

MODAL ANALYSIS OF AN ECC DUCT FOR APR+ REACTOR BARREL

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Abstract

Advanced Power Reactor Plus (APR+) provides four Direct Vessel Injection (DVI) ducts on the reactor barrel to enhance the performance of Emergency Core Cooling System (ECCS). Several studies on safety analysis have verified the excellent performance of the DVI duct. In this study, from the viewpoint of mechanical integrity, modal analyses of two full-scaled DVI ducts have been presented; both numerical analysis and modal tests have been performed in air and water. It was found that the numerical simulation and modal test coincide with each other. The DVI duct is a thin shell of 5 mm thickness, so that harmonic responses to RCP blade passing frequencies should be checked. The dominant passing frequencies are known to be 20, 40, 60, 120 and 240 Hz. In addition, an interesting thing in this study is that added mass effect by coolant seems to be so significant that the natural frequency of the ducts under water could be considerably low as compared with those in air; the natural frequency under water is 60 % lower than that in air.

1. Introduction

Korea Atomic Energy Research Institute (KAERI) is developing an APR⁺ (Advanced Power Reactor plus), which is one of Gen-III+ PWR reactors. This reactor adopts new design features that are believed to contribute not only to enhancements in nuclear safety but also to improvements in economic competitiveness [1]. Among these safety features, there are four Emergency Core Barrel (ECB) ducts that are attached at the outer surface of the reactor barrel to guide the ECC water well from the Direct Vessel Injection (DVI) lines to the reactor core when necessary. By a previous study [2], the vibration characteristics of the APR⁺ barrel with four ECB ducts were mostly identified, and comparison was made with a conventional barrel. The conclusion was that the ECB ducts have a negligible effect on the vibrational behavior of the barrel even in water. For the previous study, FE analysis and a vibration (modal) test for a 1/5-scaled model were carried out in air and in quiescent water.

Since the 1/5-scaled model test was made, there has been a growing need to identify the vibration characteristics of a full scale duct. In this study, for this reason, modal tests and analyses for two different types of ducts have been carried out. The DVI duct is a thin shell of 5 mm thickness, so that harmonic responses to RCP blade passing frequencies should be checked. The dominant passing frequencies are known to be 20, 40, 60, 120 and 240 Hz.

It is well known that more mass could be effectively added to the reactor barrel as the gap becomes narrower; in a previous study [2], a 1/5-scaled model in the narrow gap showed that the effect could be 8 times higher than in a reasonably big gap. In this study, therefore, added mass effect by coolant in terms of the gap between the DVI duct and the reactor barrel is considered in an actual sized model.

2. Experiment

Two different types of full-scale models have been built to identify the vibrational characteristics. Figure 1 shows brief dimensions of the two models on one body, which have flat and arch shapes.

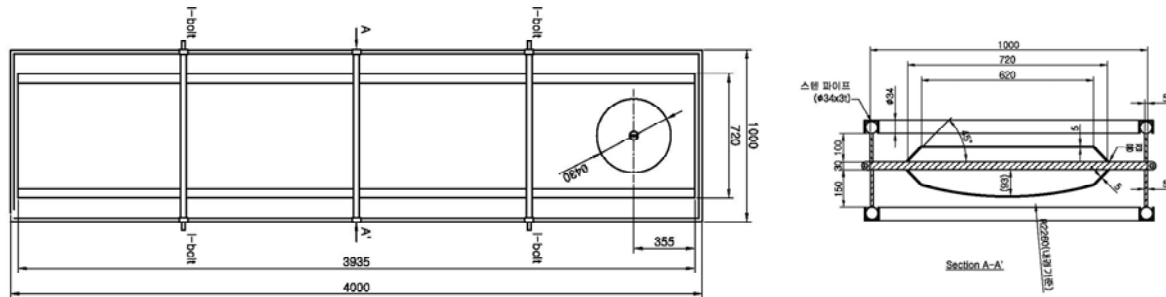


Figure 1 Two different ducts on a test bench

The two ducts built in one body are designed for the sake of test convenience. Vibration tests for the ducts not only in air but also under water can be easily attained by utilizing a test bench. For a typical modal test, six accelerometers are installed, and a robber-capped impact hammer is used as shown in Fig. 2.

