Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

# Assessment of failure for fretting-wear of steam generator U-tubes

**Kim I.K.**
*Korea Atomic Energy Research Institute, Korea*

## ABSTRACT

An analysis method to predict fretting-wear damage caused by turbulence-induced excitation in steam generator(SG) tubes is investigated. U-bend region of type D tube of Westinghouse SG model 51 is studied. Thermal-hydraulic analysis is performed to obtain the non-uniform flow distributions. Nonlinear impact analysis to predict the dynamic interaction between tube and tube support is also performed. The fretting-wear prediction can be done through the correlation of the calculated impact force and wear.

## 1. INTRODUCTION

Tube failures in SG are often caused by flow induced vibrations. In the nuclear industry, these tube failures can result in costly repairs and station outages. Among the mechanisms of flow-induced vibration the turbulence-induced excitation generates random pressure fluctuations around the surface of tubes forcing them to vibrate and may induce enough vibration response to cause long-term fretting-wear damage. Therefore, it is very important to assess the potential for SG tube failure due to turbulence-induced excitation to prevent the flow-induced tube vibration problems at the design stage.

Generically, a procedure of the potential for a tube failure caused by turbulence-induced excitation has been established and is outlined in Fig.1. This paper outlines a predictive methodology of SG tube failures caused by turbulence-induced excitation in operating nuclear power plants. In the present study, U-bend region of type D tube of Westinghouse SG model 51 shown in Fig.2 is modeled for life assessment due to fretting-wear damage. According to steps in Fig.1, as the first stage in analytical procedure the thermal-hydraulic analysis of the tube is performed by 3-dimensional finite difference code ATHOS3 to obtain the non-uniform flow distributions in the U-bend region and fluid density of secondary side. For free vibration analysis the effective mass per unit length of the tube is come from the sum of masses of tube metal, primary fluid and added. Thus, the natural frequencies and mode shapes of the tube is obtained by finite element method. For the fretting-wear damage prediction. a nonlinear impact analysis code DAGS is used to predict the dynamic interaction between tube and tube-support. The nonlinear impact model of the tube includes some gaps at its support positions. The random excitation force simulating turbulence-induced excitation is applied where the flow velocity calculated from thermal-hydraulic analysis is the highest. The fretting-wear prediction is done by Archard's wear equation which correlated the impact force and wear.

## 2. THERMAL-HYDRAULIC AND NONLINEAR IMPACT ANALYSIS

### 2.1 Thermal-Hydraulic Analysis

The first step in understanding flow-induced vibration of SG tube is to assess the flow condition. A detailed knowledge of local flow conditions is required for flow-vibration analysis since problems occur mostly in regions where high flow velocities exist. Secondary side flow distribution along SG tube is major prerequisites to the present assessment, which can be determined from a 3-dimensional two-phase thermal-hydraulic analysis for SG.

The computer code ATHOS3[1] is one of the most widely used codes in the industry for 3-dimensional thermal-hydraulic analysis of SGs, which is known to be a well documented and validated code. Fig.3 shows input grid model for SG flow velocity analysis. Because of geometric and thermal-hydraulic symmetricity of SG the half part respecting to vertical plane is chosen for modeling. Normal-to-tube cross flow gap velocity and density distributions over entire length of U-tube can be obtained from the ATHOS3 calculation results, by using the simple computer program ATOPP[2]. Typical results indicating non-uniform flow distributions in the U-bend region of type D tube are shown in Fig.4. This figure illustrates the secondary side flow imbalance between hot and cold sides in the U-bend region of type D tube. The regions of tube affected by high cross-flow velocity are defined to U-bend and down-comer inlet.

### 2.2 Free Vibration Analysis

In addition to the SG thermal-hydraulic analysis the free vibration analysis for calculating natural frequencies and mode shapes of U-tube is one of the requisites for fretting-wear assessment due to turbulence-induced excitation of SG U-tubes. The model for free vibration analysis is given in Fig.5. The distribution of effective mass per unit length of the tube would be determined from the following equation.

$$m_e(x) = m_t(x) + m_{pf}(x) + m_a(x) \tag{1}$$

where $m$ and $x$ are mass per unit length of the tube and the distance along the tube length from the upper surface of tube sheet, respectively. The subscripts in equation (1) $e$, $t$, $pf$ and $a$ denote effective, tube metal, primary fluid and added, respectively. The added mass of secondary side is calculated from Pettigrew's experimental data on two-phase flow field[3]. As shown in Fig.5 the tube sheet position is modeled to fixed condition. The analysis is performed by employing code GTSTRUDL[4].

