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ACOUSTIC FREQUENCIES OF COOLANT IN PRIMARY CIRCUIT OF NPP TEMELIN AND POSSIBILITY OF RESONANCES WITH FUEL ASSEMBLY TVSA-T

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Abstract: *On the basis of electromechanical analogy is as criterion of possible interaction of acoustic waves in primary circuit of NPP Temelin derived so-called quality factor Q. The Q value determines a range of coolant acoustic frequencies in which there is a natural frequency of fuel assembly and in which resonance is realized. The range of fuel assembly frequency is named as pass band. Estimated values of Q and pass band are given. The developed methods algorithms of calculation and quantitative estimations of coolant pulsation frequencies, Q factor and pass band allow developing coolant parameter control actions necessary for prevention of resonances.*

Keywords: Electromechanical analogy, Quality factor *Q*, Coolant acoustic frequencies, Fuel assembly natural frequency, Resonances.

1. Introduction

In primary circuit of PWR reactors the three types of standing acoustic waves exist:

- in primary piping including steam generator and reactor,
- in primary piping, steam generator, reactor and pressurizer,
- only in the hot leg between output from reactor and input in pressurizer.

Calculation of eigen frequencies is possible to perform either using of electromechanical analogy (Pecinka, 2004) or solution of coolant momentum equation and Euler equation (Pecinka, 2006) in all possible operation states. From the experimental point of view the coolant pressure pulsation are measured using pressure sensors installed on the primary piping (cold leg and hot leg).

2. Electromechanical Analogy

Acoustic scheme of primary coolant in reactor core is illustrated in Fig. 1 where denote: *R* acoustic resistance, *m* acoustic mass, *C* acoustic compliance, V_0 volumetric coolant flow in reactor core, ΔP pressure drop in reactor core.

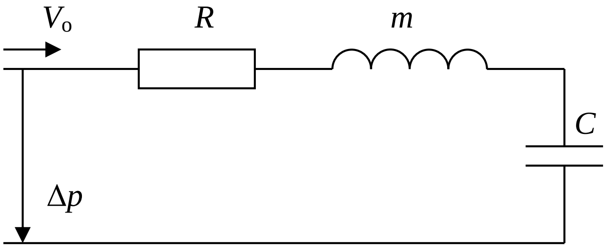

Fig. 1: Acoustic scheme of coolant in reactor core.

Analogy between acoustic and electronic parameters is illustrated in next Tab. 1.

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Tab. 1: Electromechanical analogy.

Acoustical hydraulic parameters			**Electrical parameters**		
Parameters	Symbol	Dimension	Parameter	Symbol	Dimension
Pressure drop	ΔP	N m^{-2}	Voltage	U	Volt
Volumetric flows	V_0	m^3 s^{-1}	Current	I	Ampere
Acoustic compliance	C	m^4 s^2 kg^{-1}	Capacitance	C	Farad
Acoustic mass	m	kg m^{-4}	Inductance	L	Henry
Acoustic resistance	R	kg s^{-1} m^4	Active resistance	R	Ohm
Differential characteristic resistance	R_d	kg s^{-1} m^4	Differential characteristic resistance	Z_c	Ohm

3. Resonance Operational State of Pressure Pulsations in Primary Circuit Induced by Sinusoidal Changes of Volumetric Flow

Two types of resonant operation states exist (Proskuriakov, 2013):

- main, i.e. resonance states of pressure pulsations,
- parallel, i.e. resonance states of volumetric flow.

Resonance operation state exists in such case, when acoustic mass and acoustic compliance are in series, see Fig. 1. In such case the following equations are valid (Gependin, 1974).

$$Z_{inlet} = R + i\left(m\omega - \frac{1}{C\omega}\right), \tag{1}$$

$$P_{inlet} = V_0 \cdot Z_{inlet}, \tag{2}$$

$$Z_{inlet} = \sqrt{R^2 + \left(m\omega - \frac{1}{C\omega}\right)^2} = \sqrt{R^2 + X^2}, \tag{3}$$

where $X = m\omega - 1/(C\omega)$.

The resonance condition requires zero of reactive component of input resistance, i.e. $X_{inpu} = 0$ and $Z_{input} = R_{input}$. After some rearrangement equation (2) takes the final form:

$$V_0 = \frac{\Delta P_{input}}{\sqrt{R^2 + \left(m\omega - \dfrac{1}{C\omega}\right)^2}} = \frac{\Delta P_{input}}{\sqrt{R^2 + X^2}}. \tag{4}$$

4. Derivation of the quality factor *Q*

Quality factor Q is defined as ratio of the pressure on the element m or C (see Fig. 1), i.e. P_{m0} or P_{e0} to the input pressure P_{inlet0}. In the case when characteristic resistance Z_c (see Table 1) represent resistance of the acoustic compliance or acoustic mass in the resonant state, i.e. if:

$$Z_C = m\omega_0 = \frac{1}{\omega_0 C} = \sqrt{\frac{m}{C}}, \tag{5}$$

where $\omega_0 = (mC)^{-1/2}$ then using equations (2), (4) and (5) after some rearrangement we obtain:

$$Q = \frac{P_{m0}}{P_{inlet0}} = \frac{P_{C0}}{P_{inlet0}} = \frac{V_{0,0} Z_C}{V_{0,0} R} \Rightarrow P_{m0} = Q \cdot P_{inlet0}; P_{C0} = Q \cdot P_{inlet0} = \frac{\sqrt{\dfrac{m}{C}}}{R} = \frac{Z_C}{R}. \tag{6}$$

Volumetric flow ratio to volumetric flow in the resonant operation state (V_0 / V_{inlet}) depend on the angular frequency ω. After some rearrangement the following equation takes the form:

$$V_1 = \frac{\Delta P_{inlet}}{\sqrt{R^2 + \left(m\omega - \frac{1}{C\omega}\right)^2}} = \frac{\Delta P_{inlet}}{R\sqrt{1 + \frac{1}{R^2}\left(m\omega - \frac{1}{C\omega}\right)^2}} = \frac{V_{0,0}}{\sqrt{1 + \frac{R_C^2}{R_0^2}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2}}$$

$$V_1 = \frac{V_{0,0}}{\sqrt{1 + Q^2\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2}}. \tag{7}$$

As the result we obtain:

$$\frac{V_0}{V_{input}} = \frac{1}{\sqrt{1 + Q^2\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2}} = \frac{1}{\sqrt{1 + \frac{X_{input}^2}{R^2}}}\ , \tag{8}$$

where $X_{input} = \omega m - 1//(C\omega)$.