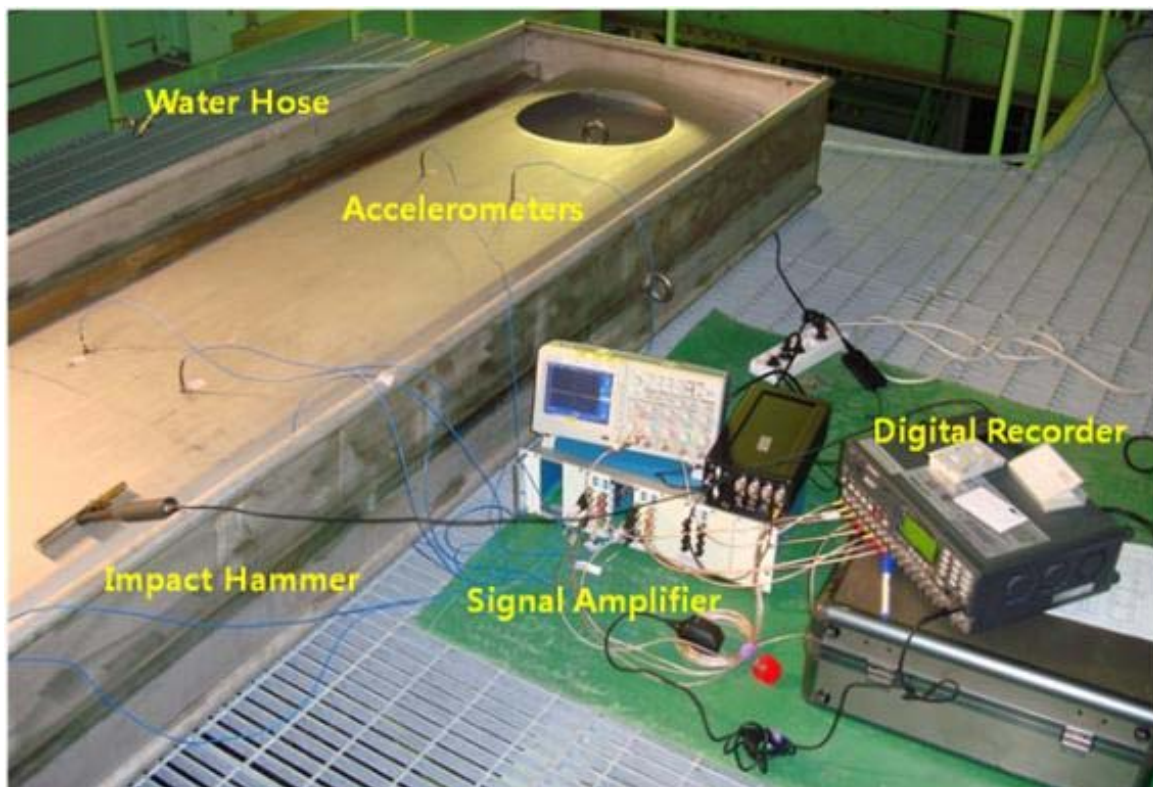


Figure 2 Photograph of the impact test layout

Impacting force from the hammer is transmitted to the voltage type accelerometers, which deliver voltage signals containing the vibration characteristics of the duct to a signal conditioner. The voltage signals coming from the conditioner are amplified and stored into a recorder at the site of the experiment. Then, the signals through HP VXI front end are analyzed by an IDEA-TDAS system.

Modal test results from four cases, two ducts in air and under water, respectively, are summarized in Table 1. Figures 3 and 4 show the frequency response functions (FRFs) obtained from the two ducts in air, and Figures 5 and 6 show the FRFs obtained from the same ducts under water.