The analysis results of the natural frequencies and the mode shapes of Type D Tube are given in Table 1 and Fig.6, respectively. The mixed in-plane and out-of-plane modes are obtained in output.

### 2.3 Nonlinear Impact Analysis

Fretting-wear studies showed that fretting damage correlates well with the impact forces resulting from the dynamic interaction between tube and tube supports. These impact forces appear to be a useful parameter linking vibration response and fretting-wear. Thus, analytical techniques to predict the dynamic interaction between tube and tube support, are necessary. A developed finite computer code DAGS[5] is used in the present study to simulate the motion of multi-span tube considering the nonlinearities due to clearances between tubes and tube-supports. An incremental form of differential equation of motion can be written as follows for any time interval between changes of gap status while stiffness remain constant.

$$M\Delta a + C\Delta v + K\Delta u = \Delta F - M\Delta x + C_0 V_0^0 + CV_0 \qquad (2)$$

where $M, C, C_0, K, \Delta a, \Delta v, \Delta u, \Delta F, \Delta x, V_0$ and $V_0^0$ are mass matrix, damping matrix, damping during previous increment, stiffness matrix, increment of unknown acceleration, increment of unknown velocity, increment of unknown displacement, increment of unknown external force, increment of unknown datum acceleration, initial velocity and velocity at the end of the previous increment, respectively. The model for nonlinear impact analysis is shown in Fig.5. The tube-to-support clearances are modeled to the gaps with stiffness. The tube supports and the anti-vibration bars in the model are simulated to the different valued equivalent impact springs which have two directional(i.e., x and z-directional) clearances. The excitation force which simulates white noise is applied to node 28 where the flow velocity is highest and is given in Fig.7.

The calculated displacement and impact force of node 28 are given in Fig.8 and 9, respectively. The analysis results show that the order of impact force level is node 28, 50, 35 and 43 and the impact force values depend on the distance from the excited node.

## 3. FRETTING-WEAR PREDICTION

Correlations between the dynamic impact interaction at the support and fretting-wear are needed to predict damage. This is done by applying Archard's adhesive equation[6], in this study, for the life assessment of U-tube excited by turbulence. The equation is

$$V_{fw} = 10^{-12} S F_w \bar{L} \qquad (3)$$

where $V_{fw}$, $S$, $F_w$ and $\bar{L}$ are the wear volume, the wear coefficient, the normal force on the contacting surface and sliding distance, respectively. From the nonlinear impact analysis results the wear volume can be obtained as $V_{fw} = 2.2754x10^{-11}t$. From the relationship between wear depth and wear volume, the time to wear through the 0.050-in wall thickness is calculated conservatively to 43.55 years.

## 4. CONCLUSION

This study has presented a comprehensive methodology to predict the potential for SG tube failure caused by turbulence-induced excitation. It is expected that the potential for turbulence-induced excitation during lifetime of SG U-tubes be successfully predicted by utilizing the predictive methodology and related technologies presented in this study.

The parameters such as the exact value of turbulence-induced excitation, sliding distance and the correlation between impact and wear are important to assess the potential of SG tube failure during lifetime due to turbulence-induced excitation.

## REFERENCES

1. Keeton, L.W., and Singhal, A.K., 1986, "ATHOS3 : A Computer Program for Thermal-Hydraulic Analysis of Steam Generators," *EPRI Report NP-4604-CCM*, Vols.1-3
2. Jo, J.C., Lee, S.K., Kim, W.S., Shin, W.K., and Eun, Y.S., 1991, "Fluidelastic Vibration Analysis of the U-Tubes of a Recirculating Type Steam Generators : Thermal-Hydraulic Analysis", *Proceedings of KNS Autumn Annual Meeting*, Vol.1, pp.77-84
3. GT-STRUDL : User's Manual, 1989, Georgia Institute of Technology
4. Kim, I.K., Park, J.M., "A Study on the Development of Tube-to-Support Nonlinear Impact Analysis Model", 1995, *Journal of KSNVE*, Vol. 5, No.6, pp. 515-524
5. Archard, J.F., 1953, "Contact and Rubbing of Flat Surfaces", *Journal of Applied Physics*. pp. 981

