence (Fig. 2.2). The 1D scanning vibrometer and sensor positioning control robot are general purpose items and can, therefore, be used independently.

The 1D scanning vibrometer can conduct

vibration measurements using lasers in a single axis direction within a timeframe or frequency range. It also comprises the built-in PSV software that features pre- and post-process functions that can be used for setting the measurement points, displaying measurement data and results of operational analysis, or as a function for performing laser scans over a specified area by controlling the mirror in the sensor section. A CCD camera is built into each laser sensor, which allows the setting of measurement points on the screen by displaying their video images using a PC. The geometry scan unit, similarly built into the sensors, can be used to measure the distances from the sensors to the measurement points.

The sensor positioning control robot is an arm-type, six-axial, articulated robot used for determining the positions of the sensors of the 1D scanning vibrometer. The sensors can be easily set to a desired position without having to mount them on a tripod or frame, unlike conventional systems.

The current MaVES-c, incidentally, is a prototype that is in the process of development and does not

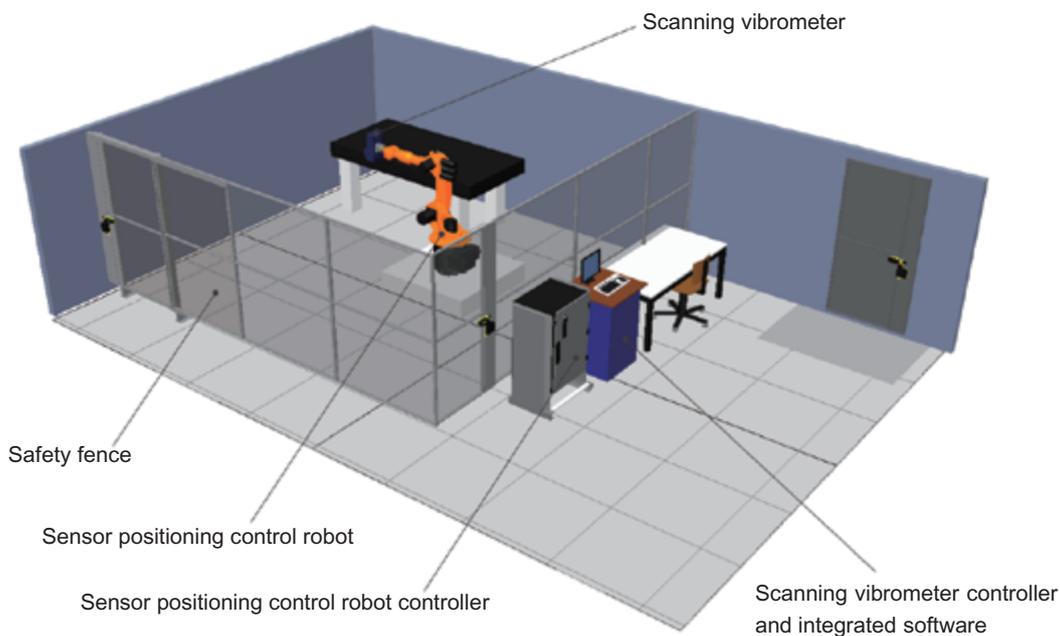


Fig.2.2 Configuration of MaVES-c

support automated measurements using a vibrometer and robot as it is not equipped with integrated software for synchronizing the operations of the scanning vibrometer and the robot (this support is being planned for the future). It can, however, measure using automated scanning within a specified area by means of the scanning functions of the vibrometer, provided the robot is manually manipulated to set the vibrometer to an arbitrary position.

The vibration characteristics data derived from the measurements conducted by the MaVES-c can be analyzed using the modal analysis software incorporated in the MaVES.

3. Details of MaVES

The hardware and software of the MaVES are described in detail in this chapter.

3.1. 3D scanning vibrometer

3.1.1. ConFIGuration of vibrometer

The 3D scanning vibrometer (PSV-400-3D; manufactured by Polytec) shown in Fig. 3.1 comprises three scanning head units (PSV-I-400), three controllers (OFV-5000), junction boxes (PSV-401-3D and PSV-E-408), and a data management system (PSV-W-400-3D; indicated as PC in Figures other than Fig. 3.1). All devices other than the scanning heads are housed in a rack (Fig. 3.2).

The three scanning heads (top, right, and left) are mounted at the tips of the arms of the sensor positioning control robot (Fig. 3.3) and they perform the projection and reception of the laser beams. A CCD-type video camera is built into each scanning head. Furthermore, a geometry scan unit (PSV-A-420) is mounted on the top of the scanning head. A trihedral Figure of the scanning head is shown in Fig. 3.4, for reference.

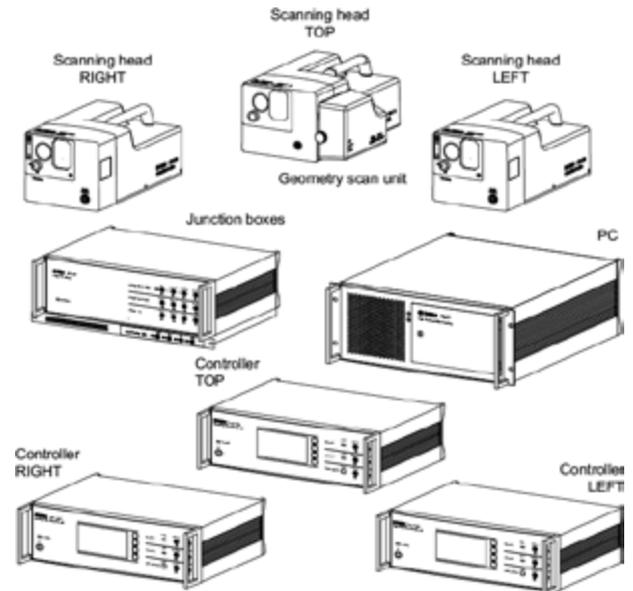


Fig.3.1 Configuration of 3D scanning vibrometer

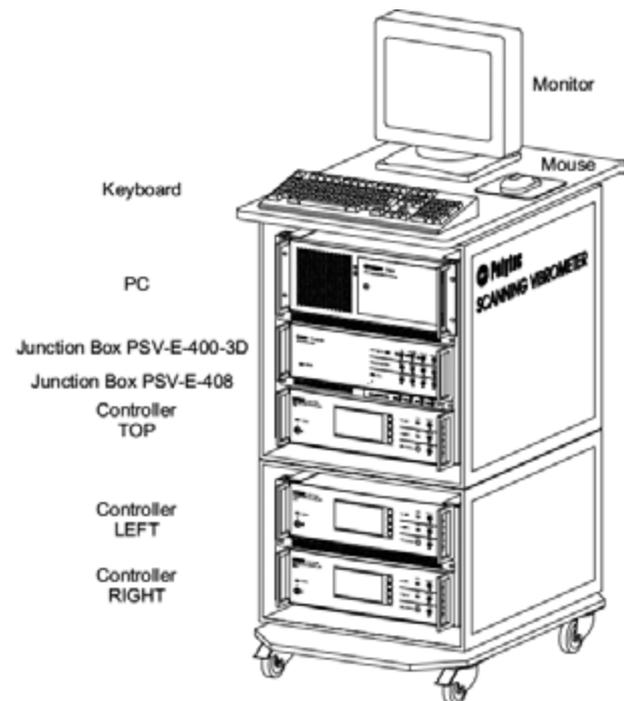


Fig.3.2 Configuration of 3D scanning vibrometer (rack)

The junction boxes input and output the analog and digital signals. The PSV-401-3D handles four inputs and four outputs, and has been expanded to handle four additional inputs with the addition of the PSV-E-408, resulting in a combination of eight inputs and four outputs.



Fig.3.3 Scanning head

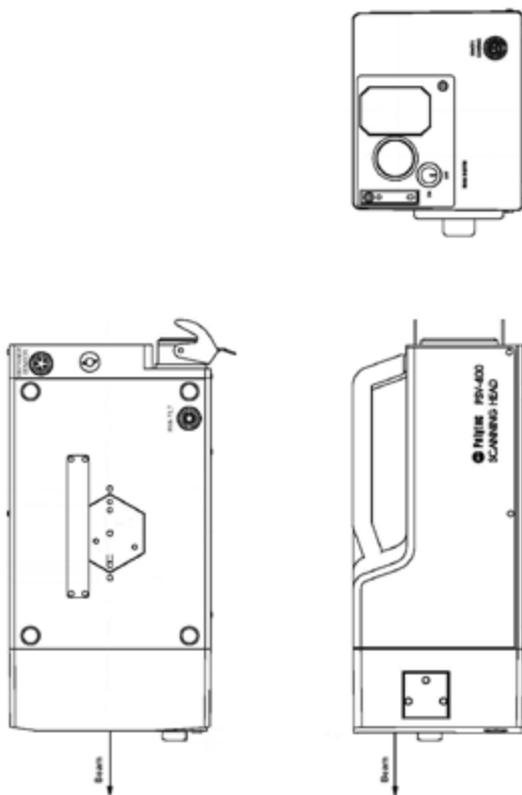


Fig.3.4 Trihedral figure of scanning head

The data management system comprises a PC and PSV software to receive and transmit data from the junction boxes, as well as process the measurement data.

3.1.2. Specifications of vibrometer

The laser unit mounted on the scanning head, which is the laser diode-type geometry scan unit, is classified as a Class 2 laser according to the

EN60825-1 safety standard for laser beams, as its frequency is in the range 400–700 nm and its visible radiation output is under 1 mW. At this level, even if the light source is projected directly into the eye, safety can be maintained through aversive reactions such as blinking.

Furthermore, the MaVES integrates two types of systems with different vibration velocity detection performances as well as input and output channels (PSV-3D-400-H and PSV-3D-400-M, referred to as the H system and M system, respectively) that can be switched.

3.1.3. Measurement functions

The vibration velocity of the test piece can be detected using a laser beam projected from the scanning head. However, as the Doppler effect is used, it can be detected in the optical axis direction of the laser. It is also possible to measure the vibration velocity components in the three directions, namely, X, Y, and Z using the three scanning head units and projecting the three laser beams to a single point and thereafter, resolving them into components of orthogonal directions. Furthermore, the individual scanning heads are equipped with a mechanism that enables them to scan the optical axis of the laser with a galvanometer mirror ($\pm 20^\circ$ in two directions), making the measurement of a specified area possible (which, for reference, would be 400–500 mm on all sides for a distance of 700 mm between the scanning head and the intended object) without moving the scanning head.

The measurement points can be set on the PC using the video images provided by the CCD-type video camera built into the scanning head. Although a video camera is built into each scanning head, only that which was mounted on the top of the scanning head was used for this purpose.

The positional coordinates of the measurement points can also be derived using a mechanism by which the positions and angles of the scanning heads are derived based on the positional coordinates of the robot and the distance between the test piece and scanning head (measured by the geometry scan unit mounted on the top of the scanning head). The light source was obtained from the laser for velocity measurement whereas the same scanning mirrors were used for ranging.

3.1.4. Optical system

A corrected Mach-Zehnder interferometer is built into the scanning head, and the configuration of its optical system is shown in Fig. 3.5. A He-Ne laser with a carrier frequency of 40 MHz was used. The deflection laser beam projected by the light source was split into the object beam and reference beam by the BS1 splitter, from which the object beam was projected onto the test piece via the BS2 splitter and the $\lambda/4$ plate. The object beam reflected off the test

piece and the reference beam came together in the BS3 splitter, the interference of which was measured using the detector. The Bragg Cell modulator offset the frequency for detecting the reverse-direction vibration velocity.

When the multimode type of laser is used, interference exists between the modes and the level of signal of the reflected light varies with the distance. The relationship between the distance and the signal level is shown in Fig. 3.6. The optimum value L (mm) for the stand-off distance between the scanning head and the intended object is given by

$$L = 99 + n * (204 \pm 1)$$

Here, n is an integer (0,1,2...). Two types of front lenses are available on the scanning head, namely, long-range (LR) and mid-range (MR). The LR lens was adopted for the MaVES. Both lenses have different minimum stand-off distances, namely 350 and 40 mm for the LR and MR, respectively).

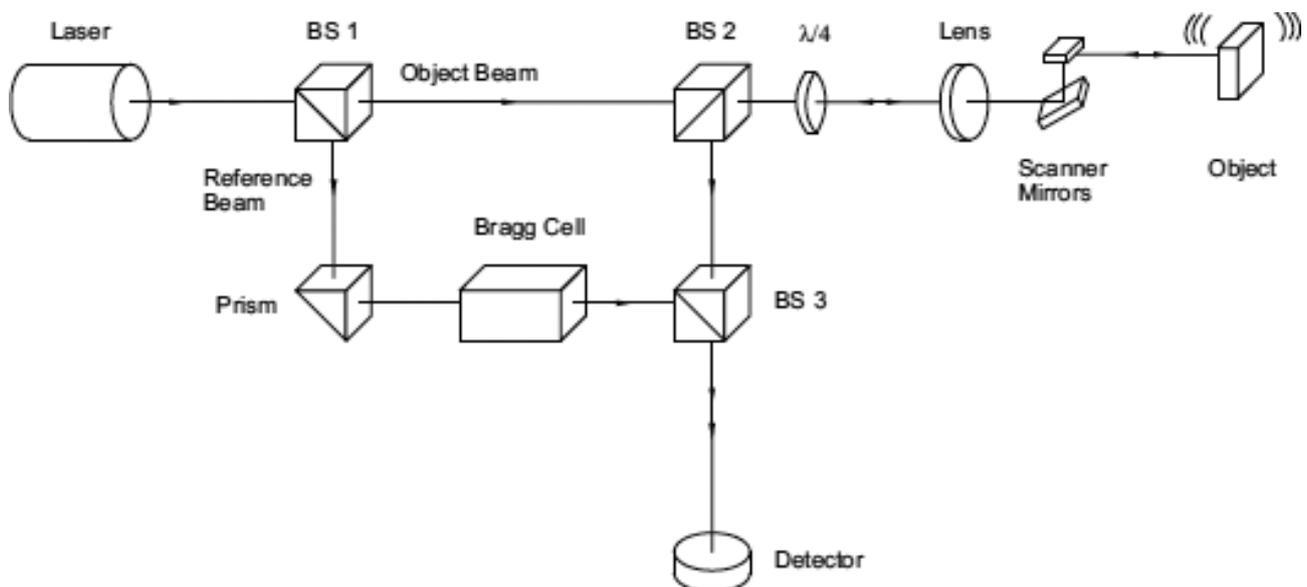


Fig.3.5 Configuration of optical system

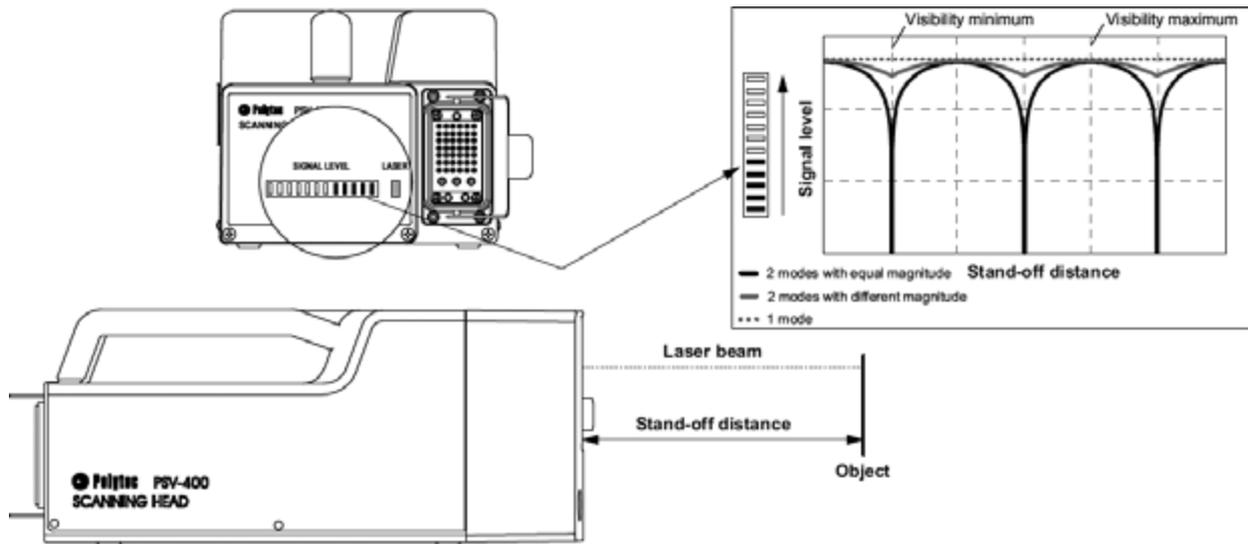


Fig.3.6 Relationship between distance and signal level

3.1.5. Vibration velocity detection performance

The mechanism used involved switching between the two types of systems (PSV-3D-400-H and PSV-3D-400-M) with varying vibration velocity detection performances, according to the intended use.

