Development for Life Assessment System for Pipes of Thermal Power Plants

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Abstract

The high-temperature steam pipes of thermal power plants are subjected to severe conditions such as creep and fatigue due to the power plant frequently being started up and shut down. To prevent critical pipes from serious damage and possible failure, inspection methods such as computational analysis and online piping displacement monitoring have been developed. However, these methods are limited in that they cannot determine the life consumption rate of a critical pipe precisely.

Therefore, we set out to develop a life assessment system, based on a three-dimensional piping displacement monitoring system, which is capable of evaluating the life consumption rate of a critical pipe. This system was installed at the “M” thermal power plant in Malaysia, and was shown to operate well in practice. The results of this study are expected to contribute to the increase safety of piping systems by minimizing stress and extending the actual life of critical piping.

Keywords: Life Assessment, Piping Support, Three-dimensional Displacement Measuring System, Thermal Power Plant, High-Temperature Steam Pipe

I. INTRODUCTION

As power plants are required to produce ever-larger amounts of electricity, the components of thermal power plants in particular are being subjected to more demanding conditions such as higher temperatures and pressures. Especially, in Korea, there is a trend for thermal power plants to be frequently shut down and then started up in response to electricity shortages. All of the facilities of thermal power plants are greatly affected by this frequent starting-up and shutting-down.

In general, major facilities are always carefully inspected. On the other hand, minor facilities such as piping systems are not checked regularly because these are assumed to be under static loads. Nevertheless, many of the issues experienced in older power plants that have been operating for more than 20 years are related to such piping systems.

Given the above, we cannot secure the stable operation of thermal power plants without continuous maintenance and careful attention to these critical pipelines. This attention to the pipelines not only helps to prevent accidents but also contributes to the economical operation of a thermal power plant. To date, however, there have been no quantifiable methods for assessing the life of a pipe.

In this study, a three-dimensional (3D) displacement measuring system (3DDMS) was adopted for application to the actual online life monitoring of the pipes of a thermal power plant. Based on this 3DDMS, a real-time advanced piping life assessment system (APLAS) is proposed. This would be capable of protecting the critical piping systems in a thermal power plant from serious damage and ultimate failure. The process flow for APLAS is shown in Fig. 1.

There are several different types of piping support, such as variable and constant spring hangers, at which the position of a pipe can be measured [1]. However, these supports only offer one-dimensional displacement information for the piping system even though the piping system can move in three directions. Therefore, researchers have expended considerable effort to resolve this problem. Some novel systems for obtaining 3D displacement information for piping systems have been suggested by many groups [2]-[4]. Among these systems, the 3D displacement measuring system (3DDMS) developed by Hyun et al. [5] was adopted for this study because this system has proven itself to be the most cost-effective system developed to date. The systems that we used are shown in Fig. 2.

II. 3D DISPLACEMENT MEASURING SYSTEM(3DDMS)

The main component of the 3DDMS is the measuring device shown in Fig. 3. This is consisted of two linear variable differential transformers (LVDTs) and three rotary encoders for measuring the linear displacement and rotational angle,
respectively. By using two types of the devices shown in the figure, we can calculate the exact X, Y, Z coordinate values at the P1, P2 positions as shown in Fig. 4(a) and (b). Here, l1, l2 are the linear position values at P1, P2 as obtained from the LVDTs. Furthermore, θ1, θ2, θ3 are the rotational angles at P1, P2 that can be obtained from the rotary encoder.

The process for obtaining the exact position of X, Y, Z is expressed by equations (1) to (4) [5]. This device is installed around the pipe to provide position data for the pipe in real time.