Table 1. Natural Frequencies of Tube D (Out-of-Plane mode)

| Mode | Frequency(Hz) |
|---|---|
| 1 | 0.1278 |
| 2 | 0.8081 |
| 3 | 1.118 |
| 4 | 2.821 |
| 5 | 4.081 |

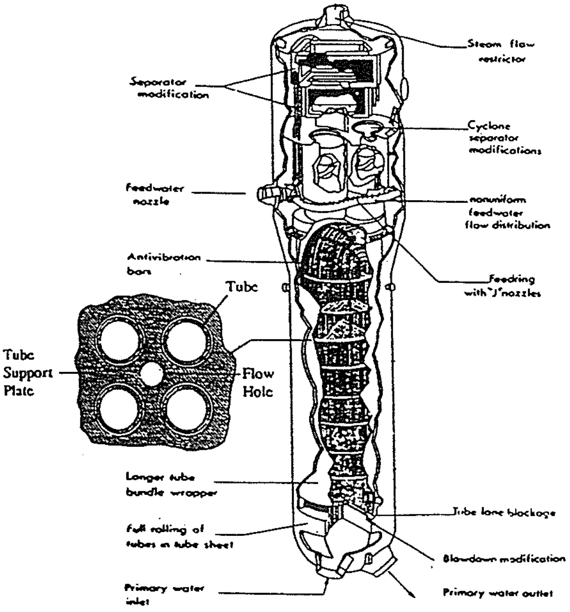


Fig.1 Configuration of Westinghouse Type Model 51 SG

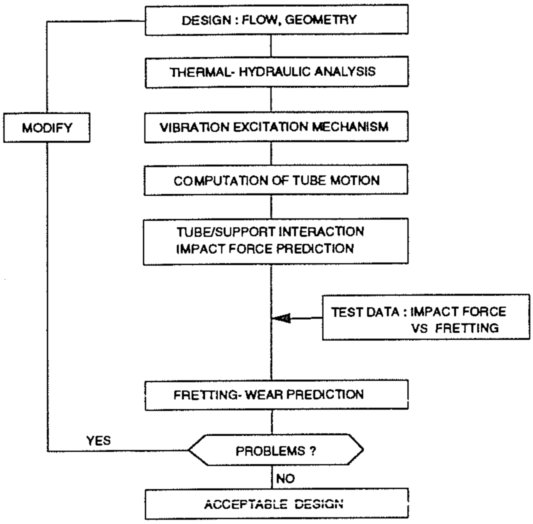
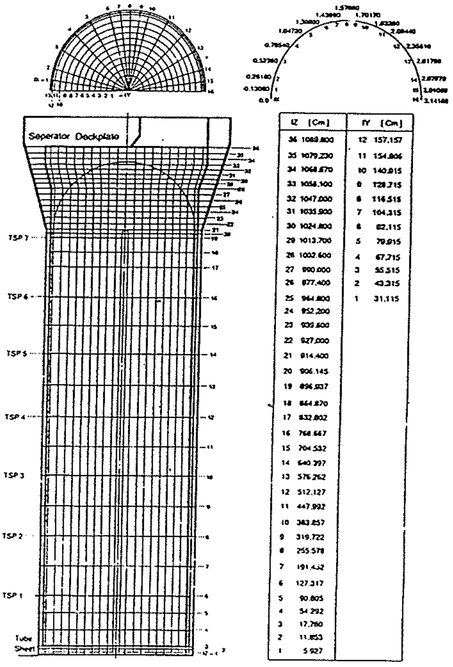
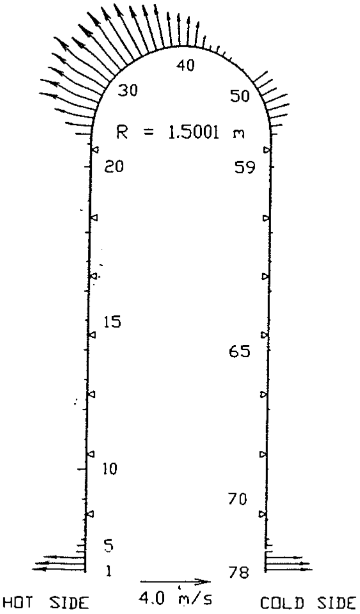