Two types of data acquisition boards (PCI-4462 and PCI-6110; manufactured by National Instruments) are built into the PC. PCI-4462 was used with PSV-3D-400-H to enable vibration measurements of up to 80 kHz (at a maximum sampling frequency of 204.8 kHz) with 24-bit resolution. PCI-6110 was used with PSV-3D-400-M to enable vibration measurements of up to 1 MHz (at a maximum sampling frequency of 2.56 MHz) with 16-bit resolution.

The vibration velocity detection performance depends on the decoder built into the controller. Two types of decoders were installed, namely, VD-08 and VD-09. VD-08 can be set to eight ranges and is capable of measuring up to 0.5 m/s of vibration velocity at a sampling frequency of 0.2–25 kHz. The sensitivity of VD-08 was optimized by adapting it to a relatively low frequency. VD-09 can also be set to eight ranges and is capable of measuring up to 10 m/s velocity at a sampling frequency of 0.1–2.5 MHz.

3.1.6. Functions of PSV software

The PSV software is used for operating basically all the controls and settings of the 3D scanning vibrometer. The control and setting items are described below.

(1) Setting of optical system

- Control of hardware: Positioning of the laser beam, focus adjustments, ON/OFF settings, and zoom and focus adjustments for the video camera.
- Image settings of live video images: Settings of contrast, brightness, and color saturation.
- Execution of 2D alignment: Alignment of laser position made to define the measurement points by moving the laser to an arbitrary position on the video camera image using a mouse.
- Execution of 3D alignment: Setting of the origin and coordinate axes, which form the basis of the coordinates of the measurement points.

(2) Setting of measurement points

Measurement points were set on the video camera images displayed by the PC. Two types of modes (standard and point) were available for setting whereas the transition from the currently set mode

was available only from the standard to the point modes and the specification did not allow a transition in the reverse direction.

- Measurement point setting in standard mode: Drawing and editing the respective geometrical shapes of lines, rectangles, ellipses, and polygons, as well as the arrangement of the measurement points on such geometries.
- Measurement point setting in point mode: Setting and fine adjustment of individual measurement points, as well as the definition and editing of line connections between them.
- Setting of video triangulation: Settings for performing triangulation measurements using the video images.
- Execution of geometry scan: The coordinates of the prepared measurement points were calculated and the coordinate values were assigned.
- Assignment of focus values: Assignment of focus values for the laser to the respective measurement points.

(3) Setting of measurement conditions

The following types of settings are available for the measurement conditions relating to the interruption of measurement data.

- General (general settings): Settings for the measurement modes (FFT, Fast Scan, Time), types of averaging (Off; Amplitude: Averaging of amplitude only when no reference signal is available; Complex: Averaging of both amplitude and phase; Peak Hold: Maximum value; Time), the number of times averaging is performed, ON/OFF setting for automated re-measurements (refer to the section on SE below), and multi-input multi-output (MIMO) measurements using principal component analysis.
- Channels (setting of measurement channels):

Settings for making enable/disable selections of channels, ranges, coupling, measurement directions, physical quantities, calibration values, and units.

- Filter (setting of digital filter for input signals): Settings for band width restrictions, types of filters (such as differentiation or integration filters), and parameters for filters.
- Frequency (setting of frequency for FFT measurements): Settings for bandwidth range, frequency range, and the number of FFT lines. The maximum number of FFT lines is 816,200.
- Window (setting of window functions for input signals): Settings for the window functions (Rectangular, Hanning, Hamming, Blackman Harris, Bartlett, Flat Top, and Exponential).
- Trigger (setting of trigger): Settings for the triggering of channels and trigger conditions (rise and fall of signals, threshold values, and pre-triggers).
- SE (expansion settings for signals): Settings for re-measurements to improve the signal-to-noise ratio by increasing the number of times averaging is performed automatically when the sensitivity declines due to problems such as the reflectance of the laser. For such instances, the ON/OFF setting is also available for spectral tracking, which is used to conduct measurements by gradually shifting the position of laser projection (by about 50 μm when the measurement range is 1 m).
- Vibrometer (setting of decoder): Settings for the types and ranges of decoders used.
- Generator (setting of function generator): Settings for excitation waveforms (sinusoidal, rectangular, triangular, ramp, sweep, cyclical chirp, simulated random, burst chirp, burst random, and user-defined), settings for the extension of time until the steady state is reached, and amplitude and

offset of signals.

- FastScan (setting of the FastScan measurement mode): Settings for performing high-speed scans at frequencies based on regression calculations using the least-square method in the time range. Frequencies and bandwidths are set.
- Time (setting of the time measurement mode): Settings for sampling frequencies and the number of samples for the measurement mode. Up to 64 mega samples (67,108,864) can be set.

(4) Execution of measurements

Two types of measurements are available, namely, single point measurement (measurement conducted for only one point) and scan measurement (measurements conducted sequentially for multiple points). The scan progression status can be verified on the screen during scan measurement.

(5) Display of data

Measurement data (Time, Power Spectral, FRF (H1 and H2), coherence, PSD, ESD, principal inputs, etc.) can be displayed. Furthermore, spectrum and operating animation for selected frequencies can be displayed for the data measured in the FFT mode. Operating animation for the time range can be displayed for the data measured in the time mode.

(6) Export of data

Various data such as spectrum and geometry can be exported to the ASCII, ME'Scope, or universal file formats.

3.2. Sensor positioning control robot

3.2.1. ConFIGuration of robot

The sensor positioning control robot (KR-150-2; manufactured by KUKA) comprises a six-axial articulated robot main body, robot control device, and teach pendant, KCP. A photograph of the robot

control device and KCP is shown in Fig. 3.7. The teach pendant is a device intended for teaching and programming the robot, equipped with a display, keyboard, and a space mouse (Fig. 3.8).



Fig.3.7 Robot control device and teach pendant KCP



2-15: KCP 前面

1	モード選択スイッチ	10	テンキー
2	駆動系 ON	11	ソフトキー
3	駆動系 OFF/SSB-GUI	12	リバースボタン
4	非常停止ボタン	13	スタートボタン
5	スペースマウス	14	停止ボタン
6	右ステータスキー	15	ウィンドウ切替ボタン
7	入力ボタン	16	ESC ボタン
8	カーソルキー	17	左ステータスキー
9	キーボード	18	メニューキー

Fig.3.8 Teach pendant KCP

3.2.2. Specifications of robot

The specifications of the robot are listed in Table 3.1. The range of the movement of the entire robot is shown in Fig. 3.9. Furthermore, the rotating

directions of the respective axes of the robot are shown in Fig. 3.10 whereas the ranges of the movement and velocities of the respective axes are listed in Table 3.2.

Table 3.1 KR150-2 specifications

Type	KR 150-2
Maximum reach	2,700 mm
Rated payload	150 kg
Suppl. Load, arm/link arm/rotating col.	50/100/300 kg
Suppl. Load, arm + link arm, max.	100 kg
Maximum total load	550 kg
Number of axes	6
Mounting position	Floor, ceiling
Variant	Cleanroom, Foundry
Positioning repeatability	±0.06 mm
Controller	KR C2 edition2005
Weight (excluding controller), approx.	1,245 kg
Temperature during operation	+10°C to + 55°C
Protection classification	IP 65
Robot footprint	1,006 mm × 1,006 mm
Connection	7.3 kVA
Noise level	< 75 dB

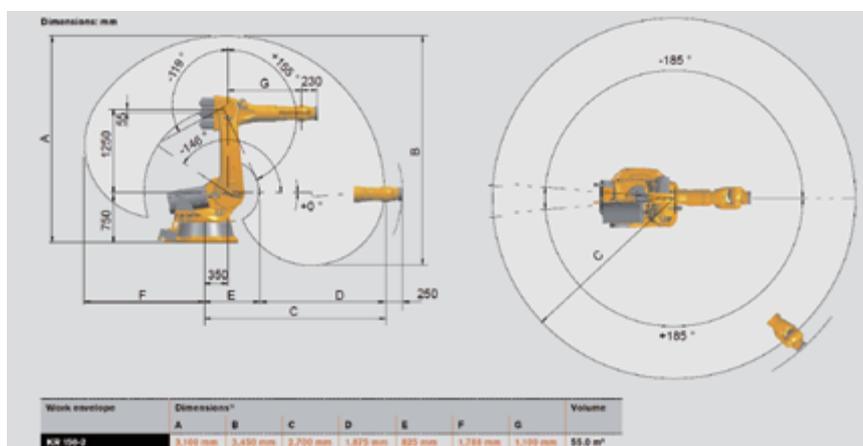


Fig.3.9 Range of robot movement



Fig.3.10 Axes of robot

Table 3.2 KR150-2 ranges of movement and velocity

Axis data	Range (software)	Speed with rated payload 150kg
Axis 1 (A1)	±185°	110°/s
Axis 2 (A2)	0°/-146°	110°/s
Axis 3 (A3)	+155°/-119°	100°/s
Axis 4 (A4)	±350°	170°/s
Axis 5 (A5)	±125°	170°/s
Axis 6 (A6)	±350°	238°/s

3.2.3. Coordinate system of robot

The following four types of coordinate systems form the basis for the robot's operations, with the respective coordinate systems set appropriately for its applications, to operate it in an efficient manner.

- **WORLD coordinate system:** The Cartesian coordinate system fixed to the tip of the foot of the robot.
- **ROBROOT coordinate system:** This is identical to the WORLD coordinate system at default. The ROBROOT coordinate system is set by defining the offset from the WORLD coordinate system.
- **BASE coordinate system:** A coordinate system based on the intended object.
- **TOOL coordinate system:** A coordinate system based on the tool mounted on the tip of the robot.

The images of the respective coordinate systems of the robot are shown in Fig. 3.11.

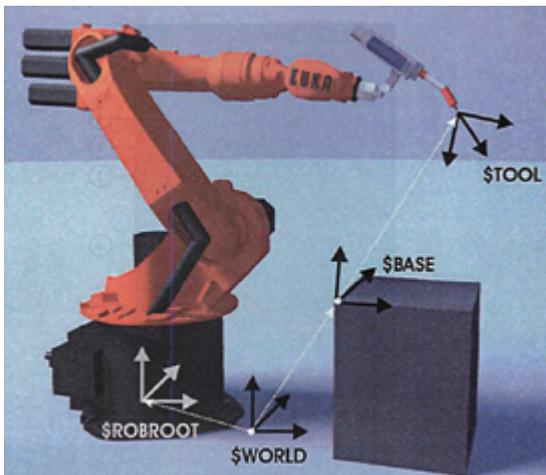


Fig.3.11 Coordinate system of robot

3.2.4. Functions of robot

The robot is equipped with a manual mode (T1: Manual low-speed mode; T2: Manual high-speed mode) and an automatic mode (AUT: Automatic mode; AUT EXT: External automatic system mode). The manual operation and programming (teaching) of the

robot are performed in the manual mode. The automatic operation of the program is performed in the automatic mode. The T2 mode is disabled in the MaVES owing to the restriction of the maximum transition velocity of the robot to 250 mm/s to protect the scanning head of the 3D scanning vibrometer. The AUT EXT mode is an automatic mode that synchronizes with the external system but not used with the MaVES.

(1) Manual operation

The robot is controlled by manipulating the space mouse or the keyboard of the teach pendant. Manual operations are performed either by controlling the respective axes of the respective coordinate systems (WORLD, BASE, or TOOL), namely X, Y, Z, A (rotation about the Z-axis), B (rotation about the Y-axis), and C (rotation about the X-axis), or by directly controlling the joint shaft of the robot.

(2) Programming

The advanced language KRL was used to program the robot to perform automatic motions. The programmable motions are described below.

- **PTP motion (point-to-point motion):** A motion that takes the path of the quickest route.
- **LIN motion (linear motion):** A motion that moves along a linear path.
- **CIRC motion (circular motion):** A motion that moves along a specified circle.
- **SPLINE motion (spline motion):** A motion that connects specified points in a smooth manner.

Other than the above, it is also possible to program the robot using control commands (such as LOOP, IF, SWITCH, WHILE, REPEAT, and FOR) and functions (such as WAIT).

3.3. Integrated software

3.3.1. Role of software

The integrated software (RoboVIB; made by

Polytec) is a software application for managing the control and PSV software of the sensor positioning control robot so as to synchronize the movements of the robot with the measurements. This software is essential for automated measurements and is installed in the PC of the data management system.

3.3.2. Functions of integrated software

The main functions of the integrated software are given below.

(1) Acquisition of positional coordinates of robot

The positional coordinates for the measurement points can be determined using the PSV software by acquiring the positional coordinates of the robot.

(2) Allocation of measurement points corresponding to positions taught to the robot

The measurement points for which accurate measurements can be made are allocated with respect to the already-taught robot positions. The possibility of measurement can be determined based on various conditions such as the maximum measurement range, angle of laser with respect to the test piece, the existence of the measurement point in the shadow of the test piece, etc. From this, the existence of any point where measurement is not possible can be determined.

(3) Synchronization of robot and measurement

The robot program and measurement using the PSV software are synchronized to enable automated measurements.

