



Volume 107

2020

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: <https://doi.org/10.20858/sjsutst.2020.107.1>

Journal homepage: <http://sjsutst.polsl.pl>



**Article citation information:**

Andrearczyk, A., Bagiński, P. Vibration analysis of a turbocharger with an additively manufactured compressor wheel. *Scientific Journal of Silesian University of Technology. Series Transport*. 2020, **107**, 05-17. ISSN: 0209-3324.

DOI: <https://doi.org/10.20858/sjsutst.2020.107.1>.

**Artur ANDREARCZYK<sup>1</sup>, Paweł BAGIŃSKI<sup>2</sup>**

## **VIBRATION ANALYSIS OF A TURBOCHARGER WITH AN ADDITIVELY MANUFACTURED COMPRESSOR WHEEL**

**Summary.** This article presents the vibration analysis of a turbocharger, whose compression wheel was manufactured using a high-precision additive manufacturing technology. Currently, there are advance studies around the world for the development of parts of innovative fluid-flow machines using additive manufacturing techniques. The experimental research was carried out under conditions of reduced flow temperatures. The tests and the analysis were performed on a wheel manufactured using a 3D printing technology and on a conventionally used aluminium wheel. Apart from an FFT analysis of the vibration signal during machine operation, a machine run-up test was conducted (up to a speed of 105,000 rpm). The results showed the positive impact of the use of a plastic wheel on the dynamics of the system at a certain speed range, which might contribute to the development of a new method to optimise the geometry of flow systems in small high-speed turbomachines. A modified automotive turbocharger was subjected to experiments on a test stand.

**Keywords:** additive manufacturing, compressor wheel, vibration analysis, polymer

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<sup>1</sup> Institute of Fluid-Flow Machinery, Polish Academy of Sciences, Fiszera 14 Street, 80-231 Gdansk, Poland.  
Email: [aandrearczyk@imp.gda.pl](mailto:aandrearczyk@imp.gda.pl)

<sup>2</sup> Institute of Fluid-Flow Machinery, Polish Academy of Sciences, Fiszera 14 Street, 80-231 Gdansk, Poland.  
Email: [pbaginski@imp.gda.pl](mailto:pbaginski@imp.gda.pl)

## 1. INTRODUCTION

The use of additive manufacturing (AM) technology to accelerate the development of prototypical solutions in machines and reduce their cost has been on the increase in recent times. Presently, research on the use of 3D printers for the development of new prototypes and the optimisation of already existing parts is being carried out. Since AM technology is widely used and many trials conducted to implement different materials in diverse fields of science and engineering [1, 2], a number of studies on the physical properties of the materials used in this technology need to be carried out. This is important as they make possible better specification of the field of application of this technology.

Vibration analysis during machine operation is essential in determining the dynamics of the system and is mainly carried out for diagnostic purposes [3, 4], more so, it is performed for the accurate identification of faults and causes of machine instability [5, 6, 7, 8, 9]. This study is based on an automotive turbocharger machine. There are a number of articles on vibration analyses performed on these types of machines [10, 11, 12], thus, making the determination of their technical conditions quick and precise, revealing the reasons behind these conditions. Article [13], based on the analysis of the vibration spectrum of a turbocharger, describes a way to measure the speed of rotation using the signals tested. This literature review indirectly contributed to the selection of a turbocharger as a research object.

So far, in the field of AM technology, vibration tests have been carried out on 3D printers to improve the quality of the elements manufactured or to speed up the printing process. It was only in the article [14] that the vibration properties of 3D-printed elements were investigated using the modal analysis to determine the natural frequencies of a research object. Given that there are no studies on the influence of the use of additively manufactured components on the dynamics of machines, a decision was made to perform vibration analysis on a turbocharger, whose compressor wheel was manufactured using a selected 3D printing technology.

This article describes the experimental tests that were carried out on a test stand used to determine the characteristics of turbocharger compressors and presents some of the selected results of the vibration analysis of the turbocharger with an aluminium (original) compressor wheel and a polymer one (3D-printed), which has been tested at high rotational speeds under various operating conditions. This article is a continuation of research on the use of 3D printing technology in the experimental verification of the optimised rotor discs that are mounted in turbomachines. Previous work established that the results of flow calculations are consistent with the experimental results obtained for aluminium and polymer discs. The aim of this work was to compare the dynamic properties of a conventional turbocharger when using a disc made of aluminium or polymer.