Fig.2 Analysis Procedure to avoid Vibration Problem in Heat Exchanger



| IZ [Cm] | IY [Cm] |
|---|---|
| 36 1089.800 | 12 157.157 |
| 35 1079.230 | 11 154.806 |
| 34 1068.670 | 10 140.915 |
| 33 1058.100 | 9 128.715 |
| 32 1047.000 | 8 116.515 |
| 31 1035.900 | 7 104.315 |
| 30 1024.800 | 6 92.115 |
| 29 1013.700 | 5 79.915 |
| 28 1002.600 | 4 67.715 |
| 27 990.000 | 3 55.515 |
| 26 977.400 | 2 43.315 |
| 25 964.800 | 1 31.115 |
| 24 952.200 | |
| 23 939.600 | |
| 22 927.000 | |
| 21 914.400 | |
| 20 906.145 | |
| 19 896.937 | |
| 18 864.870 | |
| 17 832.802 | |
| 16 768.667 | |
| 15 704.532 | |
| 14 640.397 | |
| 13 576.262 | |
| 12 512.127 | |
| 11 447.992 | |
| 10 383.857 | |
| 9 319.722 | |
| 8 255.578 | |
| 7 191.452 | |
| 6 127.317 | |
| 5 90.805 | |
| 4 54.292 | |
| 3 17.780 | |
| 2 11.853 | |
| 1 5.927 | |

Fig.3. Finite Difference Grid of ATHOS3 Code for SG Thermal-Hydraulic Analysis



| No. of element | Velocity [m/s] | Void fraction | Density [kg/m³] |
|---|---|---|---|
| 1 | 2.619 | 0.000 | 741.7 |
| 2 | 2.493 | 0.000 | 741.7 |
| 3 | 2.070 | 0.000 | 741.7 |
| 4 | 0.444 | 0.000 | 741.7 |
| 5 | 0.370 | 0.000 | 741.7 |
| 6 | 0.184 | 0.000 | 741.7 |
| 7 | 0.044 | 0.000 | 741.7 |
| 8 | 0.103 | 0.000 | 741.7 |
| 9 | 0.171 | 0.268 | 553.8 |
| 10 | 0.391 | 0.501 | 389.7 |
| 11 | 0.054 | 0.580 | 334.4 |
| 12 | 0.160 | 0.644 | 289.2 |
| 13 | 0.100 | 0.675 | 267.1 |
| 14 | 0.136 | 0.715 | 238.2 |
| 15 | 0.106 | 0.733 | 225.9 |
| 16 | 0.148 | 0.762 | 205.1 |
| 17 | 0.098 | 0.773 | 197.4 |
| 18 | 0.162 | 0.795 | 182.1 |
| 19 | 0.065 | 0.800 | 178.5 |
| 20 | 0.227 | 0.815 | 167.9 |
| 21 | 0.135 | 0.811 | 170.9 |
| 22 | 0.685 | 0.809 | 171.8 |
| 23 | 1.366 | 0.809 | 171.8 |
| 24 | 2.168 | 0.809 | 171.8 |
| 25 | 2.998 | 0.808 | 173.0 |
| 26 | 3.208 | 0.875 | 125.2 |
| 27 | 3.215 | 0.871 | 128.0 |
| 28 | 3.497 | 0.905 | 103.4 |
| 29 | 3.893 | 0.905 | 103.4 |
| 30 | 3.088 | 0.913 | 97.9 |
| 31 | 3.310 | 0.932 | 84.9 |
| 32 | 3.552 | 0.932 | 84.9 |
| 33 | 3.416 | 0.940 | 79.1 |
| 34 | 3.189 | 0.943 | 76.8 |
| 35 | 2.744 | 0.891 | 114.1 |
| 36 | 2.557 | 0.887 | 116.2 |
| 37 | 2.456 | 0.875 | 124.8 |
| 38 | 1.898 | 0.842 | 148.4 |
| 39 | 1.766 | 0.812 | 170.0 |
| 40 | 1.596 | 0.783 | 190.4 |
| 41 | 1.376 | 0.778 | 194.3 |
| 42 | 0.682 | 0.761 | 206.2 |
| 43 | 0.248 | 0.757 | 208.7 |
| 44 | 0.394 | 0.735 | 224.1 |
| 45 | 0.302 | 0.803 | 176.3 |
| 46 | 0.179 | 0.786 | 188.5 |
| 47 | 0.041 | 0.770 | 199.4 |
| 48 | 0.096 | 0.770 | 199.4 |
| 49 | 0.043 | 0.756 | 209.9 |
| 50 | 0.982 | 0.739 | 221.7 |
| 51 | 0.960 | 0.739 | 221.7 |
| 52 | 0.939 | 0.688 | 257.5 |
| 53 | 1.298 | 0.704 | 246.6 |
| 54 | 1.217 | 0.632 | 297.8 |
| 55 | 0.987 | 0.632 | 297.2 |
| 56 | 0.616 | 0.632 | 297.2 |
| 57 | 0.288 | 0.632 | 297.2 |
| 58 | 0.000 | 0.631 | 298.1 |
| 59 | 0.151 | 0.633 | 296.5 |
| 60 | 0.082 | 0.608 | 314.7 |
| 61 | 0.130 | 0.592 | 325.6 |
| 62 | 0.089 | 0.560 | 348.2 |
| 63 | 0.122 | 0.538 | 364.0 |
| 64 | 0.089 | 0.497 | 393.1 |
| 65 | 0.114 | 0.463 | 416.9 |
| 66 | 0.085 | 0.402 | 459.7 |
| 67 | 0.120 | 0.341 | 502.6 |
| 68 | 0.005 | 0.241 | 573.0 |
| 69 | 0.063 | 0.117 | 659.9 |
| 70 | 0.035 | 0.000 | 741.7 |
| 71 | 0.090 | 0.000 | 741.7 |
| 72 | 0.051 | 0.000 | 741.7 |
| 73 | 0.162 | 0.000 | 741.7 |
| 74 | 0.327 | 0.000 | 741.7 |
| 75 | 0.365 | 0.000 | 741.7 |
| 76 | 1.952 | 0.000 | 741.7 |
| 77 | 2.330 | 0.000 | 741.7 |
| 78 | 2.441 | 0.000 | 741.7 |