Using the 3DDMS, we can find the relationship between the displacement of the pipe and the temperature, as well as the resulting stress. Then, this relationship is used to calculate any fatigue and creep damage.

$$P_{1x'} = l_1 \cos \theta_1$$
$$P_{1y'} = l_1 \sin \theta_1$$

$$P_{2x'} = l_2 \cos (\theta_1 - \theta_2) + P_{1x'}$$
$$P_{2y'} = l_2 \sin (\theta_1 - \theta_2) + P_{1y'}$$

$$P_{1x} = l_1 \cos \theta_1 \cos \theta_3$$
$$P_{1y} = l_1 \sin \theta_1$$
$$P_{1z} = l_1 \cos \theta_1 \sin \theta_3$$

$$P_{2x} = P_{2x'} \sin \theta_3 + P_{1x}$$
$$P_{2y} = l_2 \sin (\theta_1 - \theta_2) + P_{1y}$$

III. CALCULATING THE REMAINING LIFE OF CRITICAL PIPES IN A THERMAL POWER PLANT

To demonstrate the accuracy and efficiency of APLAS, a test was conducted and the results are presented in this subchapter. Among many pipes of a thermal power plant, main steam pipe (MSP) was selected for the test because this is exposed to more severe conditions. The installed measuring devices are shown in Fig. 5. In general, two main factors are considered when calculating the damage to the facilities at high temperatures and under high pressure [6].

The first of these is damage resulting from low-cycle fatigue, and the second is that caused by creep. These two factors are also considered in our study. In the following chapter, the specific procedure for calculating the remaining life of a pipe is described.

A. Calculating the life consumption of major pipes subject to low-cycle fatigue damage

Given that the temperature of the pipe being considered was relatively low and its vibration amplitude was high, we assumed that the pipe is subjected to low-cycle fatigue even before steady-state operation of the power plant. We usually consider four kinds of stress when performing a stress analysis on a pipe in a thermal power plant. These are the hoop, longitudinal, principal, and ASME code stresses, all of which are widely used for the stress
First, hoop stress refers to a stress distribution with rotational symmetry, as given by equation (5). Here, $P$ (KPa), $D_o$ (mm), $t$ (mm), and $ca$ (mm) indicate the design pressure, outside pipe diameter, pipe wall thickness, and corrosion allowance, respectively.

$$\varepsilon_u = \frac{P}{2(D_o - 2t - ca)} - 0.4 \quad (5)$$

Second, longitudinal stress, which is a normal stress acting parallel to the axis of cylindrical symmetry, is written as equation (6). Here, $Z$ (mm), $i$ (dimensionless), $M_i$ (Nmm), $i_o$ (dimensionless), $M_o$ (Nmm), $F_a$ (Kgf), $P_o$ (Kgf), and $A_c$ (mm) indicate the section modulus, in-plane stress intensification factor, in-plane moment, out-of-plane stress intensification factor, out-of-plane moment, axial force, axial force from internal pressure, and corroded cross-sectional area, respectively.

$$S_H = \frac{P}{2(t - ca)}$$

$$S_L = (i_oM_o)^{1/2} + \frac{F_a + P_o}{A_c} \quad (6)$$

Third, the principal stress, which is the maximum stress in the cylinder, is expressed by equation (7.a) and (7.b). Here, $M_a$ is the torsional moment.

Finally, the ASME code stress is composed of three kinds of stress, namely, sustained, sustainer plus occasional (as given by equation (8)), and expansion stress. Here, $D_o$ (mm), $t_n$ (mm), $Z$ (mm), $M_a$ (Nmm), $M_o$ (Nmm), $M_c$ (Nmm), $i$ (dimensionless) indicate the pipe outside diameter, radius of the pipe, section modulus, resultant moment loading on the cross-section due to the weight and other sustained load, resultant moment loading on the cross-section due to the weight and other occasional load, and range of resultant moments due to thermal expansion, respectively [7].

$$S_P = \frac{S_L + S_H}{2} + S_{SH} \quad (7.a)$$

$$S_{SH} = \left[ \left( \frac{S_L - S_H}{2} \right)^2 + \left( \frac{M_a}{2Z} \right)^2 \right]^{1/2} \quad (7.b)$$

$$S_L = \frac{PD_o}{4\pi n} + \frac{0.75i_oM_a}{Z} \quad (8.a)$$
The data shown on Fig. 11 are after the trimming process, we can count the number of stress applied at a certain stress which can be used for calculating fatigue damage.