## 2. MANUFACTURING TECHNOLOGY

The Institute of Fluid-Flow Machinery, Polish Academy of Sciences (IMP PAN) uses three different AM technologies. Based on criteria such as printing precision, printing time and cost of mass production, the MultiJet Printing (MJP) technology used in a printer produced by the 3D Systems Company (model HD 3500 Max) was selected. This technology makes achieving very high printing precision (the thickness of a single layer printed by the device is 16  $\mu\text{m}$  with an accuracy of up to 1  $\mu\text{m}$ ) possible. The producer offers a range of materials that have different mechanical properties. The material sold under the trade name VisiJet M3 X in

the form of a fluid polymer resin was chosen to manufacture the compressor disc as it has the best properties. The studies carried out on its mechanical properties showed that the tensile strength is about 54 MPa [15].

The manufacturing process, which is based on MultiJet Printing technology, is characterised by putting layers of material through printhead jets that are distributed over the entire printing platform. The MJP method is based on the inkjet approach to create 3D elements and photo-cure the printed photopolymer layers using ultraviolet light.

However, this method should not be used at high ambient temperatures as it may cause errors during the printing process. MultiJet Printing is one of the most precise 3D printing technologies; it uses piezoelectric nozzles located in a printhead to deposit thin layers of photocurable resin and wax (support material). MJP is used to create parts with complex shapes, that is, parts with large amounts of details and complex geometries. The use of the support material (wax) is a huge advantage of this method as it dissolves at a temperature of 60°C leaving no trace on the printed element. According to the producer, the selected building material plasticises at a low temperature (88°C).

### **3. RESEARCH OBJECT AND MEASURING EQUIPMENT**

As earlier mentioned, a turbocharger was selected for the experiments. It is a machine widely used in the automotive industry. In combustion engines, the compressor rotor supplies additional air to the combustion chamber through the intake manifold. Nowadays, one of the most important components of a modern engine is the turbocharger. It is a rotating machine, which consists of a turbine and a compressor, both mounted on a common shaft. The operating principle and main components of the turbocharger are shown in Fig. 1. The following factors influenced the choice of this machine: the nature of its operation (in terms of dynamics) as documented in the literature, its high rotational speed, its construction, the easy assembling and disassembling of the components. The machine casing is divided into three sections, which perform different functions, even though the machine has only one shaft. In the supply section of the machine (red colour), there is a spiral casing that supplies exhaust to the turbine blades to set it in motion and transmit the torque to the compressor disc via the shaft. The central section of the machine (green colour) supply oil to the slide bearings and the thrust bearing, necessary for their lubrication. The supercharging section of the machine (blue colour) is for the pressure charging of the engine. This section was chosen for experimental purposes as it is a cool section (from the viewpoint of the operating temperature) and the rotor disc can be easily disassembled.

The compressor disc is the part of the turbocharger that has been manufactured using MJP technology. The printed polymer disc and the original aluminium disc are shown in Fig. 2. A 3D laser scanner was used to reproduce the original geometry of the aluminium disc and a cloud of points was obtained this way, which was then used to create a model for use in a 3D printer. The geometric dimensions of the two discs were checked and no manufacturing inaccuracies were detected. The polymer disc has the same dimensions as the aluminium disc and they are as follows: diameter near the split blades – 42.5 mm, diameter near the supply of the compressor (that is, near the non-split blades) – 30 mm. The discs used in the experiments are shown in Fig. 2.

Conventional turbocharger test stands use engine exhaust, as in the case of this paper [16]. Due to the properties of the material from which the tested disc was made, particularly due to its maximum operating temperature (88°C), it was necessary to carry out this study on the test

stand at reduced supply temperatures. Compressed air (which could be heated to a temperature between 30°C and 150°C, respectively) was used instead of engine exhaust.