Resonance curves of the coolant volumetric flow are illustrated on the Fig. 2.

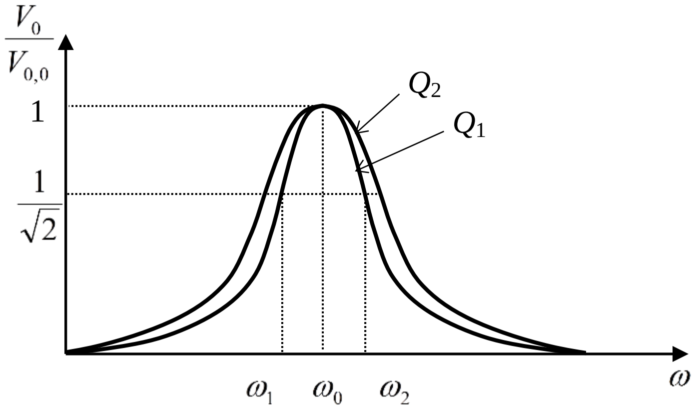

Fig. 2: Resonant curves of the coolant volumetric flow.

5. Definition of the Frequency Pass Band

According Fig. 2, the frequencies ω_1 and ω_2 defined the frequency pass band based on the ratio $V_0/V_{0,0} = 0.707$. As the result can be written:

$$\frac{V_0}{V_{0,0}} = \frac{1}{\sqrt{1 + \frac{1}{R^2}X_{vstup}^2}} = \frac{1}{\sqrt{2}}. \tag{9}$$

Finally $1 + X_{input}^2/R^2 = 2 \Rightarrow X^2/R^2 = 1 \Rightarrow X = R$.

Correlation between bounding frequencies ω_1, ω_2, resonant frequency ω_0 and Q factor may be derived as follows:

$$\frac{V_0}{V_{0,0}} = \frac{1}{\sqrt{1 + Q^2\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2}} = \frac{1}{\sqrt{2}}, \quad \frac{\omega_{1,2}}{\omega_0} - \frac{\omega_0}{\omega_{1,2}} = \pm\frac{1}{Q}, \quad \text{where } \omega_1 < \omega_0 < \omega_2.$$

As the result we obtain:

$$\frac{\omega_2}{\omega_0}-\frac{\omega_0}{\omega_2}=+\frac{1}{Q},$$
$$\frac{\omega_1}{\omega_0}-\frac{\omega_0}{\omega_1}=-\frac{1}{Q}. \tag{10}$$

After some rearrangement as the results we obtain:

$$\omega_0=\sqrt{\omega_1\omega_2}, \tag{11}$$

$$Q=\frac{\omega_0}{\omega_1-\omega_2}. \tag{12}$$

Assessment of the reactor V1000 ETE core Q factor using equation (4) and (6), the Q factor is defined as:

$$Q=\frac{\sqrt{\frac{m}{C}}}{\frac{\Delta P}{V_0}}. \tag{13}$$

The following expressions may be used (Pecinka, 2004):

$$m=\frac{\rho\cdot l}{A}; \qquad C=\frac{A\cdot l}{\rho\cdot c^2}.$$

As the result we obtain:

$$Q=\frac{\rho\cdot c\cdot V_0}{\Delta P\cdot A}. \tag{14}$$

In the next will be performed application to core of reactor V1000 ETE in level A Service limit. Input data of coolant and core are follows: ρ = 726 kg·m^{-3}; c = 940 m·s^{-1}; A = 7.84 m^2; ΔP = 0.5 MPa; V_0 = 23.6 m^3·s^{-1}.

As the results we obtain quality factor Q = 4.1. The lowest acoustic frequency of the coolant in the loop without pressurizer is f_0 = 6.95 Hz (Pecinka, 2006). Using equation (12) the related frequency pass band is $f_2 - f_1$ = 6.95 / 4.1 = 1.7 Hz. The first bending frequency of the fresh fuel assembly is 4.94 Hz. According Fig. 2 left and right half of the frequency pass band is 1.695 / 2 = 0.85 Hz. It means that the lower boundary of the frequency band is 4.97 − 0.847 = 4.123 Hz and upper boundary is 4.97 + 0.847 = 5.82 Hz. We can conclude that coolant frequency 6.95 Hz is out of frequency pass band.

Similar situation exists for the loop with pressurizer and the fuel assembly at the end of fuel cycle. In this case the lowest frequency is 1.066 Hz (Pecinka, 2004) and the first bending frequency of the fuel assembly decrease to 2.63 Hz. Using the same methodology as in previous case, the upper frequency of the frequency pass band is 1.19 Hz. It means that the fuel assembly 2.63 Hz is out of the frequency pass band.

6. Conclusion

Using electromechanical analogy the so called quality factor Q has been derived as the criterion of the acoustic waves interaction with reactor internals. This methodology represents specific branch in fluid-structure interactions. Practical applications exist in PWR reactors of Russian type.

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