Table 1 Natural frequency obtained from a modal test (Hz)

Condition	In air		In water	
	Flat duct	Arch duct	Flat duct	Arch duct
Mode 1	63.25	100.6	38.63	38.9
Mode 2	67.0	103.4	40.9	42.2
Mode 3	74.9	108.1	46.3	59.5
Mode 4	78.05	118.5	52.8	63.3
Mode 5	83.55	132.0	56.3	71.7
Mode 6	93.9	151.0	58.5	77.6
Mode 7	106.5	155.8	67	87.2
Mode 8	121.2	166.4	74.25	94.5

Many modes come together in a narrow frequency range; more than ten modes of the flat duct are found from 60 Hz to 150 Hz while those of the arch duct are from 100 Hz to 200 Hz. In air tests, peaks between 50 Hz and 60 Hz in Figure 3 and 80 Hz and 100 Hz in Figure 4 are considered not to be real duct modes, but to be complex modes coming from the whole test bench; two ducts are built in one body for test convenience as shown in Figures 1 and 2. In contrast to the experiments in air, signals from the experiments under water are not relatively good, as shown in Figures 5 and 6. Commonly, however, it is not difficult to identify several lower modes.

As expected, the first natural frequency of the arch duct is the higher of the two, which means the arch duct is the stiffer of the two no matter what the test environment is. An interesting observation is that the added mass effect by water seems to be so significant that the natural frequency plummets. The natural frequencies from a water environment are approximately 40% lower than those from an air environment. In water, the ducts become heavier due to the water effect; called an added mass effect. The added mass by the fluid has been known to be obtained approximately by the displaced volume multiplied by fluid density [3]. In that sense, the natural frequency differences seem to be significant. The ducts were made by a thin plate of 5 mm

thickness. Not only the added mass but also fluid damping exerts a significant influence. One can find the fluid damping effects by comparison with the FRFs in air, in Figure 3 and 4, and with the FRFs under water, in Figures 5 and 6; the peaks in the FRFs from water are blunter than those from air.