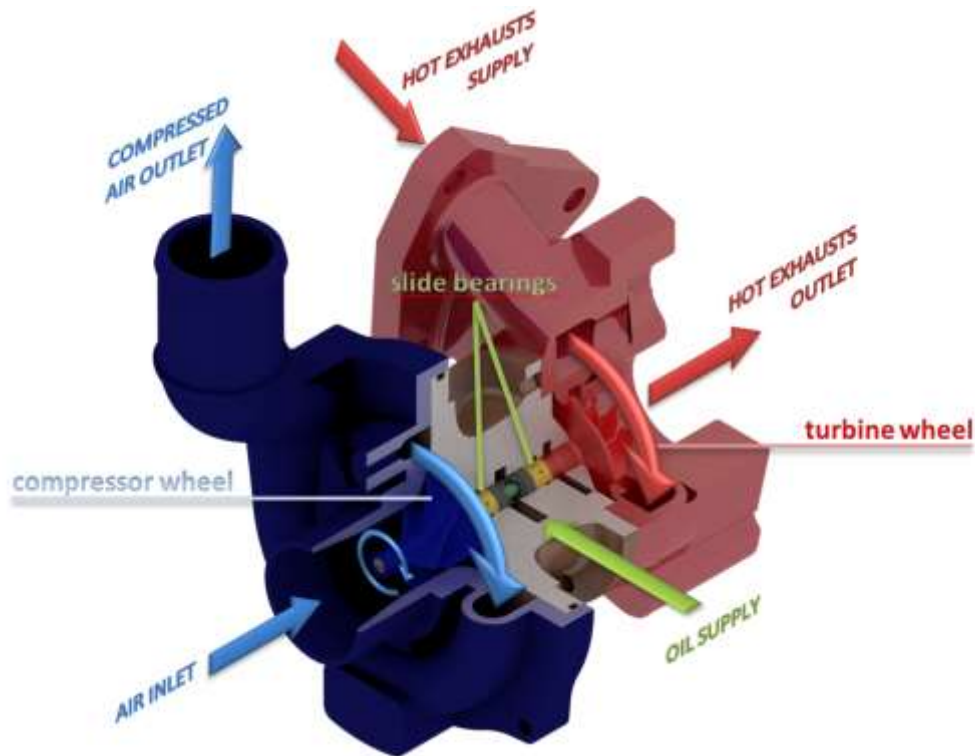


Fig. 1. Design and operation of a turbocharger divided into three sections: compressor section (blue colour), lubrication system (green colour) and turbine section (red colour)



Fig. 2. Compressor wheel manufactured using the MJM method (left) and the original one (right)

Heating was used to maintain the appropriate temperature at the turbine outlet. Due to the expansion of the air, the temperature of the medium could have dropped significantly (even below zero degrees Celsius), which could have caused damage to the machine. The test stand [17] was equipped with all the necessary elements such as a lubrication system, a heating system, sensors and valves used to regulate the rotational speed of the device. Furthermore, the oil supply pressure to the bearings has a considerable impact on the machine vibrations. In a combustion engine, the oil pressure is regulated by the engine speed. Since the test stand was not equipped with such a system, an oil pump was used for this purpose, which maintained the oil pressure in the range of 2.5-4 bar (using an inverter), depending on the current speed of the compressor. The test stand, as well as the marked sensors required to perform measurements, are shown in Fig. 3.

