Vibration Analysis of an Exhaust Fan in the Exhaust Gas Duct of a Power Plant Unit

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Abstract. The subject of this paper is a vibration analysis of an exhaust fan in a power plant unit. Excessive vibrations were observed during the exploitation of the fan, preventing it from proper operation. In order to identify the causes of excessive vibrations, FEM calculations of the vibrations of flue gas ducts, shaft assembly, and measurements on the actual object were conducted. Based on the numerical vibration analysis, the occurrence of resonant vibrations of the flue gas duct and the shaft assembly was demonstrated. Calculations carried out with the use of a laser vibrometer confirmed the occurrence of vibrations with frequencies similar to the frequency forced by the movement of the exhaust fan's rotor. The results of the analysis contributed to the modification of the shaft assembly and to the introduction of additional stiffening to the walls of pressure and suction ducts.

Keywords: Axial fans · Fan vibrations · FEM · Laser vibrometer

1 Introduction

Axial fans are utilized in many industries [1, 8, 9], especially in energetics, steelworks, mining, chemical industry, etc. Due to the way machines work, they often fall into excessive vibration, which is exceedingly dangerous to large-size fans of great power [2, 3, 5, 7]. Vibrations of both large-size axial and centrifugal fans are the subject of numerous studies and simulations [10, 12–14]. During the exploitation of flue gas ducts, excessive vibrations of an exhaust fan of one of the power plant units were observed. An axial action exhaust fan with the efficiency of 300 m^3/s, total pressure rise of 3580 Pa, power on the shaft of 1500 kW, and rotational speed of 745 rpm was applied to the duct. Each of power plant units utilizes two exhaust systems no. 1 and no. 2 with exhaust fans operating in a parallel configuration. Figure 1 presents the ducts and the exhaust fan no. 1. What is characteristic to the issue is that the vibrations occur only if the order in which the fans are turned on is changed. If the fans are started in the proper order (first, the no. 1 fan is started, then the no. 2), the vibrations do not occur. However, if the order is reversed, vibrations occur at the fan no. 1.

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Fig. 1. Flue gas duct with an axial exhaust fan

In order to identify the cause of vibrations, a FEM model of the suction duct and pressure duct was created, and the measurements that should be carried out on the object had been planned.

2 FEM Numerical Analysis of Flue Gas Ducts

A shell model with a stiffening in the form of beam finite elements was developed in order to numerically calculate the vibrations of flue gas ducts [6, 11]. The geometrical shell model is visible in Fig. 2. The frequency of excessive vibrations is associated with

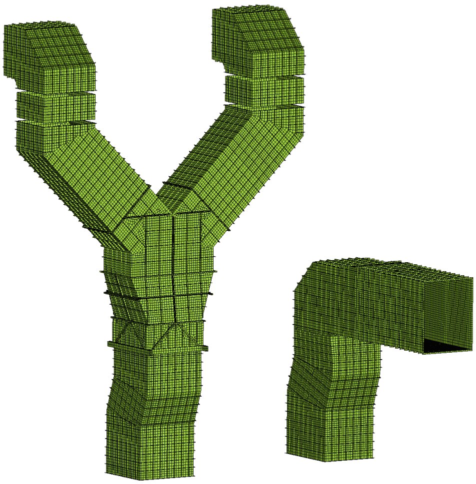

Fig. 2. The discrete model of the suction and pressure ducts of the flue gas duct

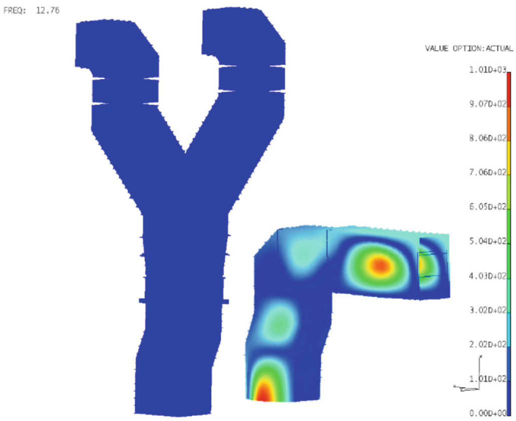

Fig. 3. The vibration mode closest to the resonant frequency f_9 = 12.76 Hz

Table 1. Natural frequencies of the flue gas duct

Mode	Frequency [Hz]
7	11.21
8	12.05
9	**12.76**
10	12.92
11	13.36

the rotation of the fan, which amounts to 12.42 Hz. Natural vibrations were calculated in a range close to the vibrations forced by the rotation of the fan. The obtained natural frequencies are presented in Table 1.

The FEM analysis of the suction and pressure ducts' natural vibrations shows that the most prone to vibrations of frequencies forced by the rotational movement of the fan are the walls of the pressure duct as shown in Fig. 3.

3 Analysis of the Vibrations of the Fan's Shaft Assembly

In order to conduct a vibration analysis of the shat assembly and the fan's rotor, a model presented in Fig. 4 was created. It is a beam model with mass elements simulating the mass, the moment of inertia, and the cross-section of the main shaft, rotor, and the shaft between two clutches.