In general, Miner’s rule is widely used for evaluating damage resulting from low-cycle fatigue. It is usually assumed that fatigue failure occurs when the cumulative damage exceeds a critical value such as $D = 1$. For example, if $1 < D$, fatigue failure occurs. For $D < 1$, however, we can determine the remaining fatigue life [8]. After calculating the number of cycles applied under each stress, we then sum all of the values at each stress to determine the total fatigue life consumption rate “$D$.” The S-N curve for P91 steel was used for this process. The calculated life consumption rate for pipes subject to low-cycle fatigue was thus found to be 1.1% for the MSP.

B. Calculating the life consumption of major pipes subject to creep damage

We considered that, during the steady operation of pipes, creep damage becomes the dominant factor determining the life consumption rate of those pipes. The Larson-Miller parameter (LMP) is widely used to evaluate the creep life consumption [9]. The LMP is expressed by equation (12).

$$LMP = T[\log(t_c)] + C$$

where $T$ is the Kelvin temperature, $t_c$ is the creep life time, and $C$ is a material-dependent constant. Specific values for each of the coefficients are listed on Table 2.

In the case of the LMP, the final objective is to calculate $t_c$. To do this, information on the stress and temperature is necessary. As mentioned above, four kinds of stress are exerted on the pipe. From these, we selected the principal stress as the input value for Eq. 12 because this is the maximum stress in the material.

This principal stress can be obtained from Fig. 11 for the MSP. The stress value after entering the steady operation region (plateau region) should be chosen as the input data for equation (12), 38.4 MPa is selected as input value for equation (12). Then, adopted for the trimming process. After the completion of trimming process, we can determine the remaining fatigue life which can be used for calculating fatigue damage.
we require a temperature value for the final goal. We installed the 3DDMS on the MSP and traced the temperature and displacement of the pipe with respect to time. The resulting graph of temperature with respect to displacement is shown in Fig. 12 for the MSP. From these graphs, it is clear that these two terms have a linear relationship like “temperature transfer function” like equation (13).

Here, \( e \) and \( f \) differ depending on the thermal power plant. Therefore, these temperature coefficients should be determined by a preliminary study. The value \( d \) is the displacement of the pipe. The specific values for "M" thermal power plant are shown on Table 3.

\[
T_{pipe} = e \cdot d + f \tag{13}
\]

Next, from the Eq. 13, we can obtain temperature information for the MSP. First we can already obtain the displacement with respect to operation time as shown in Fig. 13, which can be used for the input value of Eq. 12. The temperature calculated from Eq. 13 is shown on Fig. 13, which is 845K (=572°C) during steady-state operation. Now, we have all the values to calculate creep life time \( t_c \). From the Eq. 12, calculated creep life is 392,265 hours. Operation time of unit #2 of "M" thermal power plant is 87,928 hours. Therefore, the calculated life consumption rate by creep is 22.42% for the MSP.

C. Total life consumption rate of major pipeline

To obtain the total life consumption rate of a pipe, we should sum the life consumption rates for both low-cycle fatigue and creep. This summation is done based on the linear summation rule. Using this method, fatigue damage and creep damage are simply added together to estimate the cumulative damage [9]. The equation of linear summation is as follows:

\[
D_{total} = D_f + D_c \tag{14}
\]

where \( D_f \) and \( D_c \) are the life consumption rate of the pipe resulting from low-cycle fatigue and creep, respectively. The input values for the calculation for determining the remaining life are listed in Table 4. \( D_{total} \) is 23.52% for the MSP.

III. CONCLUSION

We have proposed a new pipe life assessment system and have verified its application to the determination of pipe life assessment as a means of ensuring the reliability of the piping systems of thermal power plants. To demonstrate the accuracy and efficiency of APLAS, we installed this system at the “M” thermal power plant in Malaysia.

We obtained the 3D displacement data with the aid of 3DDMS. With the 3D displacement we performed the calculations for fatigue and creep damage. We went on to estimate the remaining life of the pipes in a thermal power plant by installing this device in an actual plant. The main advantage of this system is that it makes it possible to simply calculate the remaining life of a pipe in real time without any additional devices. Before our study, there has been no method to deal with accurate damage on pipes in a thermal power plant. We believe that the results of this study will contribute to the safety and reliable maintenance of piping systems, by minimizing stress and extending the life of critical piping.

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