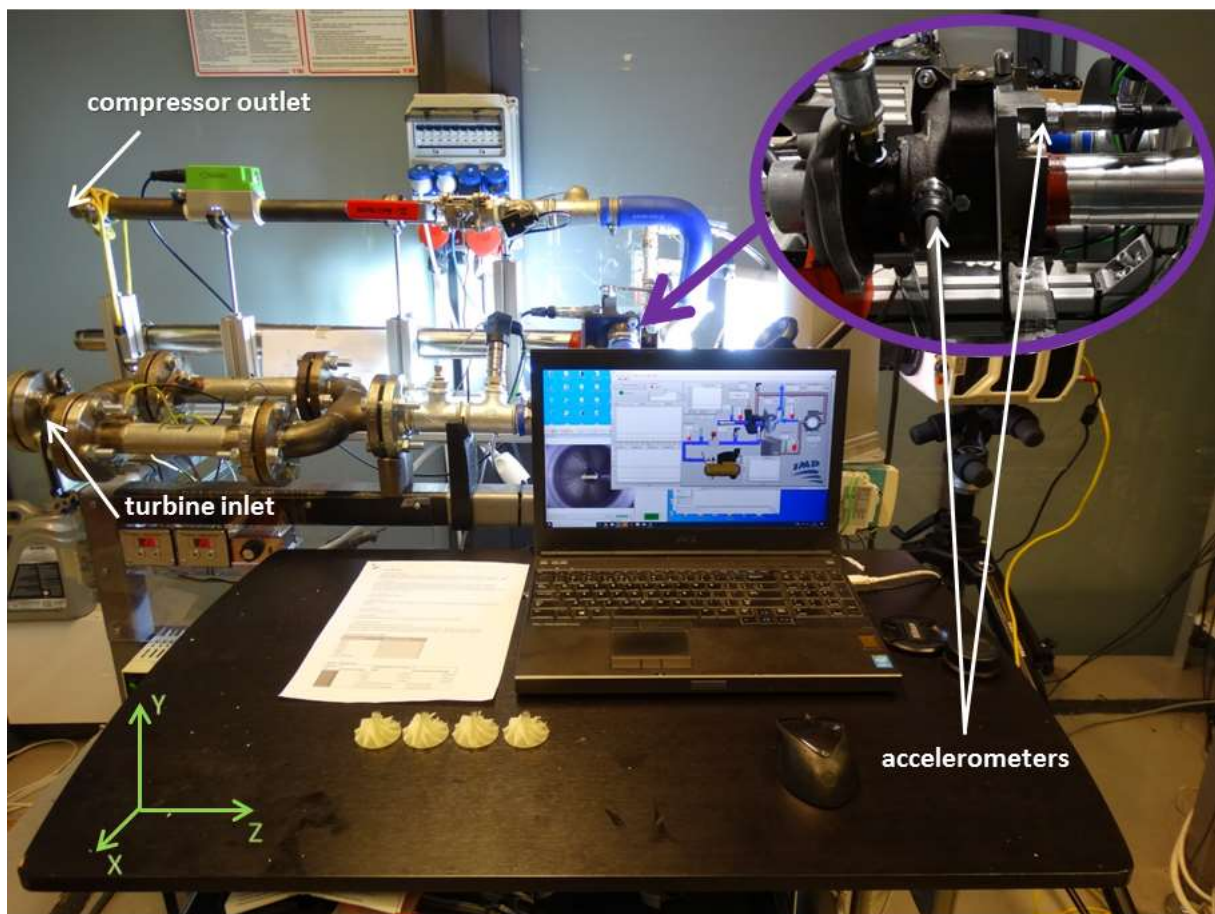


Fig. 3. Turbocharger test stand

Vibration sensors were mounted in the X- and Z-direction (Cartesian coordinate system shown in Fig. 3). Besides vibrations, other parameters were also measured (such as temperatures on both sides of the turbocharger, supply pressure and flow rate) to test the operating parameters, but were not discussed in this paper. Accelerometers produced by the PCB Piezotronics Company were used to measure vibrations.

#### 4. RESULTS OF THE EXPERIMENT

The first part of the experiment involved testing the compressor using different compressor wheels. During the tests, a throttle valve was used to regulate the mass flow, thus, a study of the different operating states of the machine was obtainable. The tests were conducted with discs made of two different materials. The aluminium disc had a mass of 16.18 g and the polymer disc, 7.26 g. First, a run-up test of the machine was carried out with the results shown in Figs. 4 and 5, respectively.