Fig.4 Flow Distribution of Model 51 SG Type D

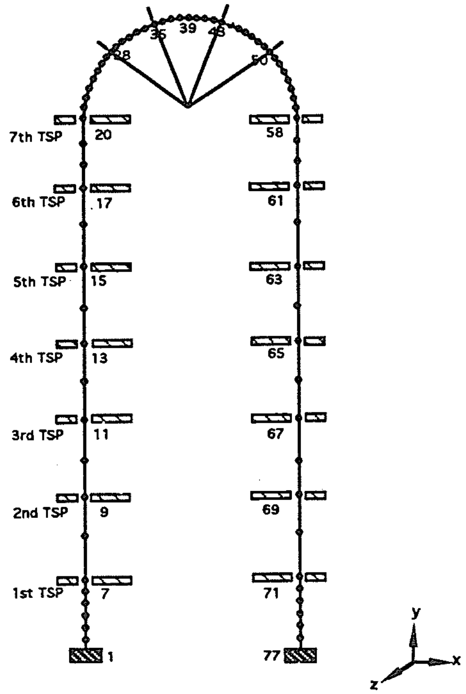
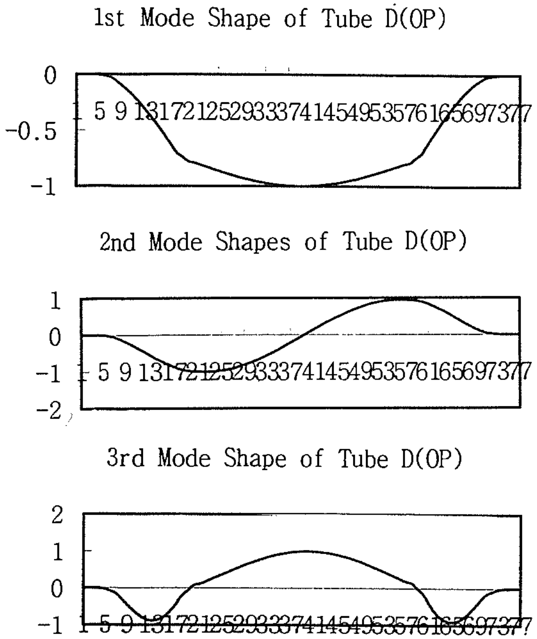