3.4. Modal analysis software

The modal analysis software (Test.Lab; made by LMS) can be used for preparing the geometry, conducting vibration measurements, and performing operational and modal analyses. The software can be used independently or in conjunction with the

MaVES, and is primarily used for performing modal analysis by importing the vibration characteristics data (in universal file format) obtained from the PSV software to the Test.Lab.

3.4.1. ConFfiguration of software

The software is comprised of multiple modules, as described below.

- Test.Lab Desktop - Advanced
- Test.Lab Frontend Driver (8-channel)
- Test.Lab Impact Testing
- Test.Lab Spectral Testing
- Test.Lab Geometry Workbook
- Test.Lab Modal Analysis
- Test.Lab Time Data Signal Calculator
- Test.Lab Source Control
- Test.Lab Time Recording Add-In
- Test.Lab PolyMAX
- Test.Lab Automatic Modal Parameter Selection
- Test.Lab Signature Throughput Processing
- Test.Lab Operational Deflection Shapes & Time Animation Workbook
- Test.Lab Operational Modal Analysis

3.4.2. Functions of modal analysis software

The modal analysis software is equipped with the following functions.

(1) Preparation of geometries

The software is capable of preparing 3D geometrical models relating to the measurement points. The models prepared in this fashion are used for 3D animations, based on the measurement and analysis data.

(2) Measurement of data

After adjusting the settings for the measurement channels, sensors, trigger conditions, window functions, excitation signal, etc., the data (Time, Octave,

Spectrum, Autopower, Crosspower, FRF, Coherence) was measured by hammering or exciting with a shaker.

(3) Modal analysis

This analysis is used for setting the analysis frequency ranges, preparing the stabilization diagrams, selecting a pole (manual selection or automatic selection), and calculating synthesized FRFs (by curve fitting), mode shapes, modal assurance criterion (MAC) values, etc. Two types of methods, namely, the least squares complex exponential time-domain (LSCE) and the least squares complex frequency-domain (PolyMAX) methods, may be selected as the curve fitting method. Animated display of mode shapes and synthesized FRF is possible from the results of the modal analysis.

(4) Operational analysis

This analysis further comprises steady-state and tracking analyses. Operational animation of the analysis results with respect to the frequency and time axes can be displayed.

(5) Operational mode analysis

It is possible to perform estimation analysis for natural modes by using operational data.

3.5. Others

3.5.1. Safety light barrier

The safety light barrier is a safety device that brings a robot in automatic operation to an emergency stop when the laser is shielded, by arranging the sets of the M4000 standard light projector and light receptor (developed by SICK) into a single unit at the four corners to surround the four sides with laser. The trihedral Figure of the safety light barrier is shown in Fig. 3.12 and its specifications are listed in Table 3.3. The overall view of the safety light barrier 3.13 and its control panel are shown in Figs. 3.13 and 3.14, respectively. The control panel is installed on the top plate of the robot control device. The power of the light curtain is turned on and the reset button is pressed to turn on the illumination lamps of the light curtains 1 through 4 (corresponding to the four sides) to green, for turning on the operation of the safety device. If the laser is shielded anywhere along the four sides, the corresponding illumination lamp turns off and the robot is brought to an emergency stop.

Table 3.3 Specifications of safety light barrier

	Light projector	Light receptor
Detectable length	60mm	
Monitoring area length	900mm	
Detectable length	—	0.5m - 6m / 5m - 19m (selectable)
Response time	—	Max. 17ms
Class	III (EN 50178:1998)	
Protection	IP 65 (EN 60529)	
Synchronization	Optical	
Safety category	Type 4 (IEC 61496), SIL3 (IEC 61508)	
Operating temperature	-0°C - +55°C	
Storage temperature	-25°C - +70°C	
Relative humidity	15% - 95% , non-condensing	
Housing dimensions	52mm x 55.5mm	
Vibration resistance	5g, 10Hz - 55Hz (IEC 60068-2-6)	
Impact resistance	10g, 16ms (IEC 60068-2-29)	
Housing material	Aluminum alloy ALMGSI 0.5	
Front screen material	Polycarbonate resin, scratch-resistant coating	

3.5.2. Scanning head installation jig

The scanning head of the 3D scanning vibrometer was installed on the tip of the robot arm via an installation jig (Fig. 3.15). The installation jig is shown in Fig. 3.16.

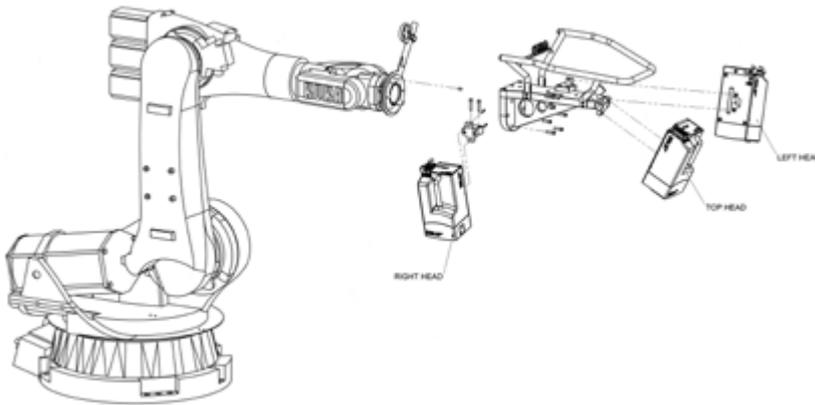


Fig.3.15 Robot and scanning head

3.5.3. Robot stand

The robot was installed on a special stand (Fig. 3.17) secured on the floor with four anchor bolts. The robot can be relocated while still being installed on the stand, by removing the anchor bolts and mounting the stand on a pallet truck.

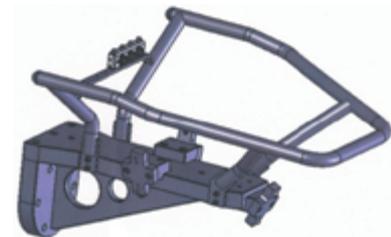


Fig.3.16 Installation jig of scanning head

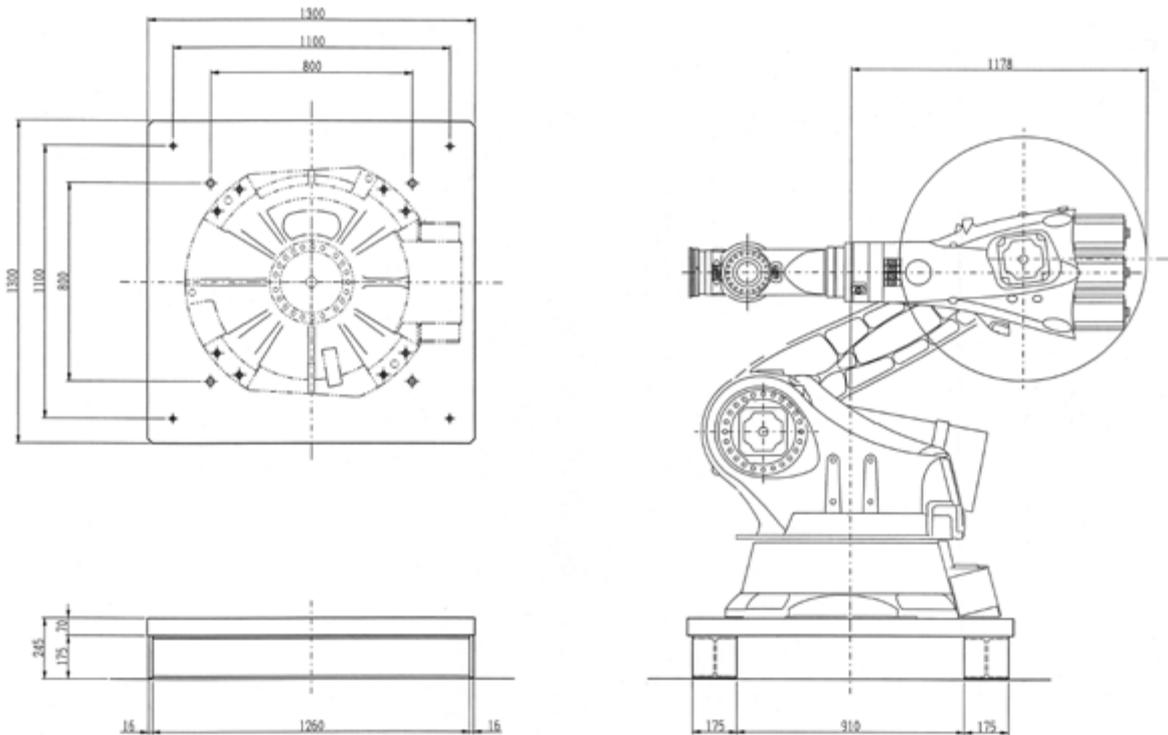


Fig.3.17 Trihedral figure of robot stand

3.5.4. PC and network

The following three units of PCs and NAS were used with the MaVES, which were linked via a local network. Microsoft Windows 7 was installed in the PC used for the 3D scanning vibrometer and Microsoft Windows XP was installed in the other PCs. The name of the work group was “MAVES-NET.”

- PC for 3D scanning vibrometer (computer name: PSV400; IP: 192.168.100.1)
- PC for sensor positioning control robot (computer name: KR150; IP: 192.168.100.11)
- PC for modal analysis software (computer name: MAVES; IP: 192.168.100.2)
- NAS for data storage (computer name: MAVESNAS; IP: 192.168.0.4)



Fig.3.18 Laser vibrometer (NLV-2500)

3.5.5. Laser vibrometer

Other than the 3D scanning vibrometer, the system is equipped with another laser vibrometer, the NLV-2500, manufactured by Polytec (Fig. 3.18). This laser vibrometer is comprised of a sensor head and a controller (NLV-2500-5). The controller is equipped with a velocity decoder that enables the setting of eight types of ranges, covering up to 10 m/s and 2.5 MHz. The range settings can be controlled using the PSV software, by connecting the PC of the 3D scanning vibrometer with an RS-232C cable. The applied criteria for the laser are listed in Table 3.4 and an outline of the system is listed in Table 3.5. The specifications of the sensor head and vibrometer controller are listed in Tables 3.6 and 3.7, respectively. Furthermore, the range diagrams for the velocities and displacements are shown in Fig. 3.19.

Table 3.4 NLV-2500 laser vibrometer (applied criteria)

Specification	
Laser safety	IEC/EN 60825-1 (CFR 1040.10, CFR 1040.11)
Electrical safety	IEC/EN 61010-1
EMC	IEC/EN 61326

Table 3.5 NLV-2500 laser vibrometer (Outline)

Device	Controller	Sensor head
Dimensions [L × W × H]	450mm × 355mm × 150mm	201mm × 38mm × 71mm
Weight	11kg	800g
Protection class	I (protective grounding)	IP64
Mains voltage		100 - 240VAC ±10%, 50/60Hz, Maximum 75W
Operating temperature		+5 - +40°C
Storage temperature		-10°C - +65°C
Relative humidity		Maximum 80%, non-condensing
Optical fiber cable length		3m (between controller and sensor head)
Output voltage		±10V
Interfaces		RS-232, Max.115kBd, Serial Port
Filters		High pass filter: 100Hz / off Low pass filter: 5kHz / 20kHz / 100kHz / off Tracking filter: slow / fast / off

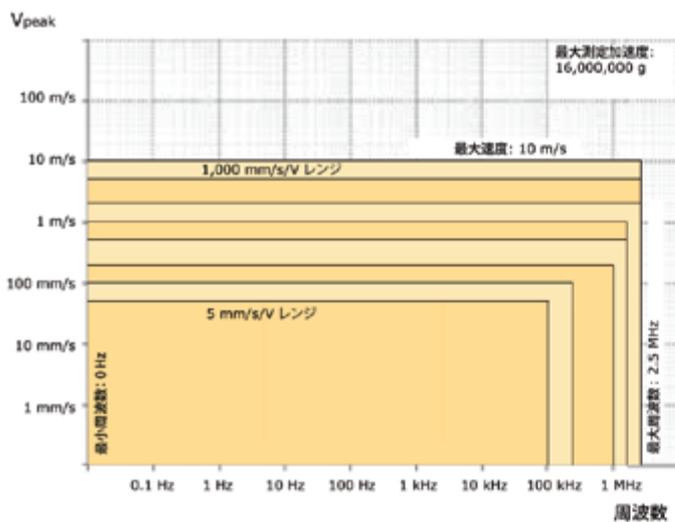
Table 3.6 NLV-2500 laser vibrometer (NLV-2500 sensor head)

Optical specifications	
Laser type	He-Ne
Laser class	Class 2, <1 mW, visible light source
Wavelength	633nm, red laser
Measurement length	200mm (without optical accessory) - infinity
Minimum spot diameter	1.5 μ m (VIB-A-20xLENS)
Coherence	287mm + n · 204mm; n=0; 1; 2; ...

Table 3.7 NLV-2500 laser vibrometer (NLV-2500-5 controller)

Decoder	Digital velocity decoder	Digital deflection decoder
Ranges	8 ranges	16 ranges
Measurement range	5 - 1,000mm s-1/V	0.05 - 5,000 μ m/V
Output scale	0.05 - 10m/s (p)	1 - 100,000 μ m (p-p)
Max. frequency	100kHz - 2.5MHz	2.5MHz
Resolution	0.01 - 4 μ m s-1/ \sqrt Hz	0.015 - 1,500nm
Max. acceleration	3,200 - 9,600,000g	-

Velocity range diagram



Displacement range diagram

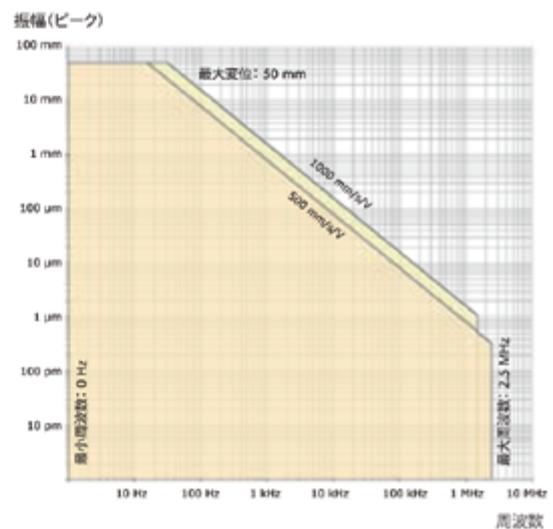


Fig.3.19 Range diagram of velocity and displacement

3.5.6. Surface plate

An optical surface plate (h-HOS-2412LA; manufactured by Sigma Koki; Fig. 3.20) is available for installing the test piece and the optical system. The top plate measures 2,400 mm × 1,200 mm and tap holes of M6 size (depth of 5 mm) are machined

on the entire surface at intervals of 25 mm. Air can be supplied using an air pump, as required, to facilitate vibration absorption by means of an air spring. The gross weight of the plate is 866 kg and the loadable weight is approximately 400 kg.



Fig.4.2 Configuration of 1D scanning vibrometer (rack)

4.1.2. Specifications of vibrometer

The laser units mounted on the scanning head, which is the laser diode-type geometry scan unit, is classified under Class 2 laser by the EN60825-1 safety standard for laser beams, as its frequency is in the range 400–700 nm and the output of visible radiation is under 1 mW. At this level, even if the light source is projected directly into the eye, safety can be maintained through aversive reactions such as blinking.