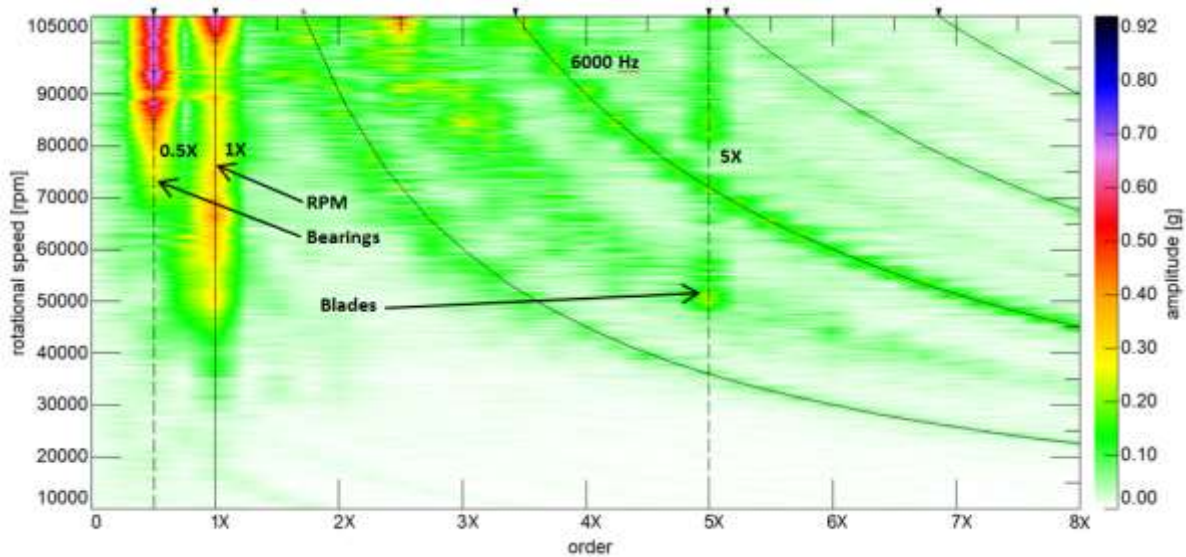


Fig. 4. Colourmap from run-up test conducted with aluminium compressor wheel (speed range: from 10,000 rpm to 105,000 rpm)

During the run-up test performed with the aluminium disc, an increased vibration level associated with 1X was observed at speeds above 50,000 rpm and was highest at a speed of 105,000 rpm (Fig. 4). Vibrations associated with the operation of the bearings (0.5X) occurred as soon as the rotational speed exceeded 70,000 rpm and they became dominant in the vibration spectrum at higher speeds. When a higher vibration amplitude developed (resulting from the unbalance), the 5X component was visible (a component that was associated with the flow of compressed air through the compressor blades, five split blades and five non-split blades). The eigenfrequency of the test stand, which was around 3,000 Hz, was characterised by a low vibration level visible in the colourmap. Its harmonics and subharmonics can be noticed.

As with the polymer disc, an increase in vibration level (1X) was observed at speeds ranging from 35,000 to 75,000 rpm (Fig. 5). The highest vibration amplitude occurred at a speed of 50,000 rpm (resonance zone) and was 0.5 g higher than that in the experiment of the aluminium disc. In comparison with the aluminium disc, component 0.5X attained a higher level of vibrations and its maximum value was 0.8 g. The eigenfrequencies of the test stand can be seen in the colourmap. Unlike in the previous test with the aluminium disc, the 5X component did not appear, which could be associated with the less efficient operation of the compressor.

To thoroughly evaluate the dynamic performance of the tested machine, it was necessary to perform the FFT analysis of the signals recorded at selected rotational speeds. The results, which were obtained in the X-direction, are shown in Figs. 6-9. They are analysed in the following part of the article.

