1. Contents of Empirical Research

1.1 Objectives of empirical research

In the shell-and-tube-type heat exchanger used at oil refineries, the tubing can frequently undergo fatigue cracking from vibrations, depending on conditions of use, and from corrosion or stress corrosion cracking due to the corrosiveness of the fluids being handled. The locations where cracking often occurs are the tube sheet, the No. 1 baffle plate, the No. 2 baffle plate, and at or near the bottom (inside) of the final obstructive plate. Technology for detecting cracks at or near tube sheet has been publicized recently, but as in the case of the ultrasonic oblique angle flaw detection method, its scanning range is limited.

In the present research, ultrasonic flaw detection technology is being developed which can detect cracks and corrosion simultaneously throughout the entire length of tubing, with no limits in scanning range, so as to assure safe operation of petroleum refining facilities.

1.2 Contents of empirical research

Technology is being developed under a three-year plan whereby detection of cracks and corrosions in heat exchanger tubing can be evaluated throughout the entire length of the tube by means of a single operation employing the ultrasonic detection immersion method. Various materials are used for heat exchanger tubing, including carbon steel, low alloy steel, stainless steel, and copper and copper alloy steel, but our research will be limited to three of these types, which are used frequently in petroleum plant heat exchangers: carbon steel tubing for boiler and heat exchanger, stainless steel tubing for boiler and heat exchanger and copper alloy seamless tubing.

In general, tube lengths are 12 m, 9 m, 6 m and 5 m, and in most cases, outer diameter is 25.4 mm or 19.0 mm; so that a flaw detection technology will be developed in which the maximum length within the applicable range of examination is 12 m, outer diameter is 25.4 mm or 19.0 mm, and thickness is 2.11 mm or 2.77 mm.

In FY1999, R&D consisted mainly of fundamental research covering detectors as a whole, plus their design and trial manufacture, together with development of data gathering software for control/display.

Overall composition is shown in Figure 1.2-1. The system is comprised of a detector, which detects cracking and corrosion signals (data), a control/display component that emits and receives ultrasonic waves and gathers and displays data (called a digital oscilloscope that includes data gathering software) and a recording component comprised of software that processes collected data and outputs and displays it.
In the last fiscal year, fundamental developments were completed on a new technology, comprised of a special (2-part) mirror and single probe, which simultaneously detects and evaluates cracks and corrosion on tubing. In the current fiscal year, work was continued as indicated below.

1.2.1 Creation of detector

(1) Creation of wide-band probe

A probe smaller in size than the probe created last year (housing diameter 9.7 mm) was investigated and fabricated.

(2) Design and fabrication of mirror

(a) Convergent mirror

The convergent mirror was studied and produced in consideration of whether greater output could be obtained than from a flat-surface mirror.

(b) Creation of a special-purpose mirror for each tube material and each detection angle

All mirrors for tube inspection by the present system were fabricated.

(3) Detector assembly (Examination of mirror rotation method)

A detector comprised of mirror, probe and mirror rotary drive motor was studied and trial produced. The detector is scheduled to be completed in the year 2000.
1.2.2 Production of test samples for comparison

All test samples for comparisons were fabricated. (Total of 12 samples)

In consideration of the limit in detection of tube cracking, for each material, a comparison test sample was designed and fabricated having a slit flaw. (Total of 3 samples for each material)

1.2.3 Development of data gathering software (Control/Display)

Data gathering software was completed.

Collected data was rendered as C scope. Together with flaw detection, C scope and A scope can be displayed on digital oscilloscope.

1.2.4 Development of output display software (Recording)

Output display software will be completed in the year 2000 as initially scheduled.

Data must be collected while mirrors are being rotated continuously and know-how obtained by analyzing this data must be reflected in the software. In order to extract data on cracking from data obtained by oblique angle flaw detection, in particular, and improve upon accuracy, large volumes of data must be gathered and analyzed.

At present, we are at the initial stage of data gathering; fundamental specifications for output display software are being established; and designs and studies are being conducted on the software in general.