4.1.3. Measurement functions

The vibration velocity of the test piece can be detected using the laser projected from the scanning head. However, as the Doppler effect is used, it can be detected in the optical axis direction of the laser. Furthermore, the scanning head is equipped with a mechanism that enables it to scan the optical axis of the laser with a galvanometer mirror ($\pm 25^\circ$ to the horizontal direction and $\pm 20^\circ$ to the vertical



Fig.4.3 Scanning Head

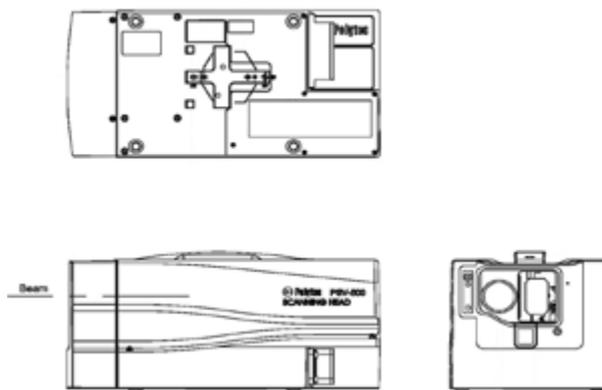


Fig.4.4 Trihedral figure of scanning head

direction of the scanning head), making it possible to conduct measurements of a specified area (which, for reference, would be 500–600 mm on all sides for a distance of 700 mm between the scanning head and the intended object) without moving the scanning head.

The measurement points can be set on the PC using the video images provided by the CMOS-type video camera built into the scanning head.

It is also possible to derive the positional coordinates of the measurement points using a mechanism based on the distance between the test piece and the scanning head, and the angle of the mirrors, using the geometry scan unit of the scanning head. The light source can be switched from the laser for velocity measurement to the laser for ranging using the same scanning mirrors.

The coherence optimizer built into the scanning head stabilizes the wavelength of the laser.

4.1.4. Optical system

Refer to Section 3.1.4 for details on the optical system.

4.1.5. Vibration velocity detection performance

A data acquisition board (PCI-6110; manufactured by National Instruments) is built into the PC, facilitating measurements of vibrations up to 1 MHz (at a maximum sampling frequency of 2.56 MHz).

The detection performance for vibration velocity depends on the decoder built into the controller. The installed DV-04 decoder unit can be set to 13 types of ranges and is capable of conducting measurements of up to 10 m/s of vibration velocity at a maximum sampling frequency of 2.56 MHz.

4.1.6. Functions of PSV software

The PSV software is used for adjusting basically all the controls and settings of the 1D scanning vibrometer. The control and setting items are similar to those of the PSV software of the MaVES.

4.2. Sensor positioning control robot

4.2.1. ConFfiguration of robot

The sensor positioning control robot (KR-16-3; manufactured by KUKA) is comprised of a six-axial articulated robot main body, robot control device, and smartPAD. A photograph of the robot control device and the smartPAD is shown in Fig. 4.5. The smartPAD is a device intended for teaching and programming the robot, equipped with a touch display and space mouse (Fig. 4.6).



Fig.4.5 Robot control device and smartPAD



Item	Description
1	Button for disconnecting the smartPAD
2	Keyswitch for calling the connection manager. The switch can only be turned if the key is inserted. The operating mode can be changed by using the connection manager.
3	EMERGENCY STOP button. Stops the robot in hazardous situations. The EMERGENCY STOP button locks itself in place when it is pressed.
4	Space Mouse: For moving the robot manually.
5	Jog keys: For moving the robot manually.
6	Key for setting the program override
7	Key for setting the jog override
8	Main menu key. Shows the menu items on the smartHMI
9	Status keys. The status keys are used primarily for setting parameters in technology packages. Their exact function depends on the technology packages installed.
10	Start key: The Start key is used to start a program.
11	Start backwards key: The Start backwards key is used to start a program backwards. The program is executed step by step.
12	STOP key: The STOP key is used to stop a program that is running.
13	Keyboard key Displays the keyboard. It is generally not necessary to press this key to display the keyboard, as the smartHMI detects when keyboard input is required and displays the keyboard automatically.

Fig.4.6 smartPAD

4.2.2. Specifications of robot

The specifications of the robot are listed in Table 4.1. The range of movement of the entire robot is shown in Fig. 4.7. Furthermore, the rotating directions of the respective axes of the robot are shown in Fig. 4.8 whereas the ranges of movement and velocities of the respective axes are listed in Table 4.2.

4.3. Others

4.3.1. Safety fence

Safety fences are installed around the system with doors at two locations (one being a sliding door and the other, a pair of double doors), along with a mechanism to automatically stop the robot when the door is opened during an automated measurement step. The trihedral Figure of the safety fence is shown in Fig. 4.9.

Work envelope ^①	Dimensions A	Dimensions B	Dimensions C	Dimensions D	Dimensions E	Dimensions F	Dimensions G	Volume
KR 15-2 S	2,025 mm	2,411 mm	1,611 mm	1,081 mm	530 mm	1,027 mm	670 mm	14.5 m ³

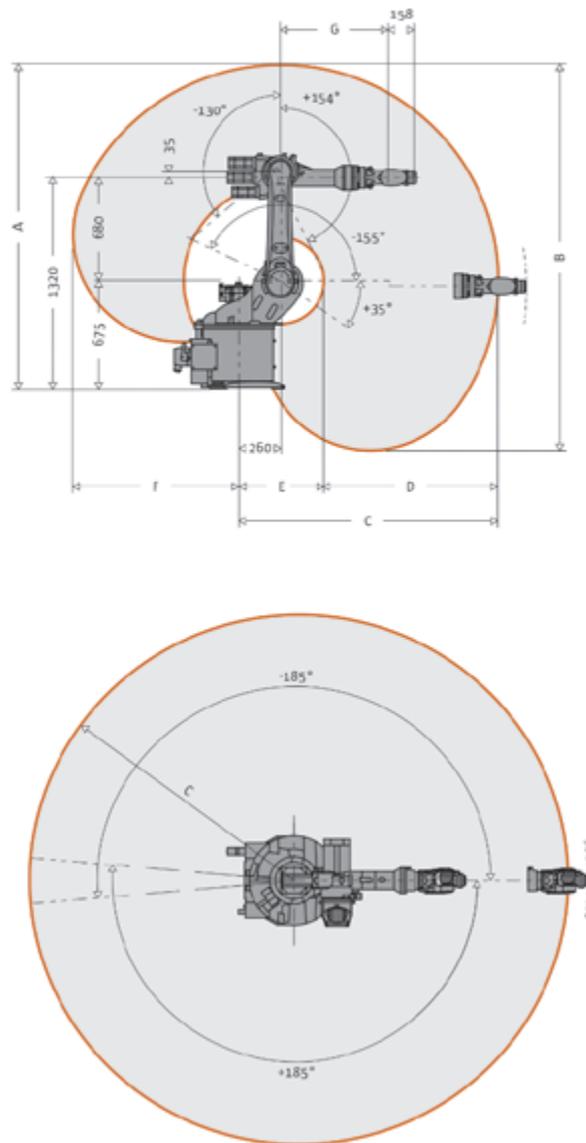


Fig.4.7 Range of robot movement

4.3.2. Installation of scanning head

The scanning head of the 1D scanning vibrometer is installed on the tip of the robot arm via an installation jig.

4.3.3. Robot stand

The robot is installed on a special stand (Fig. 4.10), which is secured on the floor with four anchor bolts. The robot can be relocated while still being

installed on the stand by removing the anchor bolts and mounting the stand on a pallet truck.

4.3.4. Surface plate

A surface plate identical to the optical surface plate (h-HOS-2412LA; manufactured by Sigma Koki; Fig. 3.20) described in Section 3.5.6 was installed separately for the MaVES-c.

Table 4.1 Specifications of robot

Type	KR 16-3
Maximum reach	1,611 mm
Rated payload	16 kg
Suppl. Load, arm/link arm/rotating col.	10/variable/20 kg
Suppl. Load, arm + link arm, max.	Variable
Maximum total load	46 kg
Number of axes	6
Mounting position	Floor, wall, ceiling
Variant	Cleanroom, Foundry, Explosion-Proof
Positioning repeatability	±0.05 mm
Controller	KR C4
Weight (excluding controller), approx.	235 kg
Temperature during operation	+5°C to + 55°C
Protection classification	IP 65
Robot footprint	500 mm × 500 mm
Connection	7.3 kVA
Noise level	< 75 dB

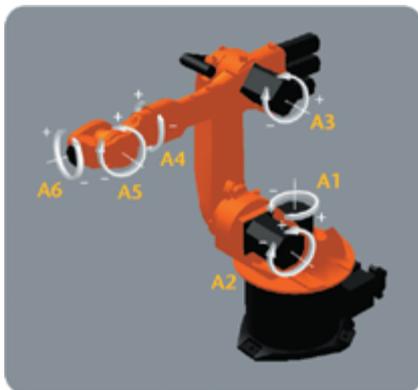


Fig.4.8 Axes of robot

Table 4.2 KR16-3ranges of movement and velocity

Axis data	Range (software)	Speed with rated payload 16kg
Axis 1 (A1)	±185°	156°/s
Axis 2 (A2)	+35°/-155°	156°/s
Axis 3 (A3)	+154°/-130°	156°/s
Axis 4 (A4)	±350°	330°/s
Axis 5 (A5)	±130°	330°/s
Axis 6 (A6)	±350°	615°/s

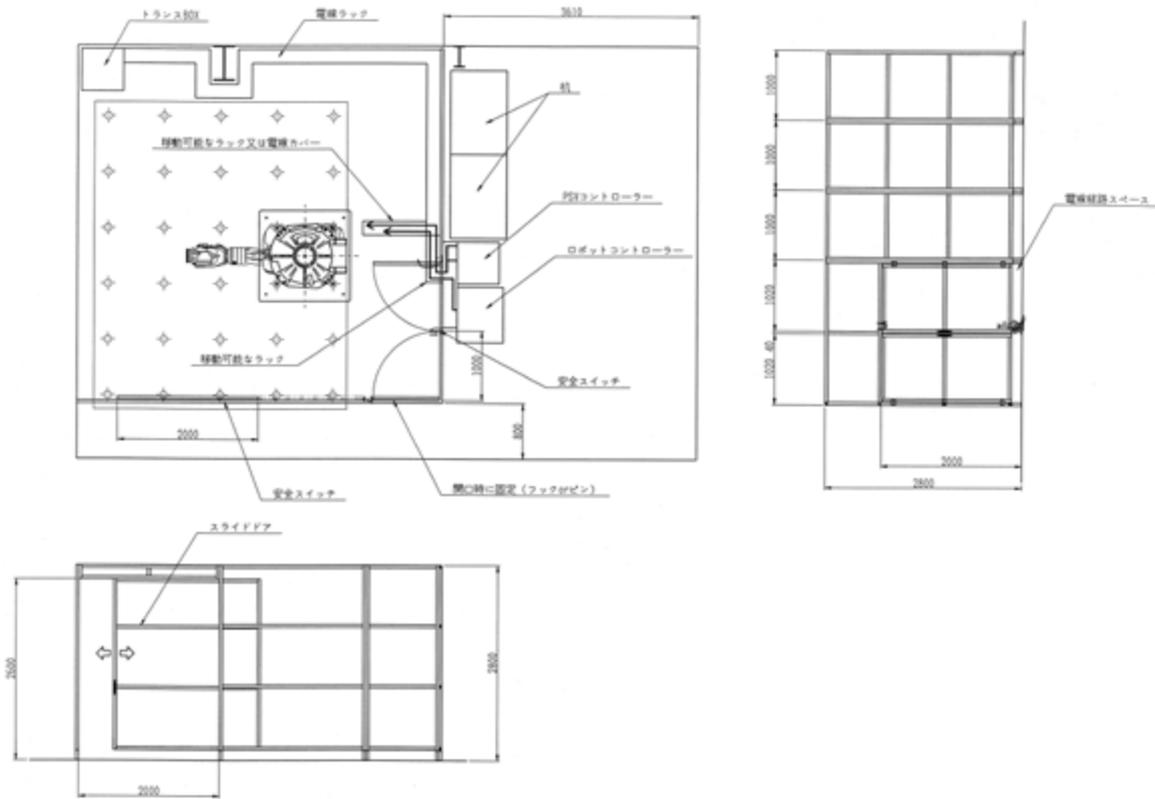


Fig.4.9 Trihedral figure of safety fence

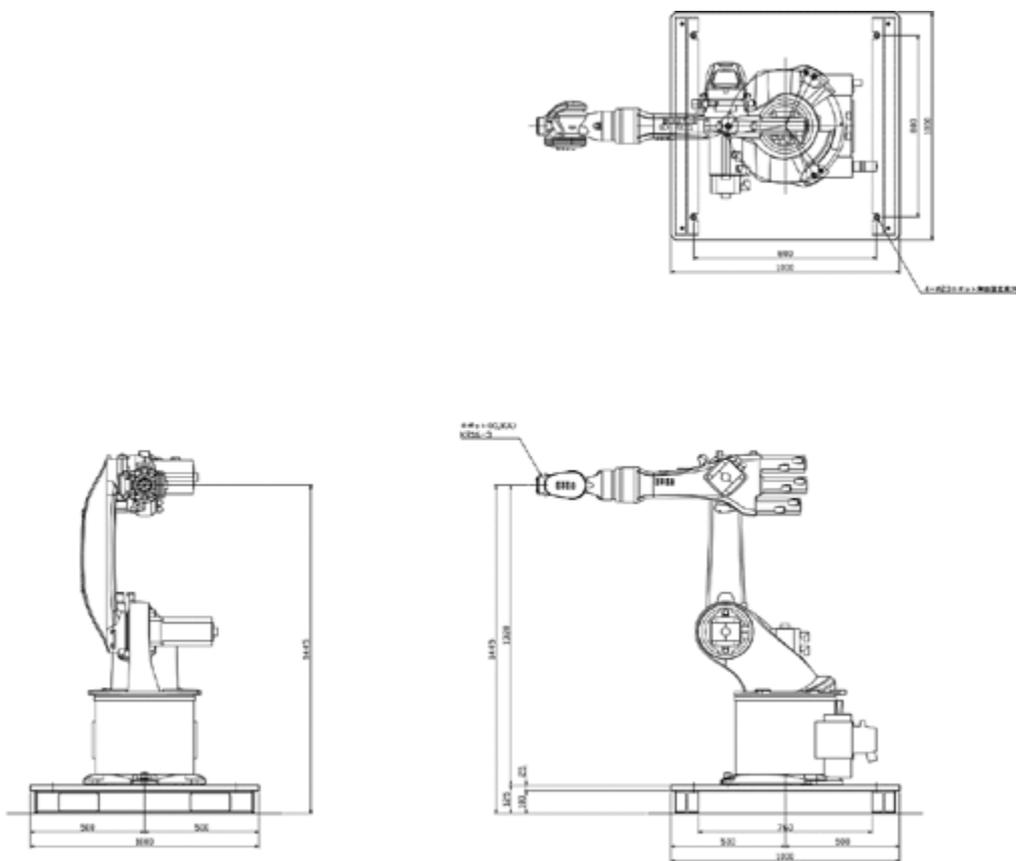


Fig.4.10 Trihedral figure of robot stand

5. Measurement Methods

A number of preparations and settings must be performed to conduct automated measurements. The series of procedures to be conducted from the preparation of measurement to the processing of its results is described below, taking the MaVES as an example.