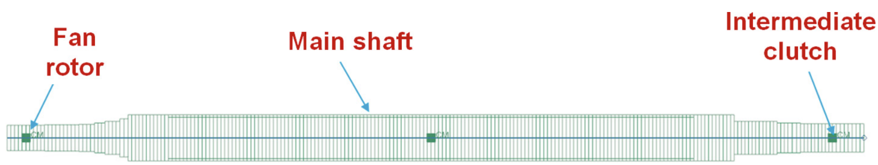

Fig. 4. FEM model of the shaft assembly with the rotor

The model uses the following data for mass and inertia moments:

- mass of the rotor wheel	m_w = 2070 kg
- flywheel effect	GD^2 = 7600 kGm^2
- rotor wheel's moment of inertia	J = 7600/4 = 1900 kgm^2
- mass of the shaft between two clutches	m_{ws} = 1291 kg
- mass of the clutch (half of the clutch)	m_s = 440 kg

As a result of the vibration analysis of the shaft assembly with the rotor, the natural frequencies and their vibration modes were obtained. Figure 5 presents the first natural vibration mode, while Table 2 the values of consequent natural frequencies.

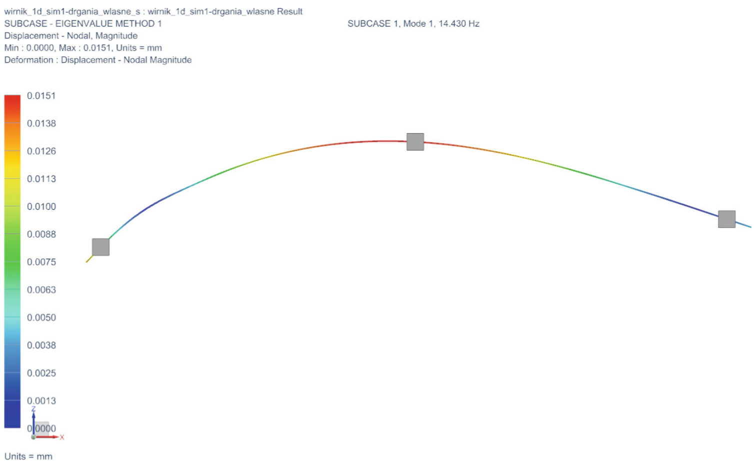

Fig. 5. The first natural vibration mode, f_1 = 14,43 Hz

Table 2. The natural frequencies of the shaft assembly with the rotor

Mode	Frequency [Hz]	Form of vibration
1	14.43	Bending
3	40.14	Bending
5	84.26	Bending
7	107.21	Bending
9	110.52	Longitudinal
10	118.16	Torsional

Based on the vibration analysis of the shaft assembly with the rotor, it can be seen that the bending vibrations dominate over the other. The base natural frequency amounts to f_1 = 14.43 Hz, which is too close for systems of fans to the resonant frequency f_{rez} = 12.42 Hz. According to the recommendations [8], the natural frequency of a system of fans should be outside of the range (0.85 ÷ 1.25) f_{rez}, i.e. 10.56 Hz < f_1 < 15.53 Hz. In case of the analyzed system, the vibration frequency amounts to f_1 = 1.16 f_{rez}, which is inside the range prone to the inducement of resonant vibration.

In order to change the natural frequency of a system of fans, either its mass or stiffness should be altered. In the analyzed case, the natural frequency should be increased by stiffening the shaft. It can be achieved by several means:

– increasing the diameter of the shaft,
– thickening the walls,
– applying stiffening ribs.

A vibration analysis of the shaft assembly with the rotor was conducted for several example diameters and wall thicknesses of the shaft made of pipes of standard dimensions. The results for the current and suggested dimensions are presented in Table 3. All of the analyzed pipes had the same inner diameter due to the connection with the rotor's shaft or similar section areas. The recommended values, for which the frequency of the system is higher than 16 Hz, are bolded.

Table 3. The suggested dimensions of the shaft and the natural frequencies of the shaft assembly with the rotor

	Unit	Ø308×16	Ø355.6×13,6	Ø406×12,5	Ø355.6×16	Ø355.6×20	Ø330×20	Ø318×20	Ø330×25	Ø330×28
t	mm	16	13.6	**12.5**	16	**20**	20	20	**25**	**28**
D	mm	308	355.6	**406**	355.6	**355.6**	330	318	**330**	**330**
d	mm	276	327.8	**381**	323.6	**315,6**	290	278	**280**	**274**
m	kg/m	115.22	114.50	**121.30**	134.00	**165.53**	152.90	146.98	**188.04**	**208.54**
f_1	Hz	*14.43*	15.4	**16.1**	15.78	**16.22**	15.6	15.26	**16.01**	**16.2**

4 Measuring the Vibration of the Flue Gas Duct with the Use of a Laser Vibrometer

In order to verify the values and vibration modes acquired numerically, a series of measurements was carried out on the actual object. Inspection holes had been created in the pressure and suction ducts through the layer of isolation to allow the vibrometer to carry out the measurements, which were then conducted both during the standard operation of the power boiler and during the occurrence of resonant vibrations [4, 15]. An example measurement is presented in Fig. 6, which shows the vibration mode and the amplitude-frequency graph.