2 Results of Empirical Research and Analysis Thereof

2.1 Creation of detector

(1) Creation of wide-band probe

Last year, a probe (hereinafter “6.4 mm probe”) consisting of a 6.4 mm diameter oscillator (9.7 mm housing diameter) made by S company was produced. Nevertheless, a small probe of even smaller housing diameter is required for detecting flaws in tube of 19 mm outer diameter. Small probes manufactured by two companies underwent testing for comparison of performance in terms of output waveform, frequency analysis and so on. As a result, a probe made by S company with an oscillator of 3.2 mm diameter (shown in Figure 2. 1-1) was selected (hereinafter “3.2 mm probe”).

Next, tests were performed to compare the output from the 3.2 mm probe with that of the 6.4 mm probe developed last year. The test method is illustrated in Figure 2.1-2.
Testing equipment was fabricated for detecting, in a water tank, flaws on the inner surface of 25.4 mm tube which had been divided in half as shown in the figure, and measurements were taken of the height of the first bottom-surface echo while the water distance was being changed. The results are shown in Figure 2.1-3.

It can be seen that output from the 3.2 mm probe is about 12 dB lower than that of the 6.4 mm probe. This is proportional to the oscillator area.

Comparison test samples were inspected for flaws (See "Results of comparison test sample detection" discussed in Section 2.5 below.), and output was slightly weaker, but the 3.2 mm probe can be used with the system.
(2) Mirror design and production

(a) Convergent mirror

With the aim of improving output from flat-surface mirror, of improving resolution of minute flaws, and of compensating for the slight weakness in output from the 3.2 mm probe, a convergent mirror was trial-produced. Convergent mirror was confined to mirror only for vertical flaw detection of stainless steel tube.

Tests were performed to compare output from convergent mirror and flat surface mirror.

The test method is presented in Figure 2.1-4. The figure was photographed from the top of a water tank. Inside the water tank, the distance between probe and mirror was kept constant and the height of surface echoes from the flat plate were measured while the distance between mirror and flat plate was varied. Outputs from convergent mirror and flat surface mirror are presented for comparison in Figure 2.1-5.

![Figure 2.1-4 Tests for comparing mirror outputs](image-url)
In the figure, the horizontal axis represents the shuttle time for ultrasonic wave between probe and flat plate surface. The vertical axis denotes echo surface height. Comparison reveals that the convergent mirror has a more practicable range than the flat-surface mirror.

When comparison test samples are used for continued verifications and favorable results can be obtained, a convergent mirror is used.

(b) Special-purpose mirror for each tube material and each detection angle

All the mirrors used for detecting flaws in tube under examination by this system were specially made. The configuration of each mirror varies with each material and with each oblique angle detected, but with carbon steel and austenite stainless steel there is little difference in sound speed, and little difference in oblique mirror angle, so such mirrors were used concurrently.

From the standpoint of mirror configuration, output from the system was in the following sequence, as shown in Figure 1.2-1: oblique angle echo, front surface echo, bottom surface echo. The distance between mirrors was determined so that the oblique angle echo does not interfere with vertical flaw detection.

Examples of specially made mirror and mirror case are given in Figure 2.1-6.

Tests were conducted to confirm output from each mirror. An example of A scope output is presented below.

Shown in Figure 2.1-7 is A scope, in which slit flaws underwent detection (comparison test sample) using an oblique-angle 70° mirror for copper alloy.

Shown in Figure 2.1-8 is A scope, in which slit flaws underwent detection (comparison test sample) using an oblique-angle 45° mirror for stainless steel.

In the confirmation tests of each mirror output, no special problems were noted regarding mirror angle or distance between mirrors.
Figure 2.1-6  Mirrors and mirror cases

Figure 2.1-7  Output sample by oblique-angle 70° mirror for copper alloy

Figure 2.1-8  Output sample by oblique-angle 45° mirror for stainless steel
(3) Detector assembly (Examination of mirror rotation method)

Studies were begun as indicated below on a detector comprised of mirrors and cases, probes, motors and outer cylinder, and it was produced.