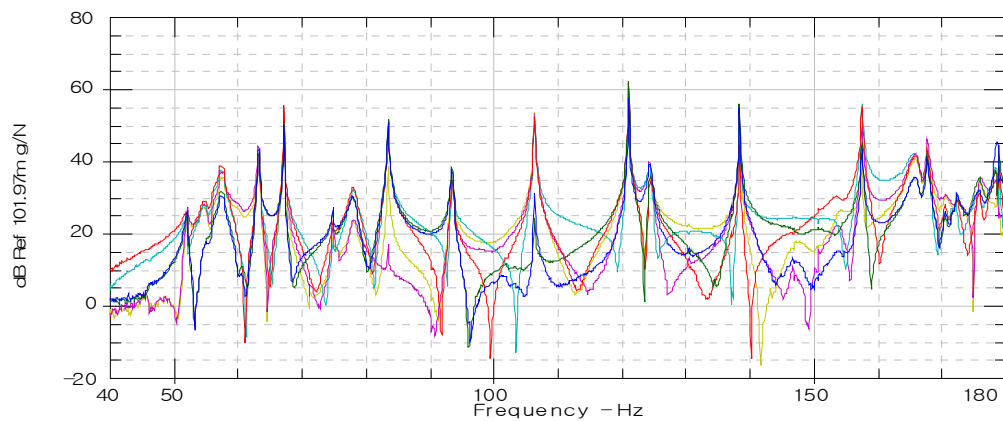


Figure 3 FRF obtained from a flat duct in air

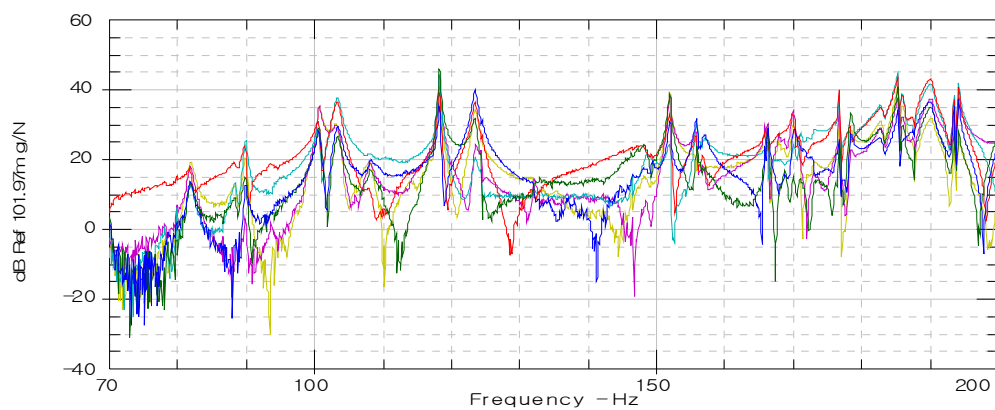


Figure 4 FRF obtained from an arch duct in air

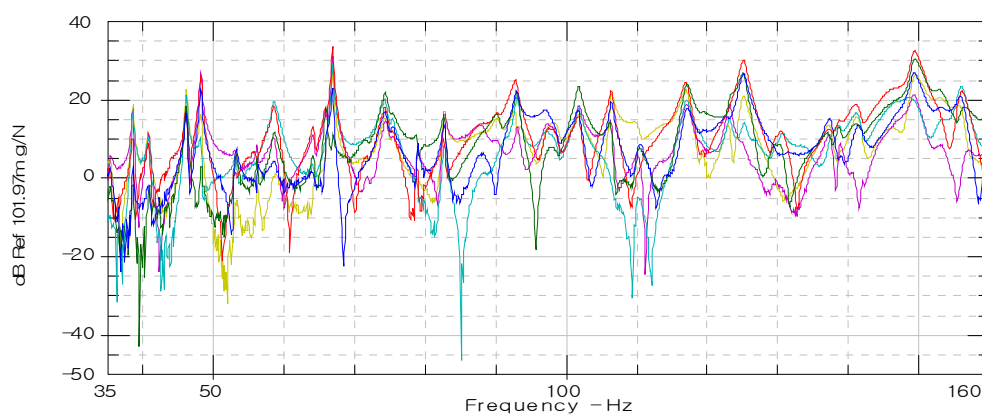


Figure 5 FRF obtained from a flat duct under water

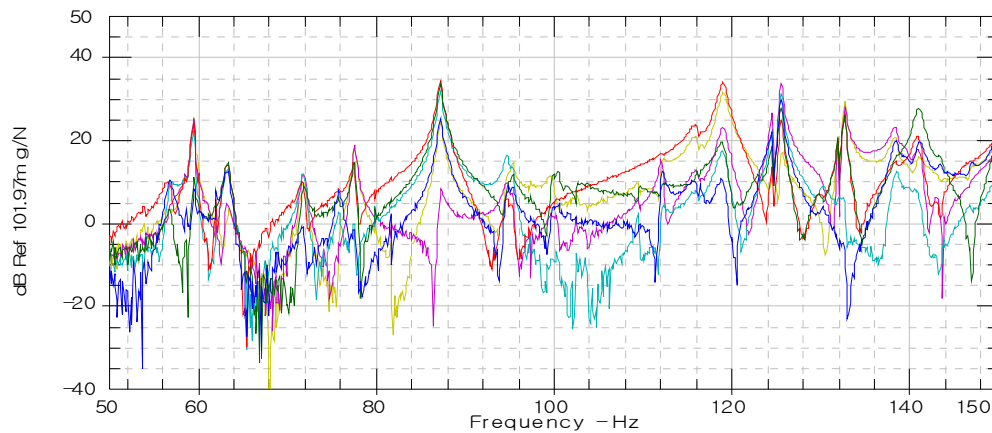


Figure 6 FRF obtained from an arch duct under water

Both arch duct and the flat ducts seem to have natural frequencies of somewhere around 120 Hz. Unfortunately, however, natural frequency higher than 200 Hz was not identified in this test.

3. Numerical Simulation

ANSYS commercial code [4] is utilized to simulate the vibration test for comparing the results with the modal test. A solid element (SOLID45) and a fluid element (FLUID30) are used for modeling the ducts and water, respectively. Finite Element (FE) models for the two ducts are shown in Figure 7.

