INSTITUTE OF FLUID-FLOW MACHINERY
POLISH ACADEMY OF SCIENCES



# TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

## 113

Selected papers from the International Conference
on *Turbines of Large Output*
devoted to 100th Anniversary of
Prof. Robert Szewalski Birthday,
Gdańsk, September 22-24, 2003

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GDAŃSK 2003

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**Aims and Scope**

*Transactions of the Institute of Fluid-Flow Machinery* have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 113, 2003, 3-4

## Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{th}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery*. At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

*Prof. Jarosław Mikielewicz*
Editor-in-Chief

*Dr Edward Śliwicki*
Managing Editor

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 113, 2003, 169-178

ANDRZEJ GARDZILEWICZ*[a], S. MARCINKOWSKI[a], A. ADAMKOWSKI[a], W. JANICKI[a] and H. SOBERA[b]

# Measuring of unsteady pressures at the steam turbine exit

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## Abstract

The paper presents results of measurements of steady and unsteady pressure at the K560 turbine stage exit under significantly variable load conditions. Simultaneously with the pressure measurement, rotor vibrations were recorded. This experimental task was done to verify calculations of turbine flow and rotor vibrations provoked by aerodynamic forces.

**Keywords:** Steam turbine; Measuring of unsteady pressures

## 1 Introduction

The large electric power networks require ever more frequently operation turbine sets under variable load conditions. This requirement involves also large power units previously operated as a rule, at nominal parameters. These general trends determine new directions of investigations, which more and more often include evaluation of unsteady effects in the aspect of the interaction between aerodynamic and electromagnetic forces in rotating turbine unit components of generating set [1].

This article presents results of some investigation concerning the steam flow downstream of the last stage exit. Along with a detailed evaluation of thermodynamic parameters under varying operating conditions, the investigation aimed at defining a relationship between examined spectrum of pressure pulsations in the steam flow and rotor vibrations. These analyses are needed for verification of modern design and diagnostics methods [2].

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## 2 Measuring instrumentation and turbine operating conditions

Flow parameters downstream of the last stage exit were measured in a 500 MW turbine of unit No. 9 in Kozienice Electric Power Plant [3]. Figure 1 shows a schematic view of the low pressure part of this turbine with marked locations of measuring probes. A standard plate probe (Fig. 2) was used for measuring aver-

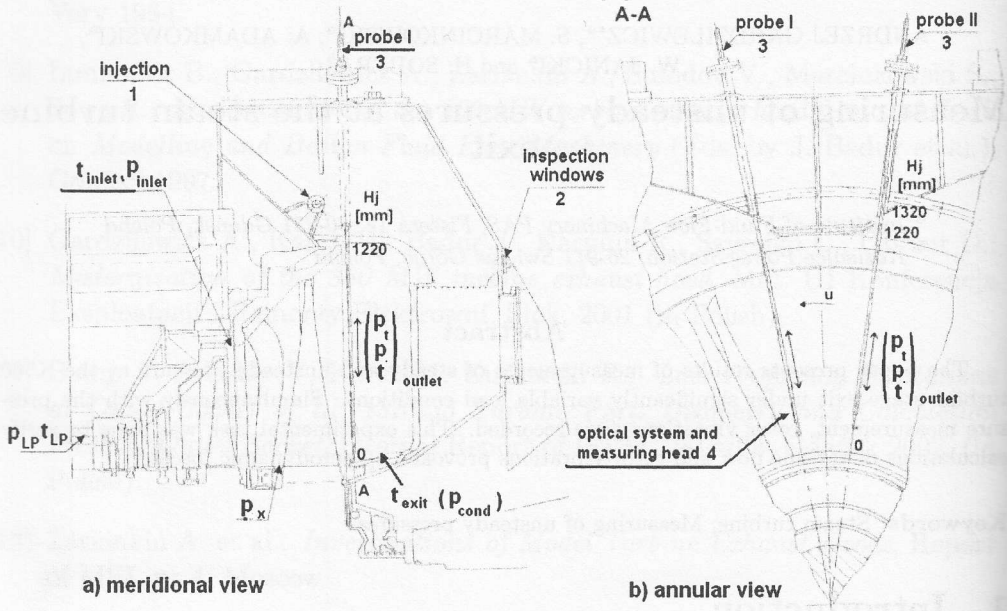


Figure 1. Low pressure part of the 500 MW turbine [3].

