Design of turbine testbed based on similarity and simulation for dynamic characteristics

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1. Introduction

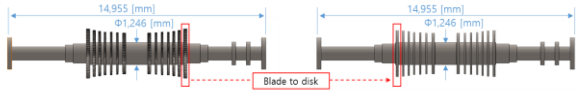
The turbine generator of an operating nuclear power plant is a key facility that converts the thermal energy produced in the nuclear reactor into electrical energy. To ensure the safety and stable operation of the nuclear power plant, highly reliable monitoring and diagnosis systems for turbines are required. When faults occur, additional analysis by signal analysis experts must be performed for precise diagnosis of faults in turbine generator and decision-making. There is a problem that the decision-making time is delayed during the expert's analysis time. In addition, analysis results may vary depending on the expert.

If artificial intelligence technology, which is developing at a remarkable speed, is applied to a turbine vibration monitoring system, it is expected that a vibration monitoring system capable of rapid diagnosis and less dependent on experts can be developed. In order to develop a databased artificial intelligence vibration monitoring system, measured data from turbines operating in normal and faulty conditions is essential. However, it is impossible to acquire data from turbines of operating nuclear power plants, which are national infrastructure facilities, because they can cause national safety problems and large economic losses. Therefore, it is a realistic alternative to secure data on various faults by utilizing a turbine testbed with dynamic characteristics similar to turbine operating in nuclear power plant. In this paper, a method for designing a turbine testbed that simulates the dynamic characteristics of a turbine of an operating nuclear power plant based on the law of similarity[1] is described.

2. Method and Results

2.1 Real-scale model analysis

Considering the size of the turbine and bearing loads, a real-scale turbine model was developed and its dynamic characteristics were verified through ANSYS Workbench simulation. With a focus on the global dynamic characteristics and 1st critical speed of the real-scale turbine, the blades were modified to discs for simplification, and the model was adjusted based on the static load of the bearings[2]. Simulation results confirmed that the range of the 1st critical speed of the developed model matched that of the operating nuclear power plant turbine, thereby validating the model's acceptability.



(a)Real-scale model (b) Simplified model

Fig. 1. HP turbine Real-scale & simplified model

Table I: Bearing size and static load

Bearing No.		Bearing size[mm]		Bearing static load		
		Diameter	Length	Unit [kN]		Unit [kg]
HP	1	508	457.2	235	565	57,653
	2	762	457.2	330		
LPA	3	762	558.8	756	1,519	155,000
	4	762	558.8	763		
LPB	5	762	588.8	756	1,519	155,000
	6	762	558.8	763		
LPC	7	762	558.8	757	1,514	154,490
	8	762	558.8	757		

2.2 Similarity method : Pi theorem

According to The Buckingham pi theorem, which is based on dimensional analysis, if the physical model can be expressed as Equation(1), the function of the dimensionless variable(pi term) can be expressed as Equation(2). π is a variable composed of the multiplication and division operations of x, and can be viewed as a kind of normalized variable. By applying this theory, it is possible to define a model based on changes in various physical quantities such as force, displacement, and time. The larger the scale of the system, the more difficult it is to carry out realistically due to the risk of experimentation and economic limitations such as time, space, and cost. The pi theorem can enable the definition of a homologous model for the main physical quantities of the target model, and can be used as a powerful tool to indirectly analyze the characteristics of the target model.