The measurements obtained with the use of a laser vibrometer show that the dominant vibration frequency of the fan's ducts is the rotational frequency f ~ 12.5 Hz. What is more, the vibration mode acquired through measurements is identical to the one obtained with the use of numerical methods.

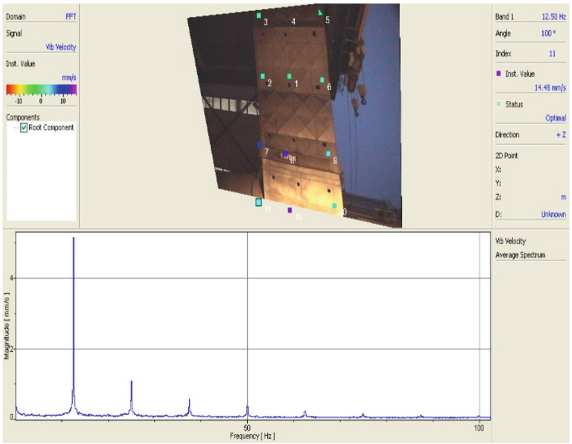

Fig. 6. The vibration mode and the amplitude-frequency graph

5 Vibration Measurements of the Shaft Assembly with the Fan's Rotor

In order to determine the natural frequency of the shaft assembly (shaft rotor), an experimental modal analysis was carried out. The vibrations were induced with an impact hammer (Fig. 7a) and the response of the system was measured with acceleration sensors. Four measuring points located on the system's shaft were determined:

- horizontal direction, at 1/4 of the distance between supports, closer to the rotor,
- vertical direction (with the sensor on the bottom), at 1/4 of the distance between supports, closer to the rotor,
- horizontal direction, at 1/2 of the distance between supports,
- vertical direction (with the sensor on the bottom), at 1/2 of the distance between supports.

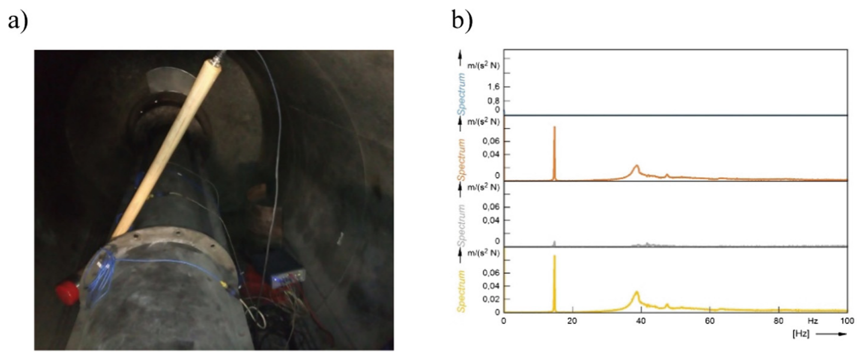

Fig. 7. Measurement system: a) impact hammer, sensors, and data recorder, b) the spectrum of the system's response to vibrations forced in the vertical direction

As a result of the analyses, it was determined that the main bending frequency of the shaft assembly amounts to about 14.7 Hz, which means it is inside the range prone to resonant vibration.

6 Summary and Conclusions

Dangerous vibrations of an exhaust fan operating in the flue gas duct of a power boiler were the subject of the research. In order to identify the causes of vibrations, computer simulations of the vibrations of pressure and suction ducts and the vibrations of the shaft assembly with the rotor were conducted. What is more, experimental tests were carried out on the actual object. The vibrations of flue gas exhausts were measured with the use a laser vibrometer, while the vibrations of the shaft assembly were determined by inducing vibrations with the use of an impact hammer. Based on the computer simulations and experimental test, the following conclusions can be formulated:

- resonant vibrations $f = 12.42$ Hz occur in the fan's assembly and flue gas duct,
- numerical FEM analysis of the flue gas ducts demonstrated vibrations $f = 12.76$ Hz, close to the frequencies induced with by the movement of the fan's rotor, mainly in the pressure duct,
- vibration simulation for the shaft assembly with the fan's rotor demonstrated bending vibrations $f = 14.43$ Hz in the range not recommended for this type of devices,
- vibration measurements conducted with the use of a laser vibrometer demonstrated vibrations of high amplitude in the pressure duct with a frequency f = 12.5 Hz,
- vibration measurements of the shaft assembly with the fan's rotor carried out while inducing vibration with an impact hammer demonstrated bending vibrations with a frequency f = 14.7 Hz,
- vibration modes and vibration frequencies of flue gas ducts and the shaft assembly obtained through computer simulations are compliant with the values acquired with the use of experimental methods,
- in order to limit the occurrence of resonant vibrations, it was suggested to stiffen the walls of pressure ducts through applying additional ribs and sprags; to limit bending vibrations of the shaft assembly with the rotor, the diameter of the shaft's pipe should be changed.

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