5.1. Flow of measurement

Prior to conducting automated measurements, it is necessary to perform the operations of the PSV software RoboVib, robot, and the respective settings.

5.2. Measurement preparations

5.2.1. Installation of test piece and measurement equipment

Install the test piece and measurement equipment. Obtain the range of movement of the robot under consideration when installing the test piece.

5.2.2. Switching of system

Select the system to be used (either PSV-3D-400-H or PSV-3D-400-M) and connect the acquisition board (used for the system in use) located on the rear surface of the PC and the junction box with a cable.

5.2.3. Startup of MaVES

- Startup of robot: Turn the power of the robot control device to ON state to revert the system to the condition it was in prior to turning it off the previous time.
- Startup of 3D scanning vibrometer: Turn ON the power of the left and right controllers (for obtaining 3D measurements; not required for 1D measurement) and subsequently, turn ON the power of the junction box (integrated with the controller at the top). Finally, turn ON the power of the PC. Once all these devices are turned ON,

the PSV and RoboVib software programs can be started in Windows.

- The Acquisition Board Selection window is displayed when the PSV software is started. Select the “National Instruments PCI-446x” and “National Instruments PCI-611x” choices for using the PSV-3D-400-H and PSV-3D-400-M, respectively.

5.3. Setting of optical system

Setting of the optical system involves the setting of the Preference, 2D alignment, 3D alignment, and calibration of the BASE coordinate system. Alignment data that presumes that the test piece is 700 mm vertically away from the center-of-gravity position of the triangle that links the tips of the three laser sensor units were available for the MaVES. Settings for the 2D and 3D alignments are unnecessary if the relative positions of the test piece and sensors are properly set. The calibration of the BASE coordinate system is also generally unnecessary. It is also possible to set arbitrary sensor positions other than the 700 mm condition, by resetting the 3D alignment.

5.3.1. Preference settings of PSV

Preference settings are made using the PSV software (Setup > Preference). Subsequently, the number of scanning head units used is set in the manner described below.

- PSV-E-401-3D: three units (Top, Right, and Left) used.
- PSV-E-401-3D (1D): three units started but only Top used.
- PSV-E-401-1D: Only Top used.

Settings for the channels used to control the vibrometer were made using the Channels tab. The detailed settings related to the scanning head were made using the Scanning Head tab. For setting

the head angle, the three scanning head units were mounted with fixed angles on the MaVES and set as Top: 0°, Left: 270°, and Right: 90°. Settings for the calculation of recommended values of the hidden points, and those for the automated calculations for the focus values were made using the Geometry tab. Settings for the standard of the dB were made using the dB Reference tab, and those for displayed system messages were made using the Messages tab.

5.3.2. Setting of 2D alignment

This setting is made to align the position of the laser in the video image to that on the actual measurement plane (Setup > 2D alignment). Using the middle button of the mouse, move the laser to an arbitrary position on the test piece on the video image displaying it and specify the point to which the laser has to be projected. Specify at least six such points for each of the lasers at the top, left, and right, to perform the 2D alignment. Upon completion, the three lasers are projected onto the point on the video image clicked using the mouse. The manual setting described in this section is not necessary when using a robot as the alignment data already set using the RoboVib software will be used.

5.3.3. Setting of 3D alignment

Settings of the coordinate system for the measurement range was performed manually (Setup > 3D alignment). While converging the projection of the three lasers at a single point on the actual test piece, specify the origin, a point on the X-axis, and a point in the positive side in the Y-axis direction to determine the coordinate system. The settings performed manually as described in this section are not necessary when using a robot as the alignment data already set using the RoboVib software will be used.

5.3.4. Calibration of BASE coordinate system

The calibration of the BASE coordinate system was made to set that of the robot. The calibration of the BASE coordinate system offers a significant advantage when the test piece, the measurement point of which has already been set (based on the BASE coordinate system), is moved in relation to the robot as in this case, the settings from a past measurement point can be used simply by redefining the BASE coordinate system with a calibration.

Except for cases in which settings from a past measurement point are used, it is not necessary to perform the calibration of the BASE coordinate system described in this section.

(1) Setting of calibration points

- Set the calibration points at four points on the test piece, which are not aligned on a single straight line.
- Determine the coordinate values for the respective calibration points.

(2) Move the laser to the origin.

- Enter into the 3D Alignment step in the acquisition mode of the PSV software.
- Execute the Select and Check Point options.
- Click on the very first alignment point in the list and move the laser to the origin.

(3) Preparation of robot program

- Open the new robot program (Fig. 5.1). All programs are described between the START_PSV_MOVEMENTS and the PTP HOME lines during teaching.
- Move the robot so that the three lasers are pointed at the first calibration point and teach the system about the robot position. The operating method for this instance shall be the PTP motion. The name of the robot position set in the second column in the PTP inline form (that pops up in the program)

shall be B1. Leave the third column empty and leave the fourth and fifth columns in their default settings (Fig. 5.2).

- Repeat the teaching with the remaining three calibration points, with the name entered in the second column in the inline form being B2, B3, and B4, respectively.
- Save the robot program.

(4) Execution of BASE calibration

- Enter the program path for the robot program for which teaching has been completed in the Preferences menu of the RoboVib software.
- Select Setup > BASE Calibration and open the BASE Calibration window.
- Enter the coordinates for the four calibration points. The coordinate system will be calculated

and transferred to the robot controller. BASE [1], which is a BASE coordinate system of the robot, is now updated.

5.4. Teaching of robot position

If the robot needs to be moved during automated measurements, it is necessary to prepare a robot program by teaching the system about the robot position in advance. The robot position is set in such a way that the test piece is located 700 mm away vertically from the center-of-gravity of the triangle that connects the tips of the three laser sensor units (3D alignment data is set at 700 mm away as standard, to maintain a balance between the signal-to-noise ratio and the range of scanning). The positional relationship between the laser sensors and the test piece is shown in Fig. 5.3.

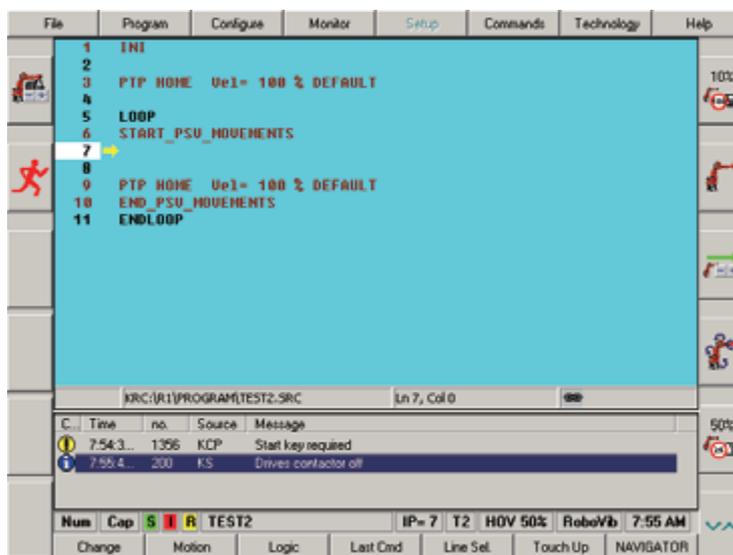


Fig.5.1 Robot program



Fig.5.2 PTP inline form

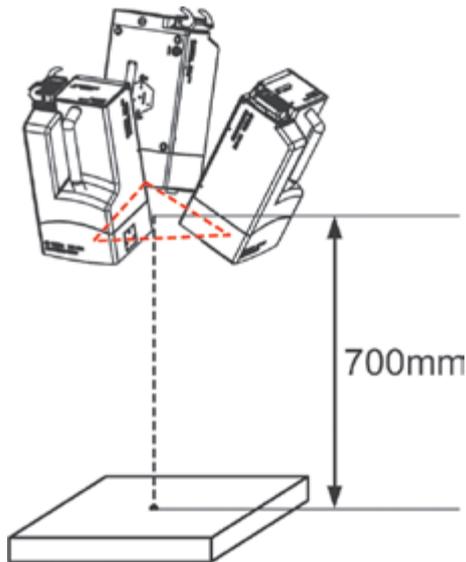


Fig.5.3 Positional relationship between laser sensor and test piece

(1) Preparation of new robot program

A new robot program is prepared using the teach pendant (refer to Fig. 5.1). The program is entirely described between the START_PSV_MOVEMENTS and the PTP HOME lines during teaching. Furthermore, the program is divided into a number of subprograms and it is also possible to create a program to call the subprograms from the main program.

(2) Teaching of robot position

Teaching the robot position is done using the teach pendant. The operation used in this instance shall be the PTP movement and the name of the robot position set in the second column on the PTP inline form shall be, in sequence, M1, M2, etc. The third column shall be left blank whereas the Tool coordinate system in the fourth column shall be Tool [1], with the BASE coordinate system on the fifth column being BASE [0]. There are cases in which dummy robot positions are set for which no measurements are made, for the purpose of preventing collision between the robot and the test piece. The operation in such an instance shall also be PTP motion and in the inline form, the

names of the robot positions shall be P1, P2, etc. The CONT is specified in the third column (which is a specification indicating to the system not to stop at the target points). The coordinate system shall be Tool [1] for the Tool coordinate system and BASE [0] for the Base coordinate system, as described above.

It is possible to do the teaching of the robot position while verifying the rough range in which measurements can be performed, during the actual scanning with lasers. This is performed by executing the macro program of the PSV software, ShowScanRangeAndZeroPos (Examples\Macros>ShowScanRanges.bas). Lasers are constantly scanned during the execution of this program and the condition will be such that the projection range of the laser can be verified.

(3) Save the robot program.

5.5. Setting of measurement points

Set the points to be actually measured and prepare the geometry (a group of measurement points). Optimize the focus of the laser for the respective measurement points.

(1) Relocation of robot position

Move the robot arm to the position saved during teaching.

(2) Setting of 3D alignment

Set the 3D alignment (including the 2D alignment) for the new robot position by executing the following:

- Open the System Control window of the RoboVib software (Setup > System Control).
- Load the current robot position by clicking on Read Position (the loaded and displayed robot position coordinates are the coordinates of the Tool [1] and BASE [1] coordinate systems).
- Set the 3D alignment by clicking on Set 3D Alignment.

(3) Preparation of geometries

Using the PSV software, prepare the measurement points on the image of the CCD camera. After preparing, execute the Geometry Scan (Scan > Geometry Scan) to conduct measurements of coordinates for the respective measurement points and complete the geometry.

If there are other robot positions that have been saved by teaching, then the following steps shall be executed and thereafter, steps (1) to (3) shall be repeated.

- Select all the prepared geometries and then select Menu > Change Indices on one of these points with a right click to apply an offset to ensure that this does not overlap with a measurement point number on other geometries.
- Export the geometry as a universal file.

Once the preparation of all geometries has been completed, complete the geometry by importing all universal files using the Import Geometry command.

(4) Setting of focus

- Select all measurement points and then select Menu > Recalculate Focus Values on one of these points with a right click.
- Verify that all measurement points are labeled as Calculated under the Laser Focus Status.
- Check Scan > Focus during Scan (enable the calculated focus).

(5) Setting of video triangulation

- Select Standard or Fast in the Triangulation menu during Scan under Scan > Video, to accurately converge the three points of lasers to a single point by using triangulation on the video image.
- The Standard command rewrites the geometry after the three points are matched. The Fast command, on the other hand, matches the three points but

does not rewrite the geometry.

- Furthermore, executing the video triangulation increases the measurement time.

(6) Saving of setup file

5.6. Analysis of measurement points

Analyze the measurement points and assign the prepared measurement points to robot positions saved by teaching. All measurement points are also screened to determine whether or not obtaining measurements is possible.

(1) Setting of analysis conditions

Analysis conditions are set using the RoboVib software (Setup > Preference). The settings are made in the Preference window, which features the General and the System 1 tabs. The following settings are performed under the General tab.

- Scan Point Definition File: The setup file that defines the measurement points is specified.
- Quality Control Folder: The folder for saving the files used for quality control is specified.
- Maximum Angle of Incidence: The maximum angle of the laser projected on the surface of the test piece (the angle between the direction of the normal line from the surface of the test piece and the laser beam) is specified (Fig. 5.4). If the actual angle exceeds this value, it is determined to be immeasurable.
- Maximum Measurement Distance: The setting for the maximum distance that can be measured (Fig. 5.5) is specified. If the actual distance exceeds this value, it is determined to be immeasurable.
- Calculate Hidden Points: Turning the checkbox ON causes the RoboVib software to calculate the measurement points that are hidden by the shape of the geometry.
- Tolerance for Calculating Hidden Points: The

tolerance value used for the determination of the Hidden Points is entered. The measurement points located at distances shorter than the tolerance value are determined as Hidden Points (Fig. 5.6). The tolerance value calculated in the Geometry tab of the setup window of Preference in the PSV software is generally entered as is (refer to Section 5.3.1).

- Calculate 3D Edges: This is checked while performing a calculation to understand which measurement point is on the 3D edge. The points on which the laser projection potentially does not reach the test piece when the measurement point is missed are determined as 3D edge points. Examples of the points that are determined and not determined as 3D edge points are shown in Fig. 5.7.