aged values of static and total pressures, temperatures, and steam flow angles in the last-stage passage. The applied method of measurement has been described in detail in [4]. Probe calibration, carried out in an aerodynamic tunnel, secured high accuracy of the temperature, pressure and angle measurements: $\Delta t < 0.5$ deg, $\Delta p < 1$ mm Hg, $\Delta\alpha < \pm 1 \div 10°$. To protect pressure measuring ducts from being filled with water, they were frequently purged with air. The investigations of flow unsteadiness downstream of the stage concerned total pressure pulsations. For this purpose the visualization system of a pneumatic probe was replaced by a miniature piezo-electric sensor, Fig. 3. The measuring range of the sensor was suited to operation behind the last stage. The accuracy class of the measurement track was 0.4 and the transmission band – up to 30 kHz. A computer-aided system of data acquisition, used in the measurement, is shown in Fig. 4. Along

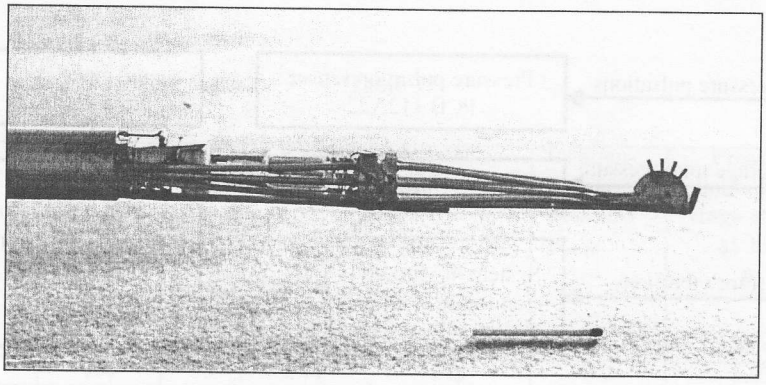

Figure 2. Measuring probe used downstream of the last stage blade.

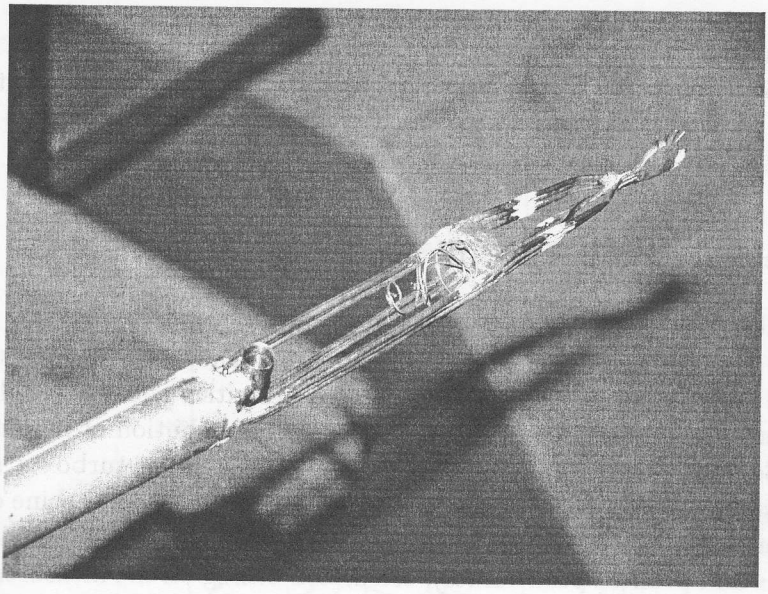

Figure 3. The end of the probe used for pressure measuring (averaged values and pulsations).

pressure signals, transmitted to this system were signals of shaft vibrations bearings, located on either side of the low pressure turbine part. The shaft signals, in vertical (Y) and horizontal (X) directions, were taken from a vibration surveillance system, of Philips delivery. During the measure- the pneumatic probe was traversed along the last stage rotor blade height, positioned in accordance with the direction of total pressure recording. The of each recording was about 30 s, and the sampling frequency: 40 kHz.