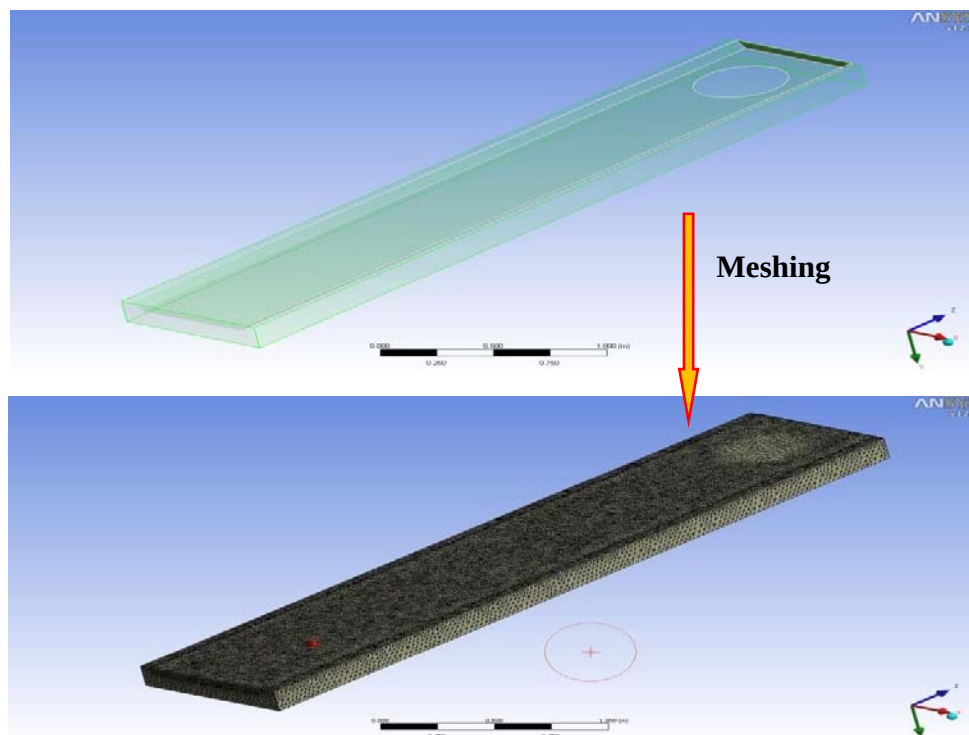


Figure 7 Finite Element model for flat duct in still water

The natural frequencies obtained through numerical calculation are summarized in Table 2. The first natural frequencies of the flat duct for two different environments are 64.7 Hz and 37.1 Hz, respectively, which are very close to the results of the modal test: 63.25 Hz and 38.63 Hz. The discrepancies of the second and third natural frequencies turned out to be insignificant. For the arch duct in air, a similar result is obtained for a few low modes. The first, second, and third natural frequencies of the simulation are 99.7 Hz, 101.8 Hz and 109.1 Hz, respectively while those from the test are 100.6 Hz, 103.4 Hz, and 108.1 Hz, respectively. For the water environment, however, the natural frequencies from the simulation are somewhat different from those of the modal test; the first and second natural frequencies of the test are 38.9 Hz and 42.2 Hz, which are relatively low as compared with the results of simulation: 50.2 Hz and 52.8 Hz. In water, the flat duct has the 25th and 26th natural frequencies of 117.9 Hz and 123.7 Hz while the arch duct has the 21st and 22nd natural frequencies of 117.1 Hz and 130.4 Hz.

Table 2 Natural frequencies obtained from FE simulation (Hz)

Condition	In air		In water	
	Flat duct	Arch duct	Flat duct	Arch duct
Mode 1	64.7	99.7	37.1	50.2
Mode 2	65.7	101.8	38.6	52.8
Mode 3	67.7	109.1	41.2	58.4
Mode 4	70.9	123.3	45.3	68.0
Mode 5	75.6	132.2	51.1	70.2
Mode 6	82.0	144.6	58.9	81.5
Mode 7	90.3	169.5	69.2	98.2
Mode 8	100.56	170.2	81.6	99.0

Simulation yields the mode shapes shown in Figure 8 for the flat duct in air, and in Figure 9 for the arch duct in air, respectively. It is hard to discriminate the modes between the flat and arch ducts although they are apparently different in shape. The mode shapes are the most likely those generally shown in a typical plate; the first mode shows a half sine wave along the length, and the second one reveals a full sine wave. Likewise, as the number of mode goes up, the number of wave increases by half a sine wave.