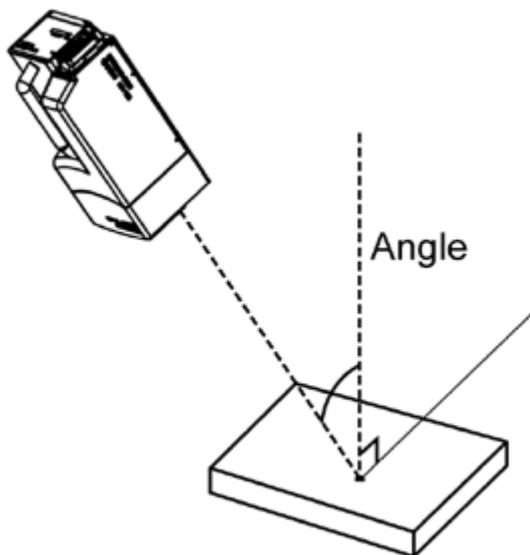


Fig.5.4 Angle of Incidence

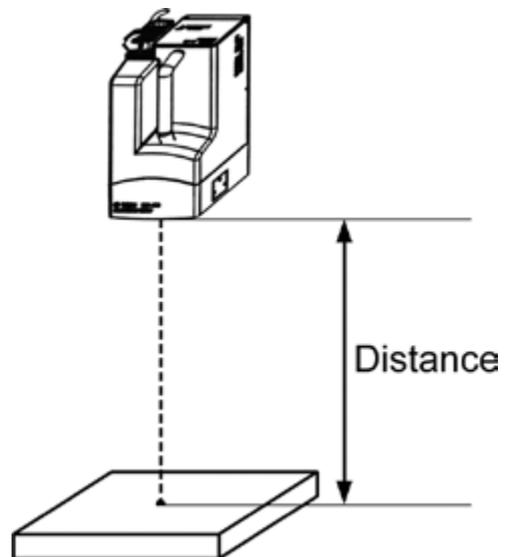


Fig.5.5 Measurement Distance

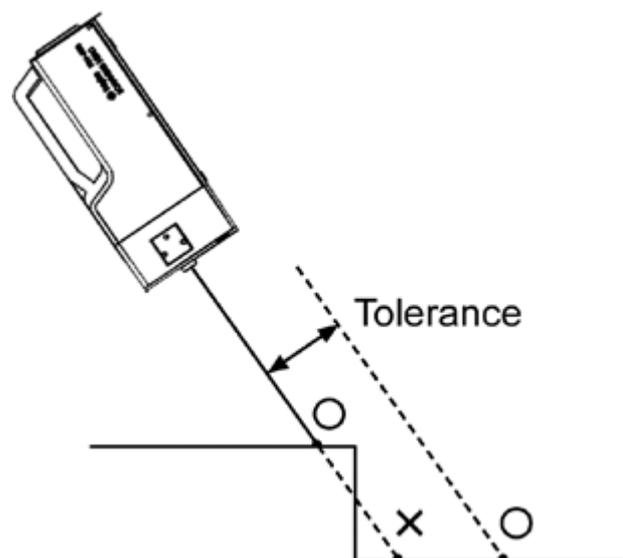


Fig.5.6 Hidden Point

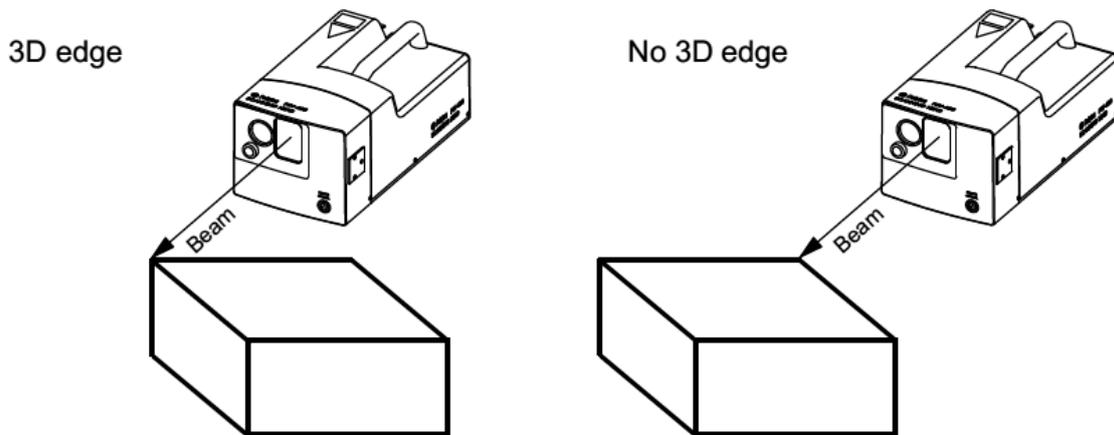


Fig.5.7 3D edge

- Robot Settling Time before Scan: The time margin, from the time the robot is moved to the position saved by teaching until the measurement starts, is set. This is used when the relocation of the robot triggers the excitation to vibrate the sensor to delay the start of measurement until the vibration settles down.

The following settings are performed in the System1 tab.

- 3D Alignment File: The setup data file of the settings for the 3D alignment is specified. Generally, this is left with default settings and no changes to the settings are required.
- Robot Positions File: The robot program prepared during teaching is specified.

(2) Execution of analysis

The measurement points are analyzed based on the set analysis conditions (Action > Prepare Measurement Settings). Once the analysis is completed, all

measurement points are assigned to a single or multiple geometry components (a group of measurement points) and a setup file is prepared in the Quality Control Folder and the Measurement Settings Folder.

The results of the assignments for all measurement points can be verified with the setup file prepared in the Quality Control Folder, MPOS_ALL.set. The measurement points determined as measurable by correlating against the set analysis conditions are assigned to the geometry components having the same names as those of the corresponding robot positions (M1, M2, etc.). Those measurement points determined as immeasurable are assigned to the existing geometry component (Table 5.1). The correction of measurement points, change of analysis conditions, etc. are performed as required.

The automated measurement is finally performed according to the setup file prepared for each geometry component in the Measurement Settings Folder.

Table 5.1 Predefined geometry components

Component	Description
ANGLE_TOL	Scan points that will not be measured, because the angle of incidence between at least one laser beam and the object surface is above the specified value.
DIST_TOL	Scan points that will not be measured, because the distance between at least one scanning head and the scan point is above the specified value.
3D-EDGE	Scan points that will not be measured, because they are on the edge of the 3D geometry for at least one laser beam.
HIDDEN	Scan points that cannot be measured, because they are hidden by another part of the geometry for at least one laser beam.
NOT_REACHABLE	Scan points that cannot be measured, because they are not reachable due to the scanning angle by at least one laser beam.
MEASURED	Scan points measured at this position.
ANGLE_NOT_BEST	Scan points that will not be measured at the current position, because the least favorable out of the three angles of incidences is more favorable at another measurement position.

5.7. Setting of measurement conditions

Measurement conditions such as vibrating conditions or data uploading conditions are set using the PSV software (Acquisition > Settings). Items that can be set are

- General (general settings)
- Channels (setting of measurement channels)
- Filter (setting of digital filtering for input signals)
- Frequency (setting of frequency for FFT measurements)
- Window (setting of window function for input signals)
- Trigger (setting of trigger) and SE (setting of signal extension)
- Vibrometer (setting of decoder)
- Generator (setting of function generator)
- FastScan (setting of the FastScan measurement mode)
- Time (setting of the Time measurement mode)

5.8. Execution of automated measurements

Automated measurements are started with the following procedure:

- Close all doors on the safety fence.
- Set the robot to the automatic mode (AUT) and start the program.

- Start the measurement sequence using the RoboVib software (Action > Start Measurement Sequence).
- Specify the file for saving the measurement results.

The automated measurement starts and the progress status is displayed in the window.

5.9. Processing of measurement results

Operational display of measurement results is possible using the PSV software (Fig. 5.8). If modal analysis is required, export the measurement results onto a universal file and load it onto the modal analysis software to perform the analysis.

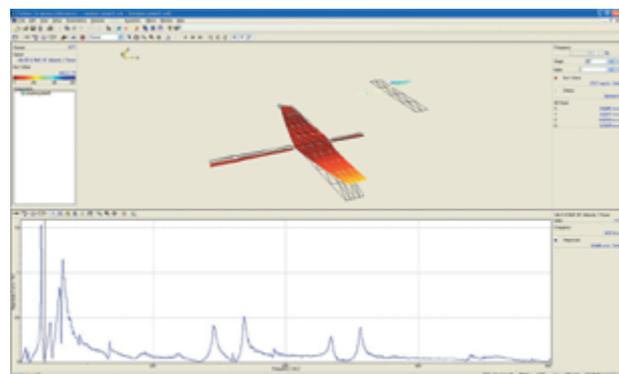


Fig.5.8 Display of measurement results

6. Measurement Examples

The actual measurement examples (natural mode and ultrasonic elastic wave transmission measurements) are shown in this chapter.

6.1. Natural mode measurements

Triaxial vibration measurements were performed on a test piece that simulates an aircraft, and operational and modal analyses were performed using the derived data.

6.1.1. Test piece

The test piece used for the measurements was of a shape simulating an aircraft, and composed of a body, main wings, vertical tail, and horizontal stabilizers, all made of aluminum. The test piece was supported at the rear end of its body with a rod made of titanium. Holes for attaching the rod for vibration were installed at the trailing edge of the tips of the main wings. The photograph of the test piece and its trihedral Figure are shown in Figs. 6.1 and 6.2, respectively.



Fig.6.1 Photograph of test piece

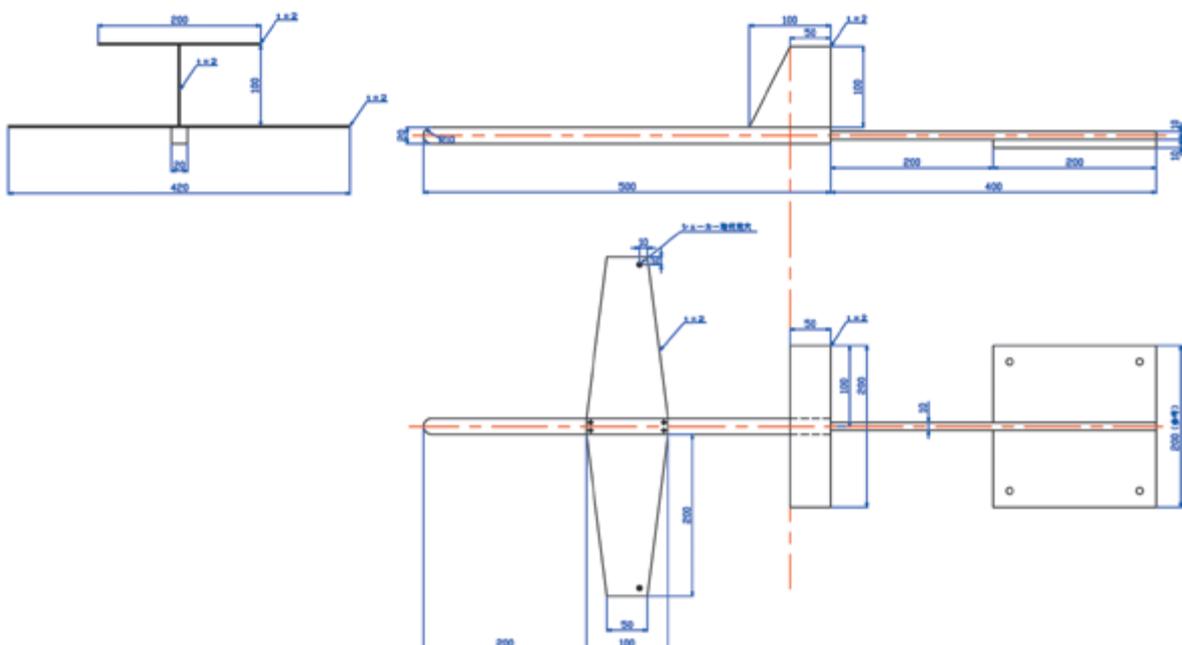


Fig.6.2 Trihedral figure of test piece

6.1.2. Setting of measurements

The trailing edge of the wing tips on the right main wing was subject to a single-point vibration using a shaker (main unit: 4801, manufactured by B&K; head: 4814; amplifier: 2707, manufactured by B&K) via a rod. A force transducer (8200; manufactured by B&K) was installed between the rod and the model, and was connected to the charge amplifier (2635; manufactured by B&K). The input signal derived from here was considered as the reference signal.

6.1.3. Robot position

There were three robot positions saved by teaching, namely M1 (main wing upper), M2 (horizontal stabilizer upper), and M3 (normal direction of the vertical tail wing), in sequence. Furthermore, a dummy robot position P1 was set for

the movement of the robot from M2 to M3 to avoid contacting the model. The respective robot positions are shown in Fig. 6.3.

6.1.4. Geometries

The prepared geometries are shown in Fig. 6.4. There are 83 measurement points in total. The geometries are comprised of the three components (M1, M2, and M3) corresponding to the robot positions, with the number of measurement points being 56, 18, and 9, respectively. The respective geometry components are shown in Fig. 6.5. Furthermore, although the three apexes and four lines from the apexes are drawn in the Figure, these indicate the positions of the three scanning head units (Top, Right, and Left) and the lines indicate the scanning range.



Position M1



Position P1



Position M2



Position M3

Fig.6.3 Robot position

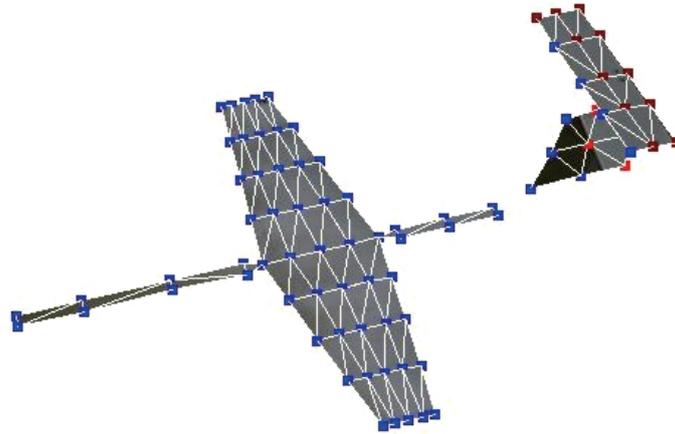
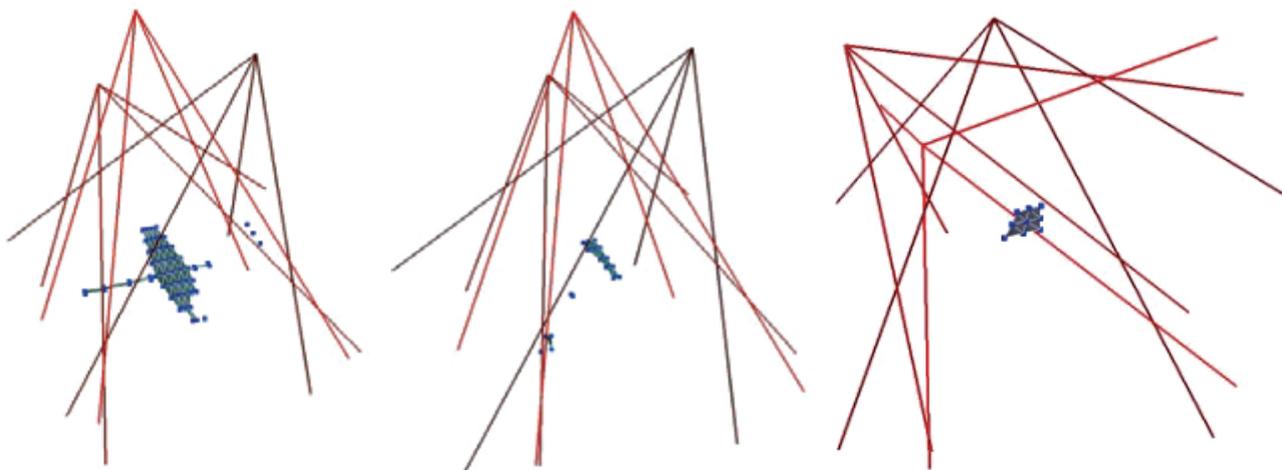


Fig.6.4 Geometry



Geometry component M1

Geometry component M2

Geometry component M3

Fig.6.5 Geometry component

6.1.5. Measurement conditions

The FRF of the velocity with respect to force was measured. The measurement conditions were a bandwidth of 0–500 Hz with 400 spectral lines (at a sampling frequency of 1,280 Hz, resolution of 1.25 Hz, and measurement time of 800 ms per frame). The excitation was burst random (excitation range of 1%–40% for each frame). The Exponential was applied for both the force and velocity of the window function. VD-

08 (of range 10 mm/s/V) was selected as the decoder.