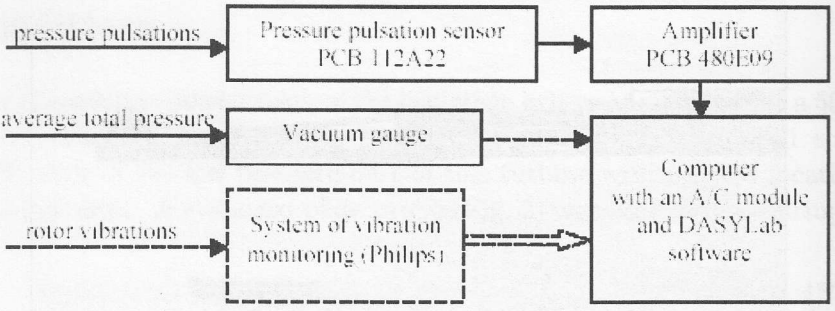


Figure 4. The schematic diagram of the measuring system.

All measurements were carried out for different turbine loads, within the range between 50 % and 100 % of the nominal load. The basic measurement data are shown in Table 1. These data provided the basis for evaluating the course of expansion in the last stage, as shown in Fig. 5 according to [5].

## 3 Measurement results and their analysis

Distributions of thermo-dynamic parameters downstream of the last stage along the passage height are shown in Figs. 6-7. They present measured pressures and temperatures, as well as calculated velocities and flow angles for the rated operating conditions. For all the loads the distribution of parameters was similar. Some of them have been shown in Fig. 6a for power turbo set minimum. In this regime, no flow separations, characteristic for low-load turbine operation, were recorded in the last stage passages. Pressure pulsations behind the last stage (rms and peak-to-peak values), calculated basing on the measurements and related to the measured average total pressure are shown in Figs. 9 and 10. They refer to the rms and peak-to-peak values.

It is noteworthy that in the examined turbine, even at the load as low as 50% of the rated value no flow separation is recorded at the hub. Unlike older constructions, the effect of leakage flow is less pronounced in the time histories of the flow parameters, which results from smaller radial gap at the rotor blade tips and relatively high humidity of steam leaving the turbine.

The magnitude of pressure pulsations depends strongly on flow velocity. Therefore relatively high values have been recorded for higher loads and their increase at the blade tips has been observed. The maximum values of the $\Delta p_{p-p}/p_c$ ratio reach $0.2 \div 0.44$, which corresponds to the flow turbulence level of about $10 \div 20\%$.

Table 1.

| Measurement No. | Power P | | LP inlet pressure $p_{LP}$ | LP inlet temp. $t_{LP}$ | Condenser pressure $p_{cond}$ | Pressure behind last stage stator, at hub $p_x$ |
|---|---|---|---|---|---|---|
| | absolute MW | percentage % | | | | |
| | | | MPa | °C | kPa | kPa |
| 1 | 400 | 80 | 2.02 | 212 | 3.2 | 5.07 |
| 2 | 500 | 100 | 2.44 | 210 | 3.55 | 7.27 |
| 3 | 250 | 60 | 1.04 | 181 | 3.0 | 3.80 |

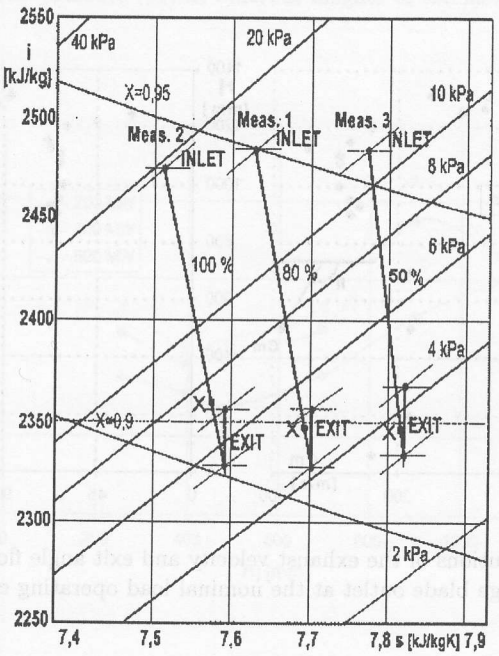


Figure 5. Steam expansion lines in the last stage of the LP turbine at different loads.