Although the natural frequencies under water are approximately half of those in air, each of the mode shapes looks alike. Similarly, even though the natural frequencies of the flat duct are 60% of those of the arch duct, each of the mode shapes is very similar.

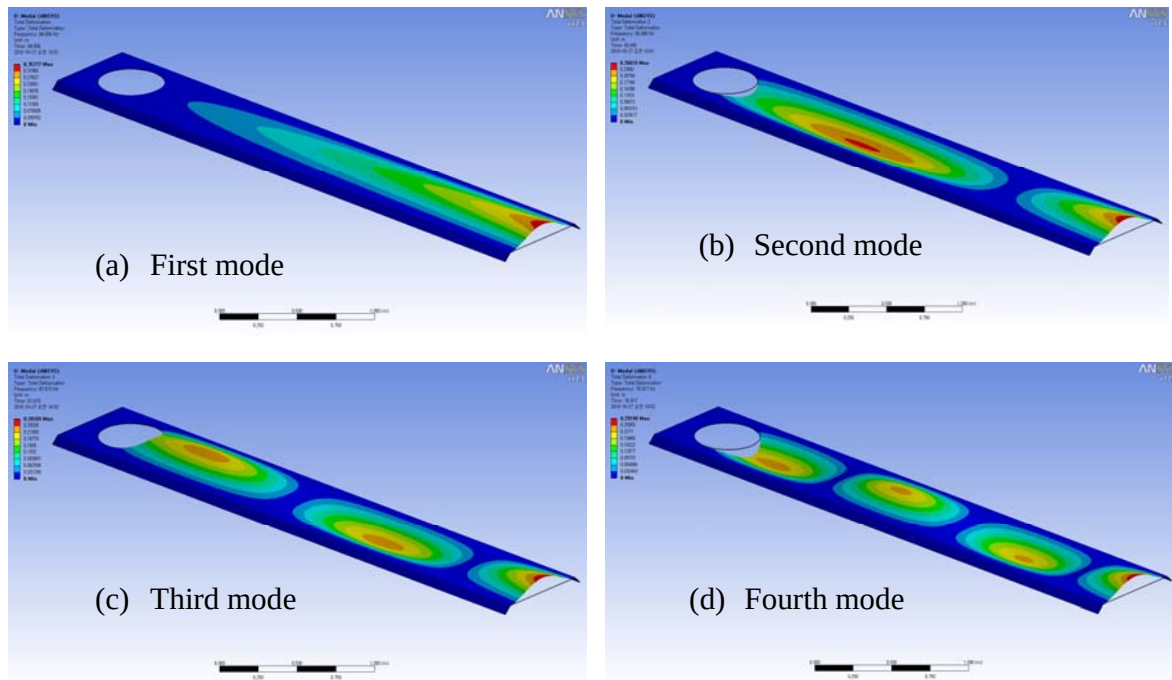


Figure 8 Four low modes of the flat duct in air obtained by ANSYS simulation

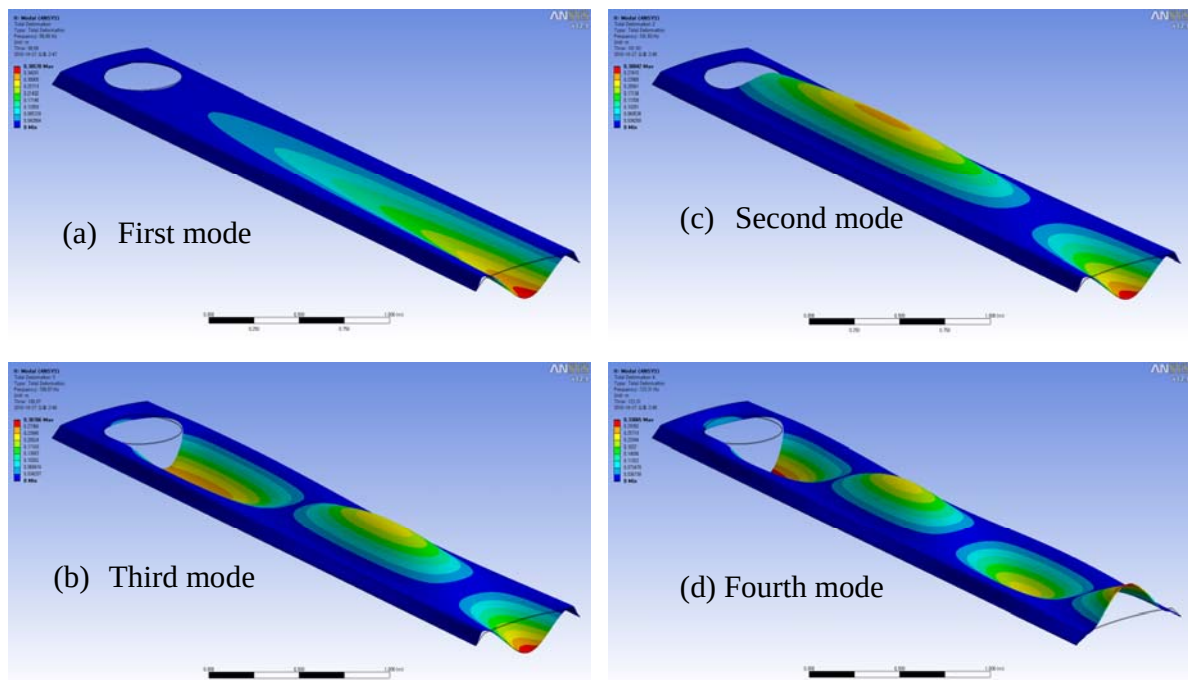


Figure 9 Four low modes of the arch duct in air obtained by ANSYS simulation

4. Results and discussion

Natural frequencies in a few low modes obtained by numerical simulation generally correspond with those of a modal test. In particular, the fundamental modes coincide within the narrow band except that of the arch duct under water; the numerical simulation gave 50.2 Hz while the modal test yielded 38.9 Hz.

The DVI duct will be attached to the outer surface of the reactor barrel, and the duct will exist inside of reactor vessel where reactor coolant flows into the reactor core. The important thing is, therefore, to check if the vibration modes of duct coincide with the harmonic components of the blade passing frequency of the Reactor Coolant Pump (RCP). The dominant passing frequencies of RCP are known to be 20, 40, 60, 120, and 240 Hz.

It is believed that approximately thirteen modes of the flat duct and ten modes of the arch duct exist between 30 Hz and 130 Hz, which, by the two present designs, hardly ward off the frequency range coming from the RCP. In addition, numerical simulations predict the 28th natural frequency of 242 Hz for the flat duct and the 24th natural frequency of 239.3 Hz for the arch duct, which are very close to the 240 