The number of times averaging was performed was 30.

6.1.6. Operational analysis

The results of the measurement of the FRF (average FRF of all measurement points) are shown in Fig. 6.6 and those of the operational analysis are listed in Table 6.1.

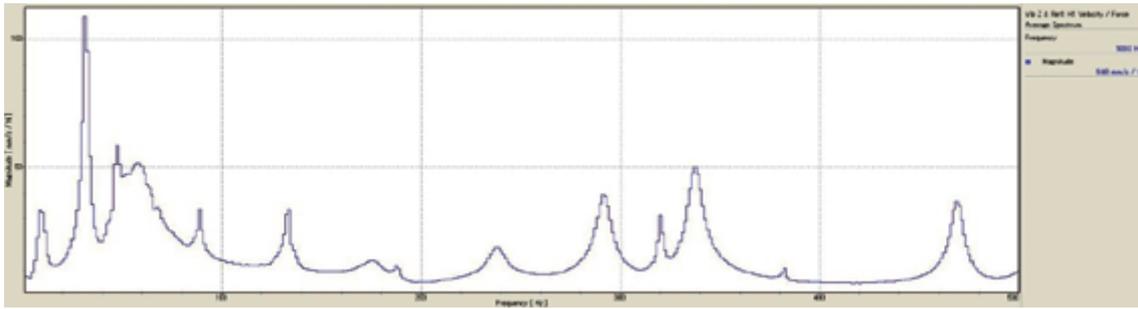
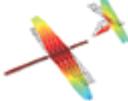


Fig.6.6 FRF

Table 6.1 Operational modal analysis

Number	1	2	3	4	5	6	7
Mode							
Frequency [Hz]	10	31	48	58	89	134	176
Number	8	9	10	11	12	13	14
Mode							
Frequency [Hz]	188	239	291	320	338	383	469

6.1.7. Modal analysis

Modal analysis was performed by exporting the FRF and geometry that correspond to all measurement points to the Test.Lab modal analysis software. The geometry in the Test.Lab is shown in Fig. 6.7 and the

stabilization diagram from the eigenvalue analysis for the 64 positions is shown in Fig. 6.8. The modal analysis results, obtained using the PolyMax method, are listed in Table 6.2. Furthermore, the MAC matrix is shown in Fig. 6.9 and listed in Table 6.3.

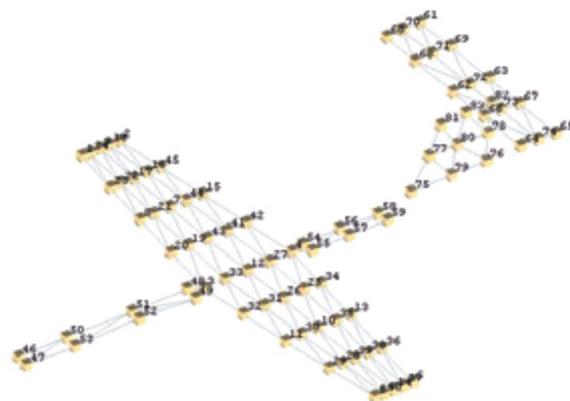


Fig.6.7 Geometry on Test.Lab

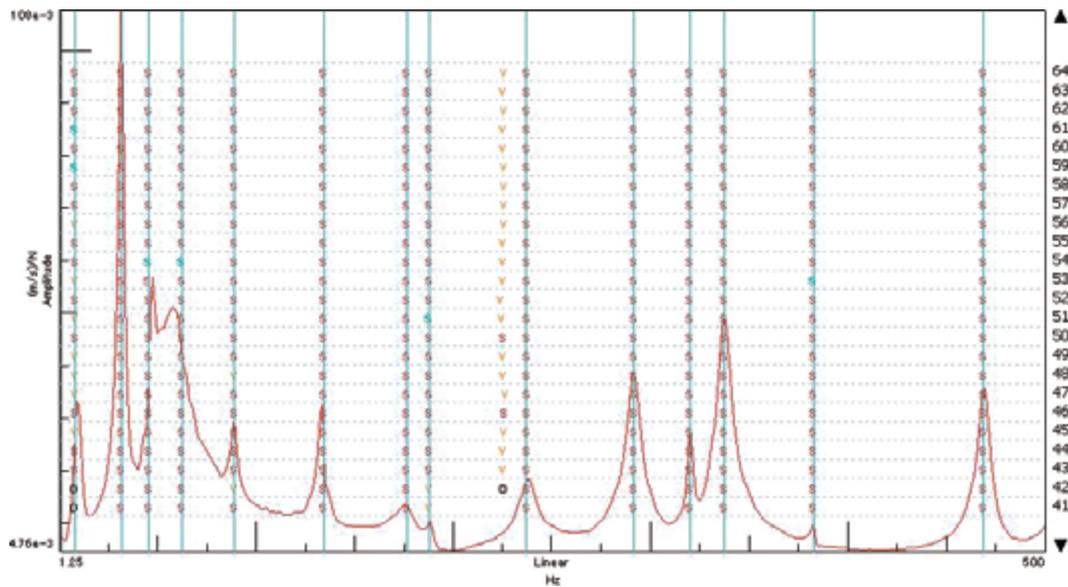


Fig.6.8 Stabilization diagram

Table 6.2 Modal analysis

Number	1	2	3	4	5	6	7
Mode							
Frequency [Hz]	8	32	45	63	89	134	176
Damping ratio [%]	6.09	3.06	4.19	10.22	0.73	1.09	3.56

Number	8	9	10	11	12	13	14
Mode							
Frequency [Hz]	188	237	292	320	337	382	469
Damping ratio [%]	0.45	1.87	1.12	0.30	0.95	0.26	0.63

Table 6.3 MAC matrix

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13	Mode 14
Mode 1	100	15.041	40.084	39.42	0.448	0.082	9.032	2.287	12.029	2.373	0.151	7.133	8.219	2.03
Mode 2	15.041	100	28.792	5.607	0.059	41.452	0.601	0.03	6.014	1.522	0.014	4.802	0.4	0.057
Mode 3	40.084	28.792	100	20.88	1.437	4.617	9.941	2.249	17.959	0.684	0.16	6.136	12.221	0.136
Mode 4	39.42	5.607	20.88	100	1.882	1.141	15.11	2.618	10.888	5.392	0.06	9.315	10.017	6.014
Mode 5	0.448	0.059	1.437	1.882	100	0.912	4.839	27.725	2.155	4.942	0.241	0.125	1.243	0.581
Mode 6	0.082	41.452	4.617	1.141	0.912	100	0.244	0.554	2.415	0.029	0.006	0.472	0.277	0.614
Mode 7	9.032	0.601	9.941	15.11	4.839	0.244	100	2.006	38.893	14.639	0.021	5.147	59.873	9.491
Mode 8	2.287	0.03	2.249	2.618	27.725	0.554	2.006	100	0.458	1.248	0.012	3.374	1.014	1.187
Mode 9	12.029	6.014	17.959	10.888	2.155	2.415	38.893	0.458	100	5.757	0.765	22.018	50.722	2.381
Mode 10	2.373	1.522	0.684	5.392	4.942	0.029	14.639	1.248	5.757	100	0.142	43.495	1.164	0.064
Mode 11	0.151	0.014	0.16	0.06	0.241	0.006	0.021	0.012	0.765	0.142	100	0.275	0.404	0.01
Mode 12	7.133	4.802	6.136	9.315	0.125	0.472	5.147	3.374	22.018	43.495	0.275	100	2.174	0.014
Mode 13	8.219	0.4	12.221	10.017	1.243	0.277	59.873	1.014	50.722	1.164	0.404	2.174	100	8.528
Mode 14	2.03	0.057	0.136	6.014	0.581	0.614	9.491	1.187	2.381	0.064	0.01	0.014	8.528	100

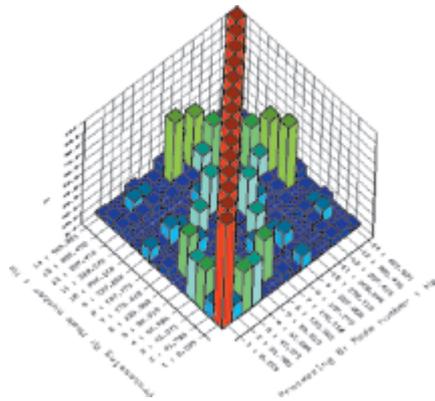


Fig.6.9 MAC matrix

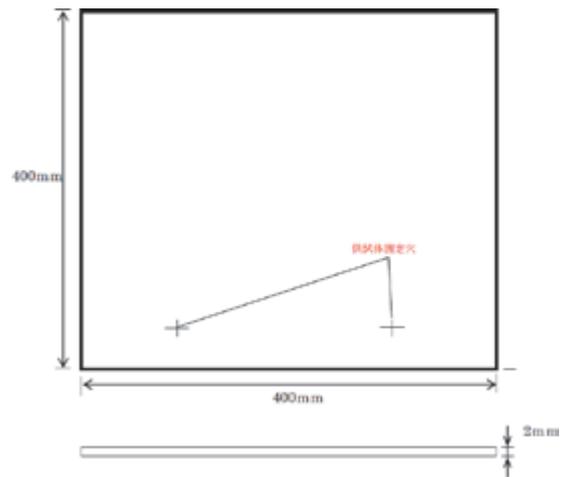


Fig.6.11 Shape of test piece

6.2. Ultrasonic elastic wave transmission measurements

Ultrasonic elastic wave (Lamb wave) measurement of a flat plate test piece was made and the transmission condition was visualized.

6.2.1. Test piece

The test piece was a flat plate made of A2024T3 material, which is an aluminum alloy. The flat dimensions were 400×400 mm and the plate thickness was 2.0 mm. The photograph of the test piece and its shape are shown in Figs. 6.10 and 6.11, respectively.



Fig.6.10 Photograph of test piece

6.2.2. Setting of measurements

The test piece was placed flat on the top of the workbench and the anchor holes on the test piece were not used for the purpose of these measurements. Furthermore, the measurement laser of only one axis (top) was used. The generator used was the multifunction generator WF1974 designed by NF Corporation, the amplifier was BA4825 (manufactured by NF Corporation) and the AE sensor was the R6 sensor (60kHz, resonance-type) manufactured by Physical Acoustics. The method of excitation involved sending a signal from the generator, which was amplified by the amplifier, and excitation applied by the AE sensor. The measurement setup conditions are shown in Fig. 6.12.

The measurement area was selected in the range of $400 \text{ mm} \times 400 \text{ mm}$ on the entire surface of the test piece panel, and the ultrasonic elastic wave (Lamb wave) was excited in the aluminum plate using an AE sensor fixed with silicon grease on the surface of the test piece. The installation position of the AE sensor is shown in Fig. 6.13. As the reflected light of the laser projected on the aluminum surface in an angle does not readily return to the sensor, developer liquid was applied on the test piece to cause the diffused reflection of light on the surface of the test piece to ensure that sufficient amount of laser beam was received by the laser receptor.



Fig.6.12 Measurement setup condition



Fig.6.14 Geometry

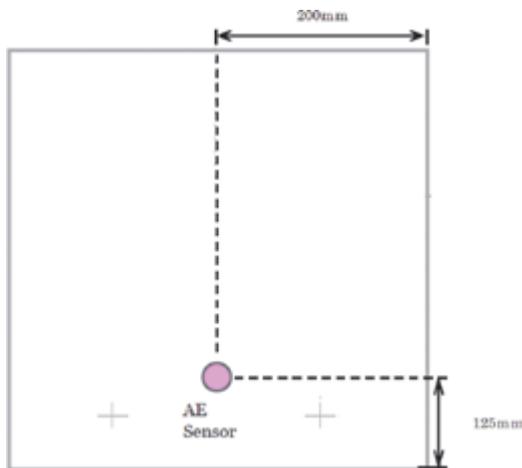


Fig.6.13 Installation position of AE sensor

6.2.3. Geometries

The 3D alignment (setting of the origin and coordinate axes, which form the basis for the coordinates of the measurement points), and geometry scan using the measurement points set (calculation of coordinates for the prepared measurement points and the assignment of coordinate values) were executed as the settings of the optical system before performing the measurements. The prepared geometry is shown in Fig. 6.14. The total number of measurement points was 4,759. Furthermore, the AE sensor section, wiring portion of the AE sensor, and the anchoring hole section of the test piece were excluded from the geometry as the reflected light of the laser beam could not be measured at these locations.

6.2.4. Measurement conditions

To derive an effective excitation frequency for the AE sensor, a verification of the excitation frequency and response spectrum was performed before conducting measurements. The measurement was conducted at a point in the vicinity of the AE sensor, defined as the representative measurement point (Fig. 6.15) and periodic chirp excitation was performed at the frequency range of 0–200 kHz (400 FFT lines). The results of the measurement indicated that the excitation frequency that generated the maximum response was 93.5 kHz. The periodic chirp excitation waveform is shown in Fig. 6.16 and the response spectrum of the representative measurement point is shown in Fig. 6.17.

The measurement conditions for elastic transmission measurement were set with the measurement time of 400 μ s (at a sampling frequency of 2.56 MHz, 1,024 samples). VD-09 was used as the decoder for the data management system with a selected range of 100 mm/s/V and pre-trigger of 4% of the measurement duration (400 ms). The trigger waveform is shown in Fig. 6.18. Furthermore, a band pass filter was set with cut-off frequencies of 1 kHz and 300 kHz, and used as the filter for the measurement signal. The number of times averaging was performed was 50 for the respective

measurement points. The excitation waveform consisted of five burst sine waves at 93.5 kHz, with amplitude of 7Vp-p, with five waves excited every 30 ms. The amplifier was set with a gain of 20 and output range

of ± 150 V. The excitation waveform is shown in Fig. 6.19 and the response waveform at the representative measurement point is shown in Fig. 6.20.