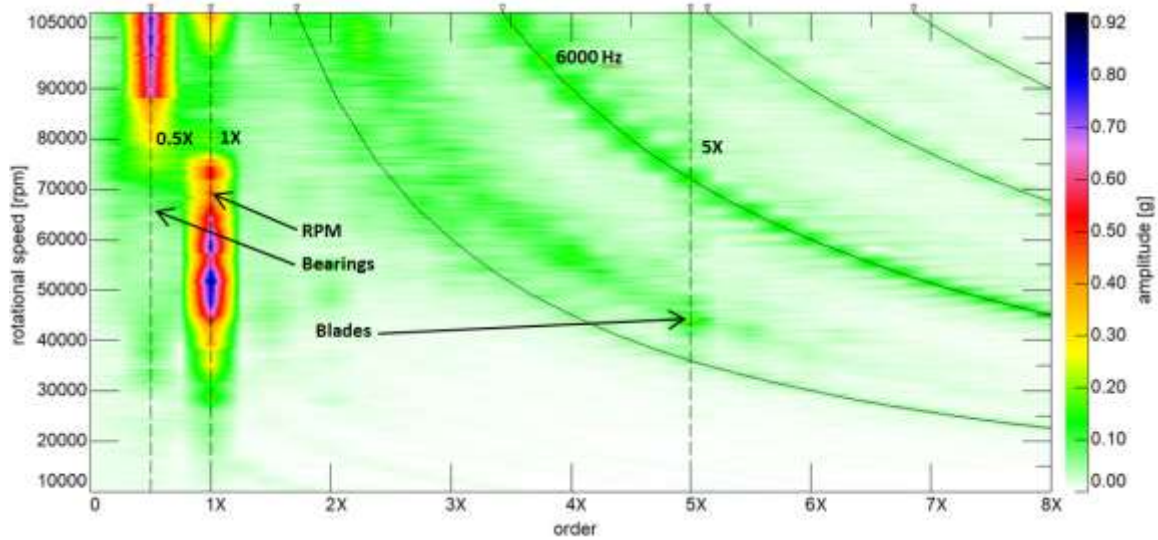


Fig. 5. Colourmap from run-up test conducted with polymeric compressor wheel (speed range: from 10,000 rpm to 105,000 rpm)

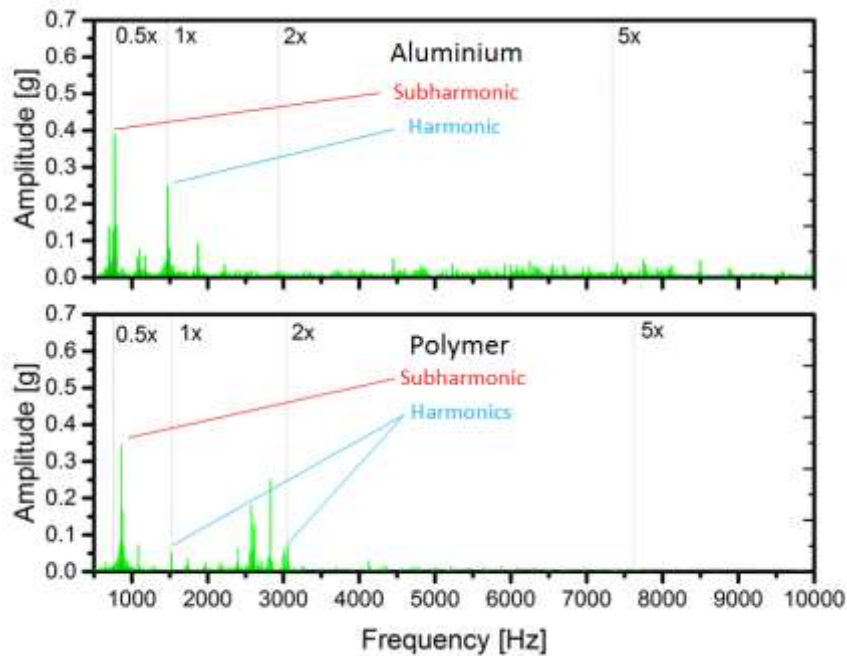


Fig. 6. Vibration amplitude spectra (in the X-direction) of the turbocharger, obtained at a rotational speed of 90,000 rpm for two different compressor wheels without throttling the flow at the compressor outlet

Fig. 6 shows frequency-amplitude graphs, for the experiments carried out with the aluminium and polymer disc without throttling the flow at the outlet of the compressor. In both experiments, the 0.5X component (associated with the vibrations of slide bearings) is dominant. In the bottom graph (polymer disc), the 1X component is about five times higher than in the top graph, however, it can be seen that the spectral components are present within the frequency range from 2,500 to 3,000 Hz.