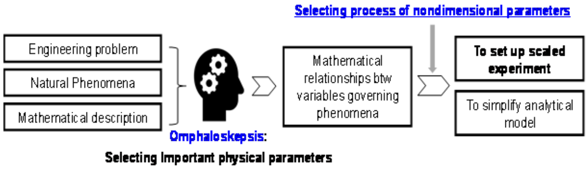


Fig. 2. Dimensional analysis concept

$$F(x_1, x_2, \cdots, x_N) = 0 \tag{1}$$

$$f(\pi_1, \pi_2, \cdots, \pi_{N-r}) = 0 \tag{2}$$

2.3 Design of turbine testbed based on similarity

To derive the specifications of the turbine testbed, dynamic characteristics parameter were defined based on the developed real-scale model and rotor dynamics, as shown in Table 2. The defined dynamic parameters were utilized in applying the Similarity Method (Pi Theorem) to derive dimensionless variables. Using the derived dimensionless variables, scale factors was defined, and the specifications of the testbed at a 1/10 scale compared to the real-scale turbine were derived. Upon reviewing the testbed model based on the derived specifications, issues were encountered with manufacturing and machining feasibility, and the requirements for fault[mass imbalance] testing were not met. Taking these issues into consideration, the specifications for the 1/10 scale turbine testbed were revised and derived.

Table II: Dynamic characteristics parameter for turbine

Parameter	Symbol	Dimension
distance between supports	L	L
distance between disks	ι	L
density	ρ	ML^{-3}
modulus of elasticity	E	$L^{-1}MT^{-2}$
second moment of cross-sectional area	J	L^4
time	T	T
diameter	D	L
mass	m	M
moment of inertia	I	ML^2
support stiffness	K	MT^{-2}
rotation frequency	f	T^{-1}

2.4 Optimization of turbine testbed specifications

The specifications of the turbine testbed, taking into account ease of manufacturing/machining and fault testing, were optimized to simulate the dynamic characteristics of the real-scale turbine. The specifications of the turbine were defined as variables in the calculation formula for static deflection, and Dunkerley's Method, capable of calculating critical speeds, was defined as the objective function. The defined objective function was applied to genetic algorithms, advantageous for multivariable global optimization, to ultimately derive the specifications of the 1/10 scale turbine testbed. Based on the derived testbed specifications, a model was developed, and modal analysis was conducted. The results confirmed that the range of critical speeds for both high-pressure and low-pressure turbines was similar to that of the real-scale turbine, validating the acceptability of the derived specifications.

$$N_c[RPM] = \frac{60}{2\pi}\sqrt{\frac{k}{m}} = \frac{60}{2\pi}\sqrt{\frac{g}{\delta}} \tag{3}$$

$$\frac{1}{{N_c}^2} = \frac{1}{{N_1}^2} + \frac{1}{{N_2}^2} + \frac{1}{{N_3}^2} + \frac{1}{{N_4}^2} + \dots + \frac{1}{{N_n}^2} \tag{4}$$

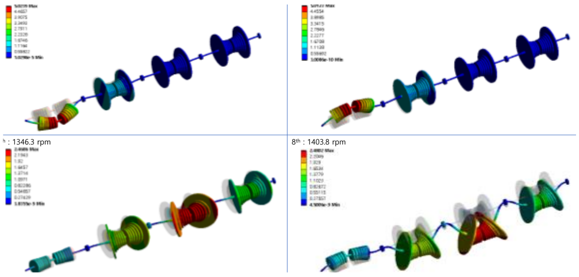


Fig. 3. Mode shape of the 1/10 scale HP&LP turbine testbed

3. Conclusions

We proposed a design approach for a turbine testbed that exhibits similar dynamic characteristics to an operational nuclear power plant turbine. Analyzing the specifications of the real-scale turbine, we developed a simulation model based on it and ensured the validity of the model through 1st critical speed analysis. Applying the Pi theorem to the real-scale model, we defined a scale factor and derived the specifications of a 1/10 scale turbine testbed. The turbine testbed specifications were optimized through genetic algorithms to ensure ease of manufacturing/machining and fault testing while securing similar dynamic characteristics to the real-scale turbine. Utilizing the defined testbed specifications, we developed a model and confirmed its similarity to the real-scale turbine through simulation results, validating its acceptability. The designed testbed will be utilized to generate big data on representative faults in rotating equipment, and the development of diagnostic algorithms and models based on artificial intelligence for vibration monitoring systems is planned.

REFERENCES

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