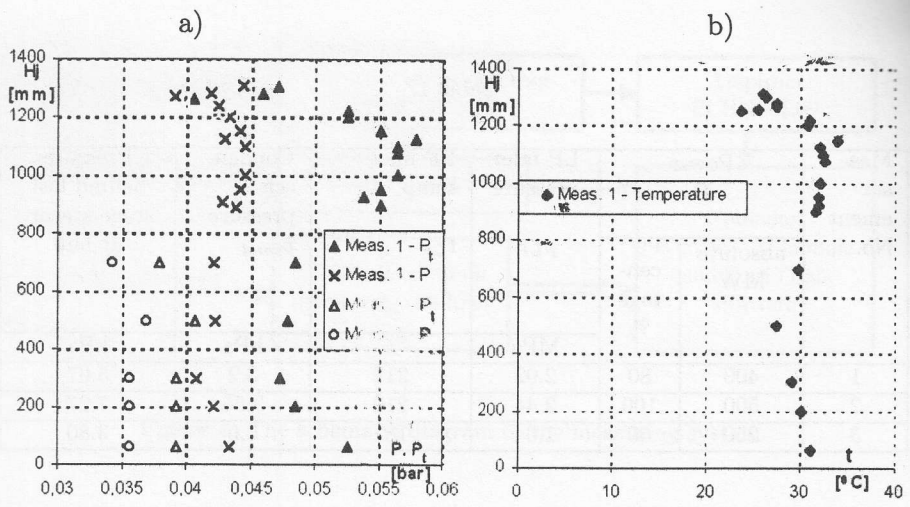


Figure 6. Radial distributions of the static pressure, total pressure and temperature downstream of the last-stage blade outlet at the nominal load operating conditions.

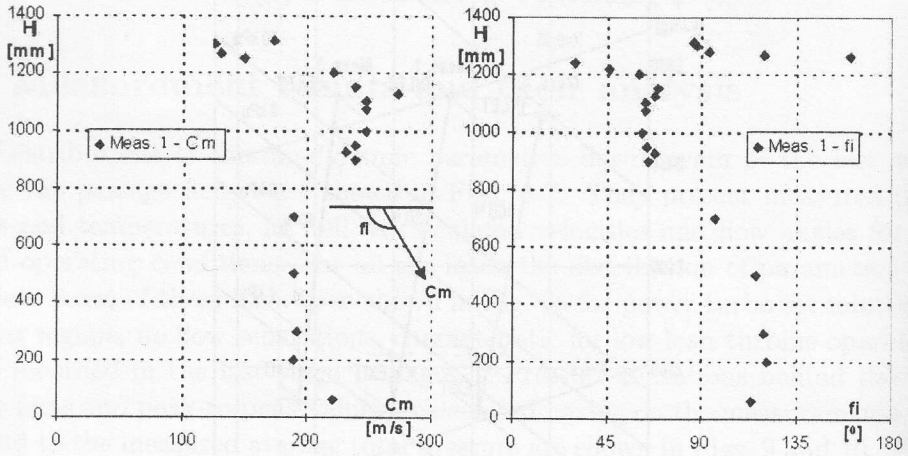


Figure 7. Radial distributions of the exhaust velocity and exit angle flow of steam downstream of the last-stage blade outlet at the nominal load operating conditions.

The calculated amplitude-frequency spectra of the pressures recorded at different blade heights are shown in Fig. 10. The predominant frequency component is linked to the rotor blade number ($i_r = 53$) and the rotation frequency $f_r = 50$ Hz:

$$f_r = i_r f_s = 2650 \text{ Hz}$$

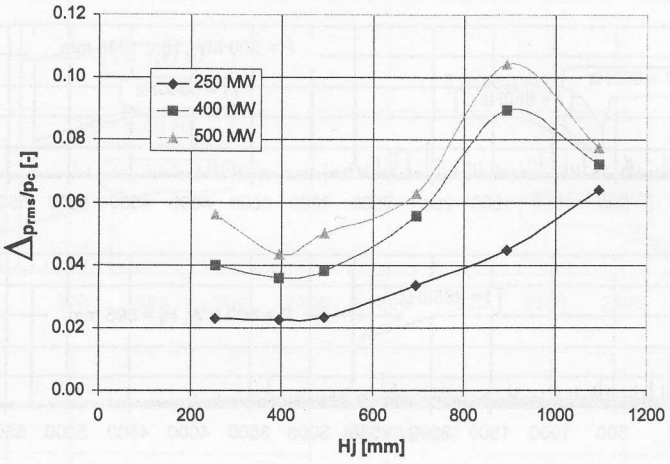


Figure 8. Root-mean-square value of the total pressure pulsations ($\Delta p_{rms}$) related to the average value of the total pressure ($p_c$) at different heights of the last stage blades (Hj).