In gathering flaw detection data (See “Production of data gathering software” discussed in Section 2.3 below.), signals indicating the location of flaw detection on tube are output and data on corresponding ultrasonic waves (oblique angle, vertical) are obtained. Consequently, before writing data-gathering software, the method of output of position signals for tube circumferential and tube longitudinal directions, that is the mirror rotation method and cable (water supply hose with built-in probe cable and motor cable) withdrawal method, must be determined.

For mirror rotation method, motors were examined.

The types of motors considered are listed below.

(a) Ultrasonic wave motor

(b) Pulse motor

(c) DC coreless motor (equipped with magnetic encoder)

   The method of recognition of rotation (circumferential position) was from pulse frequency by controller for (a) and (b) motors and by encoder for (c) motor. The pulse motor (b) and DC coreless motor (c) used are shown in Figure 2.1-9, and their specifications are presented in Table 2.1-1.

Figure 2.1-9 Small motors
<table>
<thead>
<tr>
<th>Motor</th>
<th>Pulse motor</th>
<th>DC coreless motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>pulse</td>
<td>DC brush</td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Nominal voltage (V)</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Continuous current (mA)</td>
<td>260</td>
<td>177</td>
</tr>
<tr>
<td>Revolutions (rpm)</td>
<td>15,000</td>
<td>12,500</td>
</tr>
<tr>
<td>Reduction gear ratio</td>
<td>1/25</td>
<td>1/16</td>
</tr>
</tbody>
</table>

Tests were conducted as indicated below to determine whether the aforesaid motors can be used in the flaw detection system.

(a) Ultrasonic wave motor

The ultrasonic wave motor used measures 11 mm in outer diameter. The principal of rotation by this motor is that rotation occurs by the synthetic force (friction force) of twisting movement and vertical movement by oscillator.

Confirmation tests revealed that the motor slipped in water, decelerated sharply and could not be used.

(b) Pulse motor

An overview of the pulse motor confirmation test is shown in Figure 2.1-10. Following is an outline of the test results.

Using an oscilloscope, the controller pulse frequency was confirmed at Max. 250 Hz. Hence the motor rpm was 15,000 rpm, precisely as specified. The rpm can be controlled by varying the pulse frequency.

The pulse motor generates heat but no anomalies such as motor body overheating, reduction of motor drive current when using a long cable (15 m in length), or noise from motor, could be noted. The motor was run continuously in water for 7 hours, but no anomalies were observed.
Next, a detector with built-in pulse motor was trial produced. The design drawing and trial-produced parts are shown in Figure 2.1-11 and Figure 2.1-12.

![Design drawing of detector with built-in pulse motor (reduction gear attached)](image1)

![Detector with built-in pulse motor](image2)

Using this detector, a comparison test sample was inspected for flaws in water and it was confirmed that data on rpm and circumferential direction at constant pitch (e.g., every 6°) could be obtained as prescribed. However, a number of disparities were discovered in motor holding method, for example, and work is scheduled to be continued next year on fabrication with improvements added.

(c) DC coreless motor

Confirmation test on DC coreless motor was performed in the same manner as for pulse motor. Motor rpm can be controlled at will by varying the motor drive voltage. Following confirmation tests exactly as for the pulse motor, it was confirmed that there are no anomalies such as current reduction or noise.

As in the case the pulse motor, the DC coreless motor was test run in water, and after 7 hours of continuous running, no anomalies could be noted.

The results of the aforesaid motor confirmation tests are presented in Table 2.1-2.

<table>
<thead>
<tr>
<th>Table 2.1-2 (Motor test results)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor</strong></td>
</tr>
<tr>
<td>Revolutions (rpm)</td>
</tr>
<tr>
<td>Current reduction</td>
</tr>
<tr>
<td>Continuous running in water</td>
</tr>
<tr>
<td>Overheating</td>
</tr>
<tr>
<td>Noise</td>
</tr>
</tbody>
</table>
Although the DC coreless motor is 2 mm larger in diameter than the pulse motor, it has the advantage of stronger rotational force (torque). Efforts are thus being directed toward producing a detector with built-in DC coreless motor that offers the same advantages as the trial-produced detector with pulse motor built in.

A device for automatic withdrawal of cable is now being investigated. A DC motor is scheduled to be used for cable traction.