Hz of the RCP blade passing frequency. Since modal test gave insufficient results for a frequency higher than 200 Hz, however, in the case of the arch duct under water, numerical simulation seems not to agree well with the test, and it is difficult to conclude at this time that the two ducts are incompatible with the current RCP. Therefore, precise tests and analyses are recommended.

For further discussion, it was calculated by ANSYS that the mass and volume of the flat duct are 110 kg and 0.01424 m³, and those of the arch duct are 112.5 kg and 0.01452 m³, respectively. If the duct is immersed in water of an infinite boundary, it is known that the added mass of the duct is approximately the displaced volume multiplied by the water density, which would be approximately 14.5 kg. Accordingly, the fluid-to-structural mass ratio may be 13 % at the most, so that as in Table 2, the natural frequency of the duct under water could not be 40 % lower than that in air only with this respect.

By virtue of the Chen [5] report, it is generally accepted that when structures are very tightly packed within a narrow gap under dense fluid, the added mass effect increases exponentially. Narrow-gap effects in dense fluid are not always necessarily small. The vibration characteristics of the duct would be influenced much more significantly by narrow confinement than by the infinite boundary [2]. When a narrow gap of 50 mm for the flat duct and 93 mm for the arch duct are considered, the added mass ratio becomes larger. This is the reason why the natural frequencies obtained from a water environment are apparently low.

5. References

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