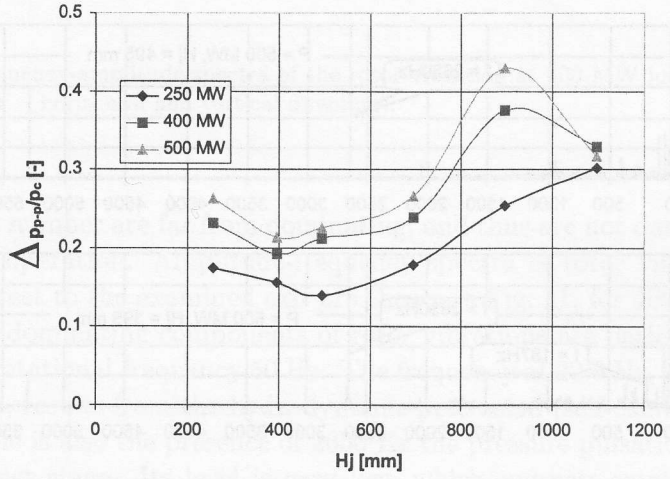


Figure 9. Peak-to-peak values of the total pressure pulsations ($\Delta p_{p-p}$) related to the average value of the total pressure ($p_c$) at different heights of the last stage blades (Hj).

Relying on the results obtained one can state that the components related to the rotation speed of the rotor, i.e. 50, 100, ... Hz, and those related to the