Fig.5 Free Vibration and Nonlinear Impact Analysis Model of SG Tube

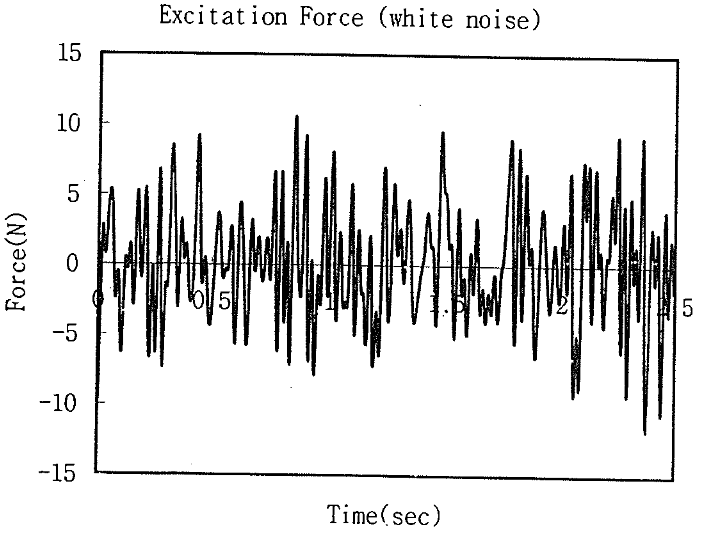


1st Mode Shape of Tube D(OP)

2nd Mode Shapes of Tube D(OP)

3rd Mode Shape of Tube D(OP)

Fig.6 Free Vibration Mode Shapes of SG Type D Tube



Excitation Force (white noise)

Fig.7 Excitation Force for Nonlinear Impact Analysis of SG Tube

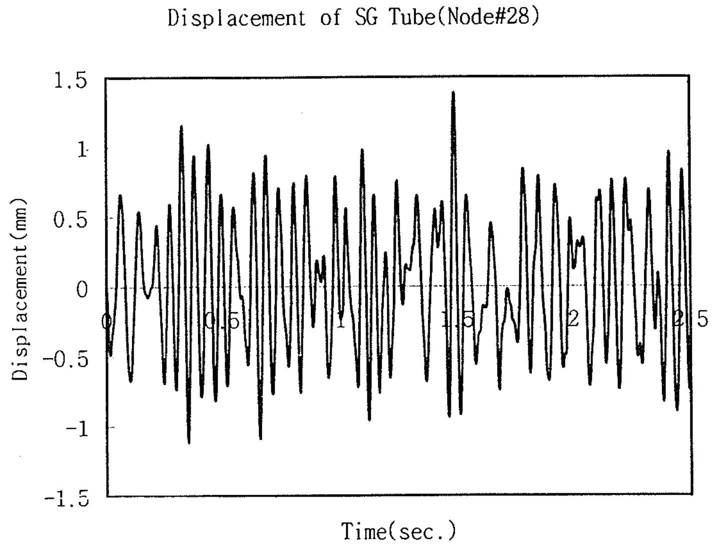


Fig.8 Displacement of Node#28 in SG Type D Tube

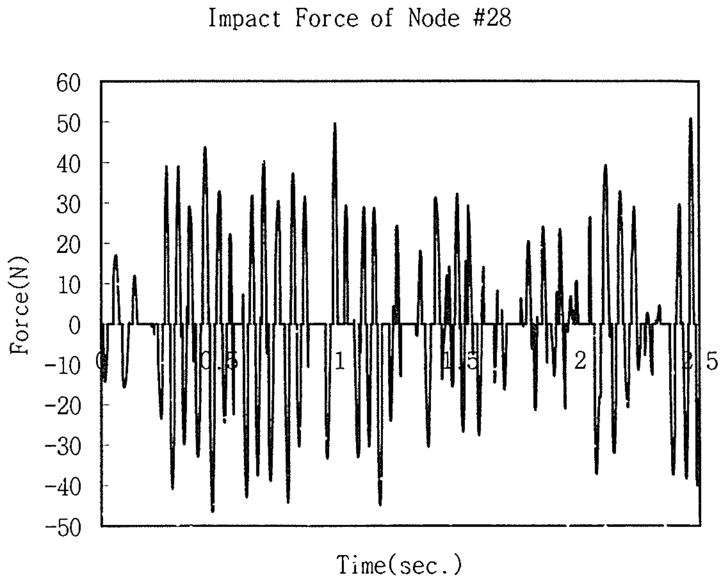


Fig.9 Impact Force of Node#28 in SG Type D Tube