2.2 Production of comparison test samples

Flaw configurations were classified and nomenclature for comparison test samples was determined.

The designations of comparison test samples for detection of cracks and corrosion were given as A-1, A-2, A-3 and A-4, and a total of 12 samples, including 2 samples made last year, were fabricated. In addition, 3 comparison test samples exclusively for slit flaws, designated as B-1 and B-2, were made for the purpose of determining the crack detection limit. The designations of comparison test samples made for each tube specification are given in Table 2.2-1.

<table>
<thead>
<tr>
<th>Table 2.2-1 Designations of comparison test samples for each tube specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
</tr>
<tr>
<td>Thickness Material</td>
</tr>
<tr>
<td>STB 340 S-C</td>
</tr>
<tr>
<td>STB 340 S-C</td>
</tr>
<tr>
<td>C6872T</td>
</tr>
<tr>
<td>C6872T</td>
</tr>
<tr>
<td>SUS 321 TB</td>
</tr>
<tr>
<td>SUS 321 TB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>A-1</th>
<th>A-3</th>
<th>A-3</th>
<th>A-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>(A-2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-2</td>
<td>(A-4)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Items in parenthesis ( ) were made in 1998.

The configurations of A-1 and B-2 are illustrated in Figure 2.2-1 and Figure 2.2-2, respectively.

Figure 2.2-1 Comparison test sample A-1
2.3 Development of data gathering software (Control/Display)

Collected data were rendered as C scope because the volume of data does not become excessive, the data are easily analyzed, and data processing is simplified.

In order to readily confirm in real time the state of tube cracking or corrosion and/or the presence/absence of data, it was arranged so that A scope and C scope can be displayed on digital oscilloscope concurrently with flaw detection during data gathering.

C scope data were collected as each gate TOF (time measurement) or Peak (echo height), and the number of collections was \( M_a \times 4 \) frames.

For example, when surface echo is taken as standard and gate is set in the first bottom-surface echo and oblique-angle echo, the four frames of TOF and Peak of the first bottom-surface echo, plus TOF and Peak of the oblique-angle echo, can be shown simultaneously on C scope. In this case, if there are no more than 4 frames, any number of C scopes can be displayed.

In C scope, the horizontal axis (X axis on display) is tube circumferential direction and the vertical axis (Y axis on display) is longitudinal direction.

An example of a frame in flaw detection data gathering is presented in Figure 2.3-1.

To facilitate easy data analysis, it was made possible to zoom (expand, contract) in on collected C scope frames, to scroll such frames and to designate ranges. Display of circumferential and longitudinal cross sections (B scope) through one-line prompt of C scope was also enabled.
2.4 Development of output display software (Recording)

Thanks to trial production of a detector with built-in motor for mirror rotation, continuous data gathering was made possible for the first time. This output data is analyzed, and the know-how thereto must be reflected in output display software. Large volumes of data must be gathered and analyzed in order to achieve high precision in assessing cracks from oblique-angle flaw detection output; that is in distinguishing between cracks and corrosion and in assessing crack size. All the procedures involved in assessing cracks are scheduled to be implemented by software.

At present, fundamental specification sheets are being compiled for output display software, and designing and study of the software in general are currently in progress.

The following is an outline of software proposals.

(1) Position correction of vertical and oblique angle data

Data gathered by mirror for vertical flaw detection and by mirror for oblique-angle detection are not from the same position on the tube. Software will be developed to correct the positions of gathered data and display again on the frame.

(2) Operational frame for data analysis

For C scope, zooming up and scrolling will be possible. It will also be possible to display cross sections (B scope) of circumferential and longitudinal directions through one-line prompt of C scope.