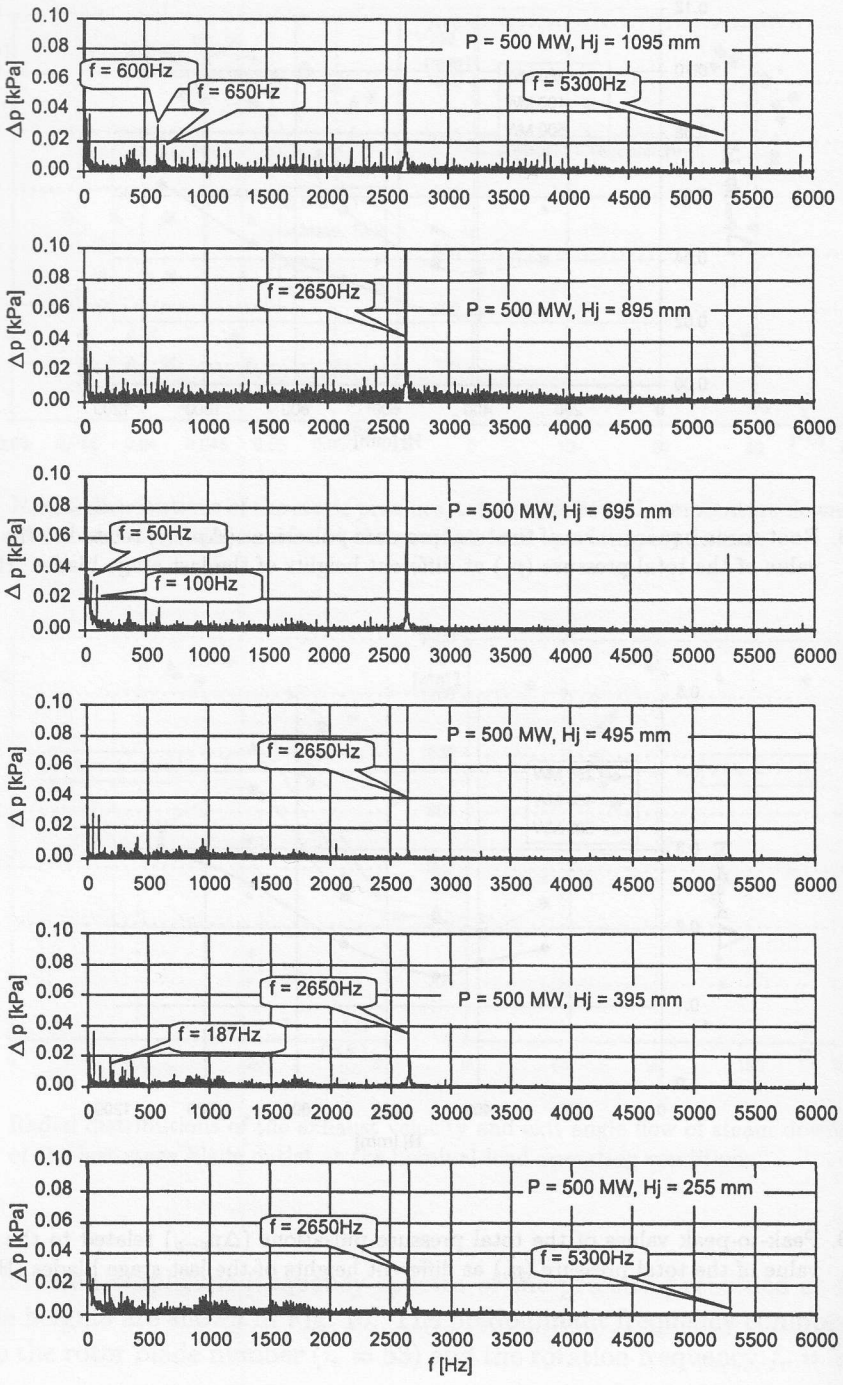


Figure 10. Frequency-amplitude spectra of the total pressure pulsation at 500 MW load.

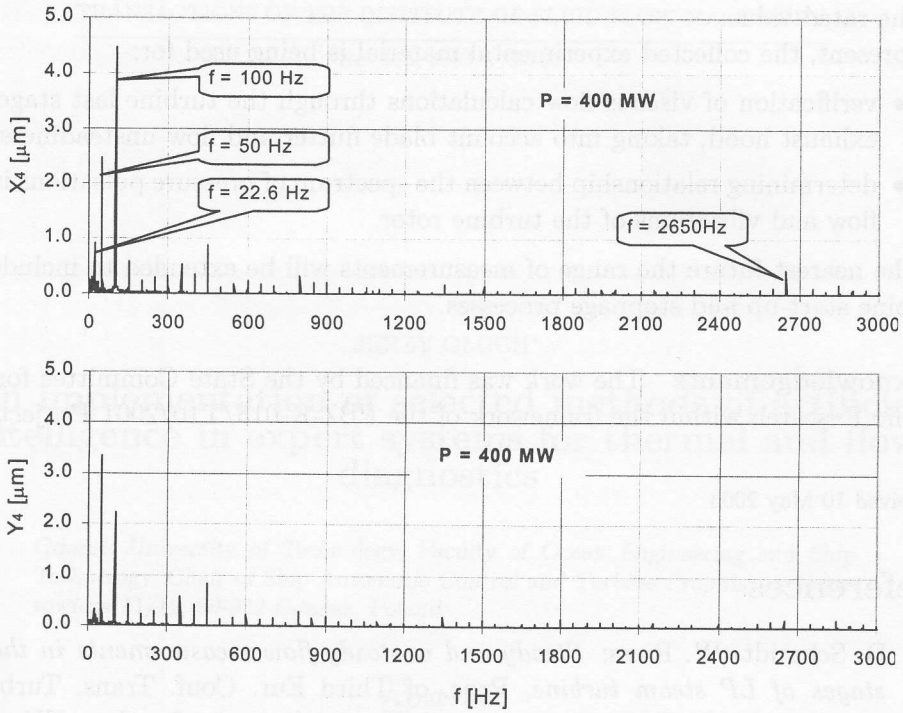


Figure 11. Frequency-amplitude spectra of the rotor vibration at 400 MW load (bearing nr 4, X, Y – horizontal and vertical direction).

stator blades number are far from dominating, and thus are not dangerous for the turbine unit operation. Amplitude-frequency spectra of rotor vibrations in the bearings nearest to the examined exit are shown in Fig. 11, for 400 MW load. In this case the dominating components of rotor vibrations are basic harmonics related to the rotational frequency 50 Hz. The frequency of 22.6 Hz, recognizable in the spectrum, results from the hydrodynamic precession (self-excited vibrations) [6]. Noticeable is also the presence of 2650 Hz the pressure pulsation component, behind the last stage. Its level is very low, which suggests small effect of last stage aerodynamic forces on the operation of bearings in the examined turbine.

## 4 Conclusions

The measurements of steady and unsteady pressure components at the turbine exit, complemented by measurements of rotor bearing vibrations, have proved stable operation of the turbine unit at loads in the range between 50 and 100 %

of the rated value.
At present, the collected experimental material is being used for:

- verification of viscous flow calculations through the turbine last stage and exhaust hood, taking into account blade flutter and flow unsteadiness,
- determining relationship between the spectrum of pressure pulsations in the flow and vibrations of the turbine rotor.

In the nearest future the range of measurements will be extended to include the turbine start-up and stoppage processes.

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