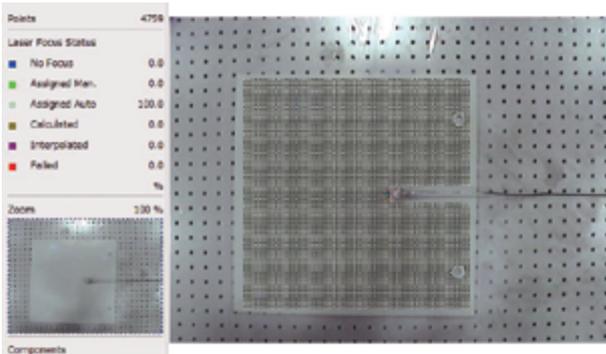


Fig.6.15 Representative measurement point

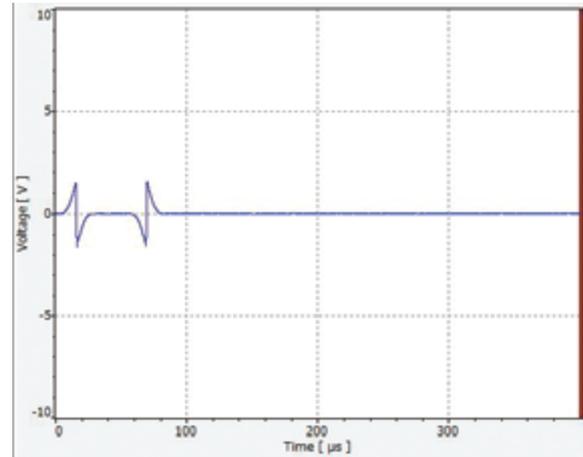


Fig.6.18 Trigger waveform

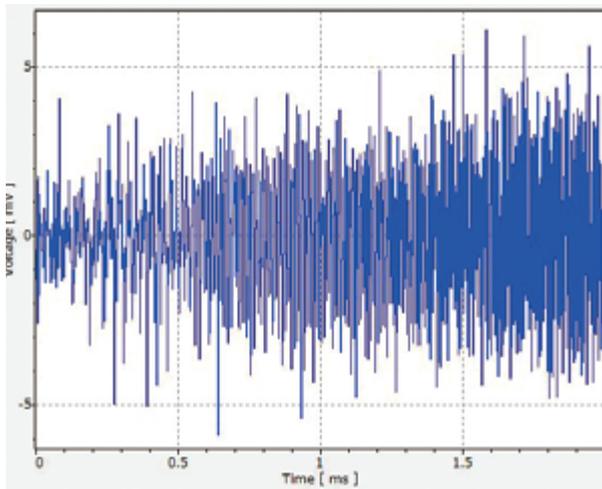


Fig.6.16 Periodic chirp excitation

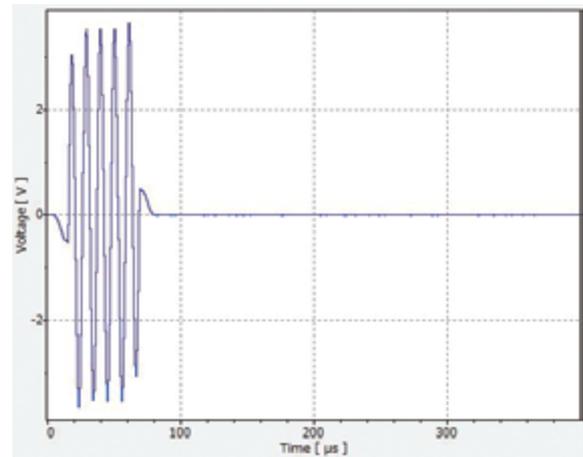


Fig.6.19 Excitation waveform

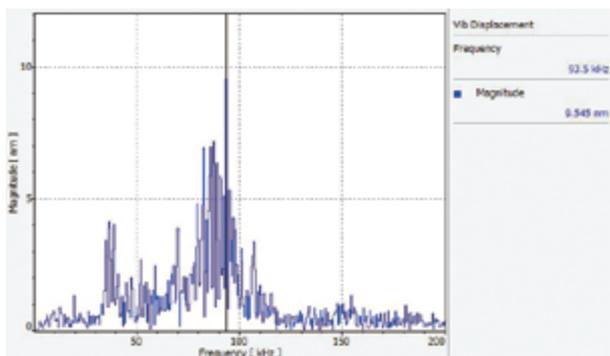


Fig.6.17 Response spectrum (representative points)

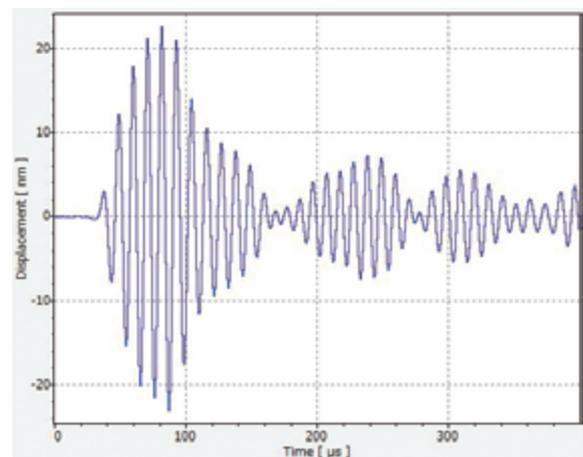
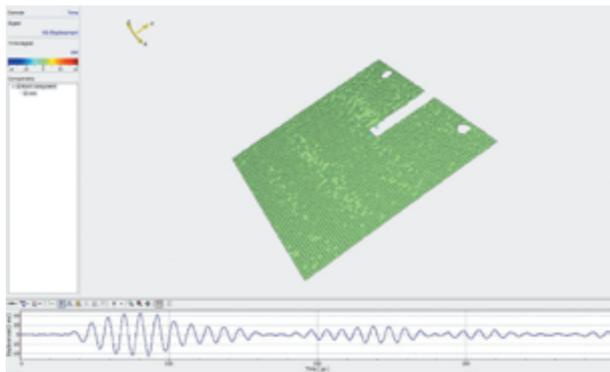


Fig.6.20 Response waveform (representative point)

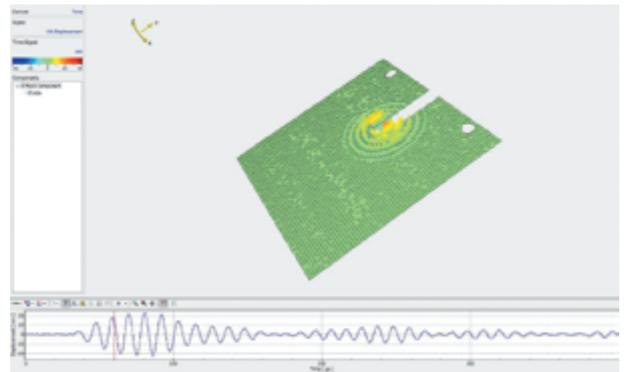
6.2.5. Ultrasonic elastic wave transmission

The 3D visualization for the condition of transmission is shown in Fig. 6.21. The condition encompassing the start of excitation through the

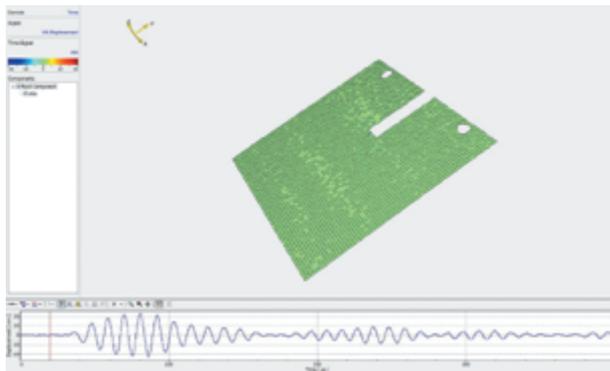
transmission of up to 200 μs is shown in Fig. 6.21. It is evident that the ultrasonic elastic wave (Lamb wave) was transmitted on the plate and further reflected at the edges of the test piece.



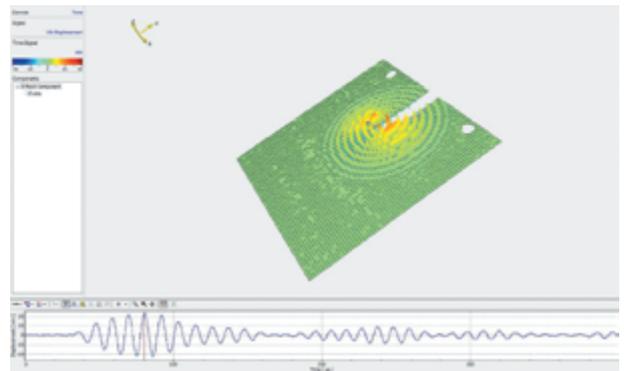
T=0 [μs]



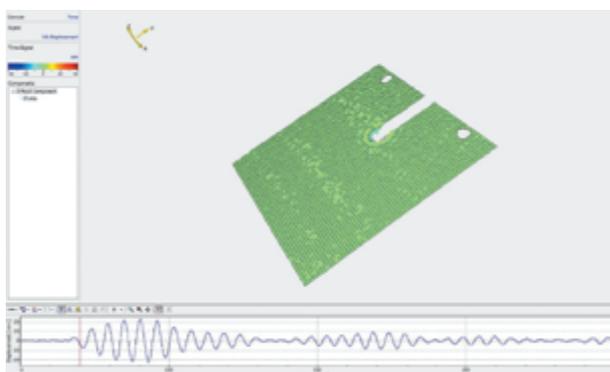
T=60 [μs]



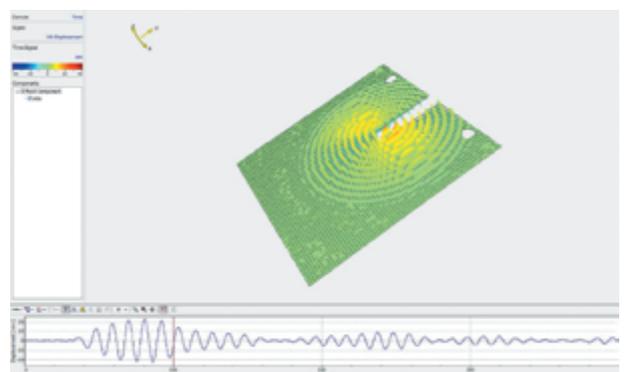
T=20 [μs]



T=80 [μs]



T=40 [μs]



T=100 [μs]

Fig.6.21 Wave transmission (1/4)

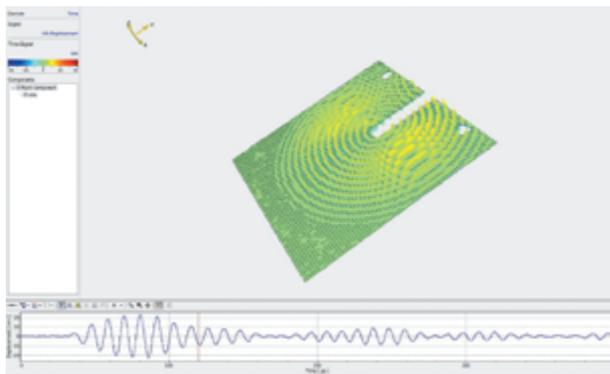
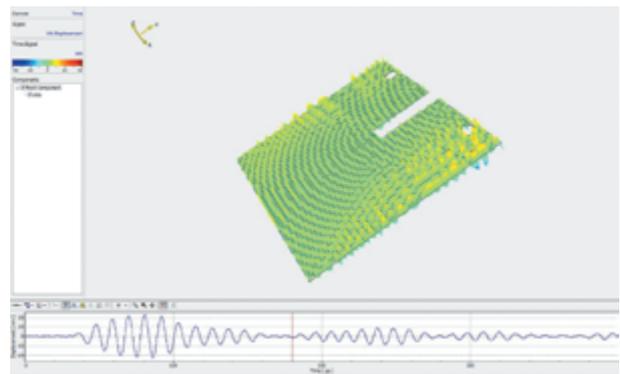
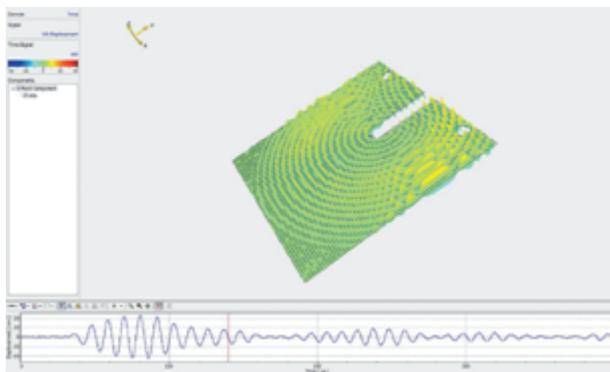
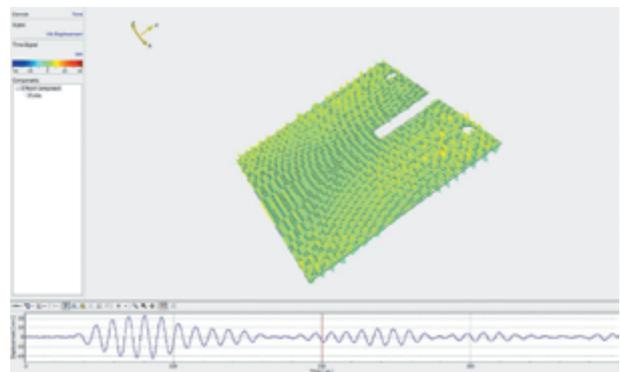
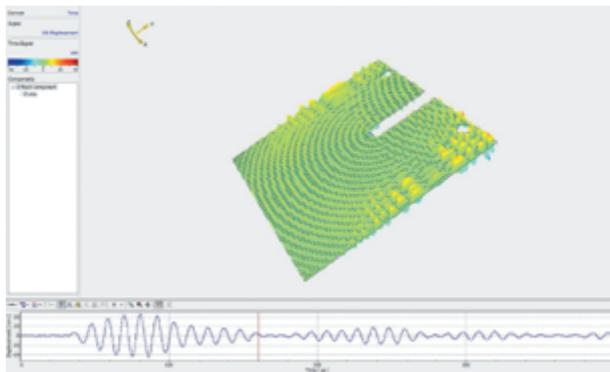
T=120 [μ s]T=180 [μ s]T=140 [μ s]T=200 [μ s]T=160 [μ s]

Fig.6.21 Wave transmission (2/4)

7. Special Training

Persons who are engaged in the duties of offering instructions or conducting inspections of industrial robots are required to have received special training according to the Article 59 of the Industrial Safety and Health Law, as well as Sections 31 and 32

under Article 36 of the Labor Safety and Health Regulations²⁾. Industrial robots, as referred to here, are defined as machines that are equipped with a manipulator and memory device, and capable of extending, bending, vertically as well as horizontally moving or rotating the manipulator according to the

information stored in the memory device, or perform such complex movements automatically. As such, the robots that comprise the MaVES and the MaVES-c are subject to these stipulations.

8. Conclusion

The functions of the MaVES non-contact, automated, multiaxial vibration measurement system were enhanced to make it conduct highly precise measurements of vibration characteristics at even higher frequencies. Additionally, a prototype MaVES-c compact, automated, non-contact, multiaxial vibration measurement system was developed for the purpose of enhancing portability. Such functional enhancements and developments were

made with significant cooperation from Polytec Japan and KUKA Robotics Japan.

The specifications of the respective hardware and software are excerpts taken from the associated manuals and data sheets of the respective hardware and software.

References

- 1) Atsushi KANDA: Development of Multi-axis Vibration Evaluating System (MaVES), JAXA Research and Development Memorandum, JAXA-RM-10-010 (2010).
- 2) Japan Industrial Safety & Health Association: Safety Essentials of Industrial Robots, Japan Industrial Safety & Health Association.

