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Technical note

Modal analysis of the helical tube in a small nuclear reactor's steam generator using a finite element method

Xin Guo [a], Jun Cai [a,*], Yandong Wang [b]

[a] School of Nuclear Science and Engineering, North China Electric Power University, Beijing 102206, China
[b] State Key Laboratory of Metal Materials, Beijing University Science and Technology, Beijing 100083, China

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ABSTRACT

A finite element method was used to simulate the vibration characteristics of helical tubes in a SMART reactor. It was found that vibrational characteristics of larger coil diameter helical tubes are different from smaller coil diameter tube (142 mm). The natural frequencies of the smaller ones were reduced by increasing helix angle. Natural frequencies of doubled length tube were also calculated. The difference in natural frequencies between the first order and the last order modes of the longer tube was found to be less than one third of the corresponding frequency difference in the original tube. It was also found that when the helix angle of a tube with 8 supports and coil diameter smaller than 100 mm is larger than 80°, the natural frequencies of the tube are lower than 700 Hz and this maybe induce fretting from the fluid through the tube.

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1. Introduction

A smaller sized advanced integral type pressurized water reactor, named SMART, has recently been under development in Korea. All the major primary components of reactor are contained within a single pressure vessel. These components include a modular type of steam generating system comprised of eight identical steam generator (SG) cassettes, located in the annular space between the reactor pressure vessel and the core support barrel. Each SG cassette is a once-through type of heat exchanger with many helically coiled tubes. The hot primary reactor coolant flows downward along the SG shell side at a high pressure, while the cold secondary feed water flows upward along the tube side at a low pressure (Jo and Jhung, 2008). At the same time the fluid-induced fretting of the helically coiled tube was studied by Jo and Jhung (2008).

The secondary side fluid causes a tube vibration that leads to a fretting between the tube and the support plate. This is one of the primary reasons for ruptures in steam generator tubes (Zhao et al., 2014; Connors, 1981; Pettigrew and Taylor, 2003). Therefore, a pipeline flow induced vibration analysis is essential to overall SG performance. The tube's natural frequency is inversely proportional to the mass ratio of the fluid elastic instability, consequently, the low natural frequency of the tube causes high flow instability. We can add supports or change the size of the helical tube to increase its natural frequencies; when fluid flows through the supported helical tube, it reduces the mass ratio on fluid elastic instability.

In order to find the natural frequencies of the helical tube, Jo and Jhung (2008) used ANSYS software to perform a modal analysis for the helical tube, however, in their work the modal analysis was not performed for smaller coil diameter tubes. Moreover, in this simulation, a 3D point-to-point contact unit CONTAC52 was applied to extract the natural frequencies of the supported helical tube. CONTAC52 is a 3D point-to-point contact unit. CONTAC52 represents two surfaces that may maintain or break physical contact and might slide relative to each other. The element is capable of supporting compression in a direction that is normal to the surfaces and the shear (Coulomb friction) in the tangential direction. The element has three degrees of freedom at each node: translations in the nodal x, y, and z directions. The CONTAC52 element requires knowing the contact position in advance, which complicates the design of the corresponding finite element model. Nie et al. (2011) and Jo et al. (2005) used a simple support on the U-shaped tube to calculate its natural frequency and found that the theoretical results correlate well with the experimental results. Bo and Ma (2001) also used a simple support method to analyze the properties of the flow-induced vibrations specific to a heat transfer tube in a 10 MW high temperature gas cooled reactor (10 MW-HTR). The simple support method is simpler than the 3D

* Corresponding author at: No. 2, Beinong Road, Zhuxinzhuang, Dewai, Beijing 102206, China.
E-mail address: caijun@ncepu.edu.cn (J. Cai).

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point-to-point contact method when dealing with the analysis of natural frequency.

In this paper, the simple support method was used to perform further modal analysis for full size helical tube. It was found that for larger coil diameter helical tubes the vibration characteristic by using the simple support method are in good agreement with the ones by Jo's works (2008) using the contact method, while for the helical tubes with smaller coil diameter (<142 mm) a novel vibration characteristic is found (<142 mm).

2. Theory and calculation method

In this paper, we used ANSYS 12.1 finite element analysis software to develop a modal analysis for a helical tube with different number of supports. Fig. 1(a) shows a helical tube with 8 supports in the SG of SMART, and Fig. 1(b) shows a three-dimensional finite element model for the helical tube. The outer area around the helical tube is its shell; 8 supports were added at the tube. For a more detailed integrated graphic of the helical tube in the SG please see Fig. 1 of Ref. Jo et al. (2009). The tube's coil diameter is 422 mm, the total length is 1000 mm, the tube's diameter is 10 mm, and tube wall thickness is 1.5 mm (Jo and Jhung, 2008). The helical tube was applied to the steam generator of a small SMART reactor. The physical parameters of the SMART helical tube are listed in Table 1.