(3) All types of output (Ledger output, Frame display)

Shown in Figure 2.4-1 is a sample (software proposal) of a frame for selection of ledger output (ledger output selection frame sample).
Ultrasonic wave examination of cracks and corrosion (5. Ledger output – 2)

5-1. Crack data (Number of cracks per tube)
5-2. Corrosion data (Minimum thickness per tube)
5-3. Crack detailed data (Output No., length, echo height per crack)
5-4. Corrosion detailed data (Output No., thickness, inner surface corrosion, outer surface corrosion per tube minimum thickness)
5-5. Inner surface corrosion data (Maximum inner surface corrosion per tube)
5-6. Outer surface corrosion data (Maximum outer surface corrosion per tube)
5-7. Crack flat surface drawing (Length, echo height per crack generation output No.)
5-8. Corrosion cross-section drawing (Cross-section drawing per tube minimum thickness output No.)

Figure 2.4-1 Ledger output selection frame sample Image

2.5 Results of comparison test sample detection

Using trial-produced detector, comparison test samples were inspected for flaws, and from the data thus obtained, the current state of the flaw detection system was verified and problematic points were checked.

A flat-plate mirror and the 3.2 mm probe shown in 2.1 (1) were installed to the detector, and a B-2 comparison test sample made of stainless steel, and consisting of slit flaws, was inspected for flaws in order to check the detector’s performance in crack detection.

The results are shown in Figure 2.5-1.

The configuration of the B-2 comparison test sample was as shown in Figure 2.2-2. From the C scope of oblique angle Peak shown in the figure, all slit cracks measuring 10 L or 5 L in length were detected. It was also found that there is a correlation between the brightness of crack prompt and crack depth. (In the figure, the oblique-angle echo is large when flaw brightness is high.) Since flaws of 0.2d × 5 L are detected, it is assumed that the target has been roughly reached.

In the C scope of vertical TOF and vertical Peak in Figure 2.5-1, black areas of high density are scattered about. These are areas where data is missing (could not be obtained). Currently under development is an automatic cable withdrawing device that pulls the detector at constant speed in the axial direction, and this explains why a withdrawal speed corresponding to the number of mirror rotations cannot be obtained. Another reason is that the lateral run out of the detector is extensive, so that the amplitude can be outside the gate.
Next, using the convergent mirror shown in 2.1 (2) (a) and a 3.2 mm probe, comparison test sample A-2, made of stainless steel, was inspected for flaws in order to check performance in corrosion detection. The C scope thus obtained is shown in Figure 2.5-2.

From the vertical TOF of the figure, it can be seen that loss of inner and outer surface circumferential thickness, stepped loss of thickness and slit flaws were all detected. Also detected were holes at four locations, including 3 mm and 2 mm diameter through holes by flat-bottom drill.
3. Empirical research results

A method was developed for realizing continuous flaw detection by having the mirrors rotated automatically, thereby surmounting one of the major hurdles in reaching the objectives of research.

The results of R&D conducted this year can be listed as follows.

1. A detector with built-in probe, mirror and small motor for mirror rotation was fabricated, and a method of continuous flaw detection was developed which can be implemented simultaneously for both vertical and oblique-angle detection.

2. Concurrently with flaw detection, C scope and A scope were displayed on digital oscilloscope in real time, and data analysis was made possible by zoom-up and other functions.

3. Data gathering at constant intervals along both circumferential and longitudinal directions of tube was made possible.

4. Special-purpose mirrors were made individually for inspecting all tube under examination, and it was verified that all these mirrors can be used for flaw detection.

4. Synopsis

Research conducted over the past 2 years has unveiled a number of problems, which are as yet unresolved, and efforts will be directed toward solutions in the next fiscal year.

The problems currently faced can be listed as follows.

1. Flaw detection echoes are obstructed by unwanted signals reflected off mirror periphery. Mirror case configurations must be studied.

2. There are no major problems with running the motor in water, but in many cases the decelerator, of inadequate strength, was damaged and rotations were not possible. Countermeasures must be taken by modifying such things as the method of securing (holding down) the motor.

3. Mirror rotation results in “run out” perpendicular to the axis, which cannot be avoided, but if the “run out” is extensive, the output signal (amplitude) drops, resulting in lost data. To avoid such data loss, run out must be kept to the very minimum. The method of detector centering must be studied.

4. There are instances in which flaw detection data are lost (cannot be obtained) because of bubbles produced while water is being supplied. This problem must be considered along with that given in (1) above when examining mirror case configurations.