The ANSYS finite element software was used to perform a modal analysis of the SMART helical tube. An elastic straight pipe element PIPE16 was used in the finite element model of the helical tube, shown in Fig. 1. The boundary conditions at the two ends of the tube were fixed. The Block Lanczos method in the modal analysis was used to calculate the natural frequencies of the helical tubes and the first twelve lowest order modes were extracted. The Block Lanczos method (Grimes et al., 1994) is as accurate as the subspace method, but faster.

In the paper, we changed the coil diameter and the helix angle of the helical tube and calculated their natural frequencies. The total length of the tube was 1000 mm and the coil diameters were 500 mm, 422 mm, 338 mm, 282 mm, 198 mm, 142 mm and 100 mm, respectively. In this work these helical tubes are respectively referred to tube A, B, C, D, E, F and G. To find the optimum geometrical structure of the helical tube against flow-induced fretting in our calculations, we took into consideration the helical tubes with different numbers of supports (see Fig. 1(a)). The geometrical parameters of the tubes with different helix angles are listed in Table 2, where the leftmost column notes the helix angles of a tube and the others express the corresponding turn number of the tube.

A second set of analyses was performed using longer helical tubes (2000 mm total length) that had the same geometric characteristics as tubes A through G, listed in Table 2. Those tubes were named A1 through G1.

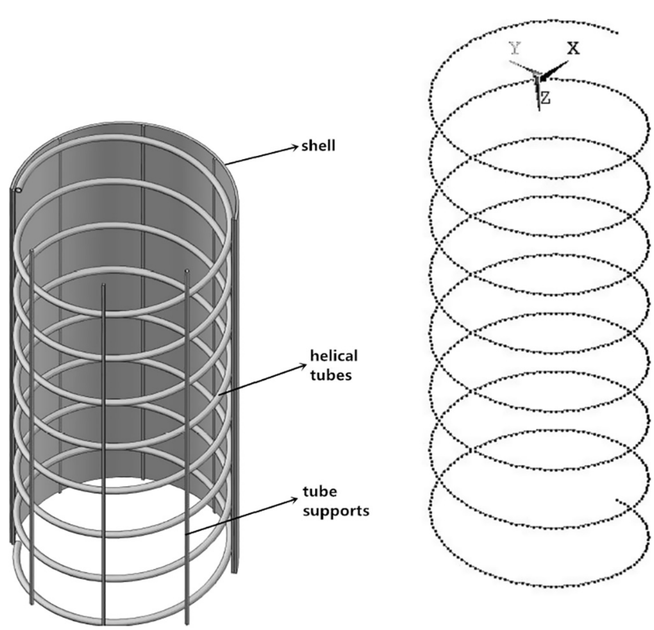

Fig. 1. (a) A helical tube with eight supports in SG, (b) the finite element model of the helical tube.

Table 1
The physical parameters of SMART helical tube (Jo et al., 2009).

Types of materials	PT-7M titanium alloy
Elasticity modulus (GPa)	112
Poisson's ratio	0.3
Density (kg/m^3)	4490
Internal fluid density (kg/m^3)	888

3. Results and discussion

In this paper, we first performed the modal analysis for the helical tube with 0, 2, 4, and 8 supports. The coil diameter of the tube was 422 mm, the total length of the tube was 1000 mm, the diameter of the tube was 10 mm, and the tube wall thickness was 1.5 mm. The first order natural frequencies for the tube with 0, 2, 4, and 8 supports were calculated to be 2.8758, 12.141, 143.91, and 700 Hz respectively. According to our numerical simulation results we found that the first order natural frequency of the tube increased with the number of supports. When comparing the first order natural frequencies for the tube, the first order natural frequency for the tube with eight supports is obviously larger than those for 0, 2, and 4 supports. As we know, the tube's natural frequency is inversely proportional to the mass ratio of the fluid elastic instability. Therefore, such a large natural frequency is beneficial in protecting the helical tube against flow instability/flow-induced fretting. The present results using a simple support method are in agreement with those determined by using their contact-contact method (Jo and Jhung, 2008). The SMART steam generator has an internal-external casing structure and the supports were welded on the helical tube; however, due to limited space it is difficult to achieve a welding process for more supports (see Fig. 1(a)). We concluded that the eight-support scheme is optimum for the helical tube with a coil diameter of 422 mm and a length of 1000 mm in order to minimize flow induced fretting. Therefore, this study does not take into consideration helical tubes with more than eight supports.

We also calculated the first order natural frequencies for tubes with different coil diameters. Fig. 2 shows the curve of the first order natural frequency vs. the coil diameter for tubes with 4 and 8 supports. In Fig. 2 we can see that with a decrease in coil diameter the first order natural frequency of the tube with 4 and 8 supports gradually increased. The first order natural frequencies were all larger than 700 Hz for all of the considered tubes with 8 supports. For four-support tubes the first order natural frequencies were larger than 700 Hz when the coil diameter was smaller than 175 mm.

In order to further understand the vibration characteristics of the helical tube, we also performed a modal analysis for tubes A–G and A1–G1 using the ANSYS finite element software. We calculated the natural frequencies of the first 12 order modes for these helical tubes. The results for tubes A, A1; tubes E, E1; and tubes G, G1 are shown in Figs. 3–5, respectively. The natural frequencies for

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