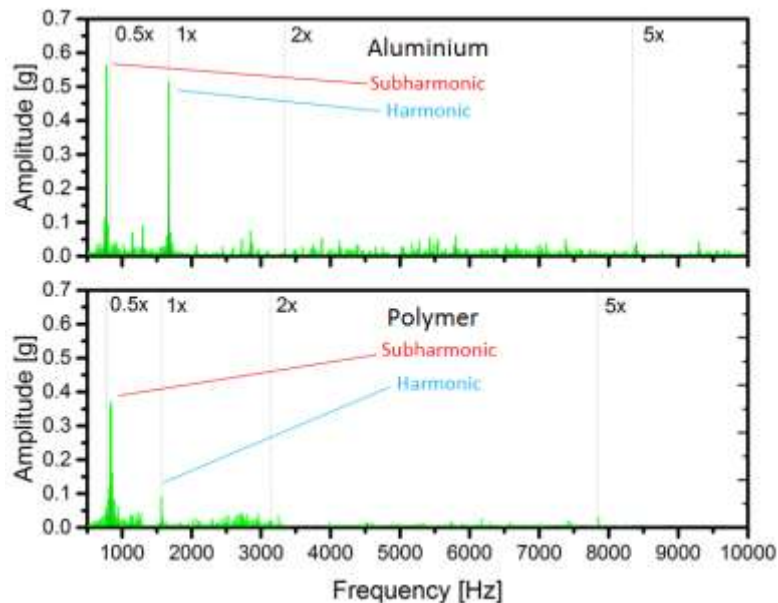


Fig. 7. Vibration amplitude spectra (in the X-direction) of the turbocharger, obtained at a rotational speed of 90,000 rpm for two different compressor wheels at a throttle level of 60%

After the flow was throttled at the compressor outlet (Fig. 7), the vibration amplitudes of the 0.5X and 1X components approximately doubled at a speed of 90,000 rpm in the case of the aluminium disc, while for the polymer disc, they were at the same level. Regarding the aluminium disc, it can be similarly observed that the component associated with the functioning of the bearings (0.48X) shifted towards lower frequencies, indicating that an oil whirl had occurred.

Similar vibration spectra were obtained at a speed of 100,000 rpm. Fig. 8 shows the results of the experiment carried out without throttling the flow. As with the aluminium disc, the vibration amplitudes increased as expected. The 0.5X and 1X components are dominant, as it was the case at a speed of 90,000 rpm. With regard to the polymer disc, a considerable increase in the vibration amplitude resulting from the unbalance (1X) was observed, however, the 0.5X component increased with an increase in the rotational speed.

During throttling the flow at the compressor outlet, the values of amplitudes were at a similar level at a speed of 100,000 rpm (Fig. 9) for both discs. As for the aluminium disc, the component associated with the functioning of the bearings moved towards the lower frequencies (to 0.4X), indicating that the oil whip instability had occurred.



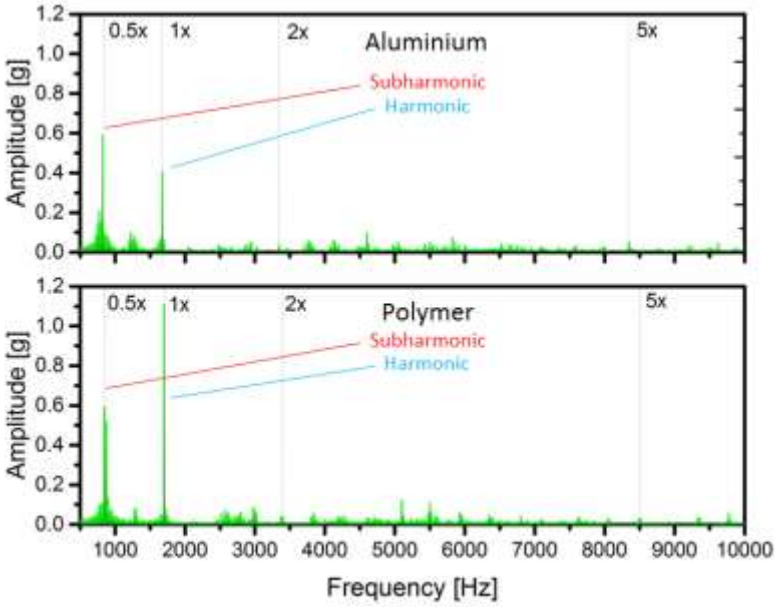


Fig. 8. Vibration amplitude spectra (in the X-direction) of the turbocharger, obtained at a rotational speed of 100,000 rpm for two different compressor wheels without throttling the flow at the compressor outlet

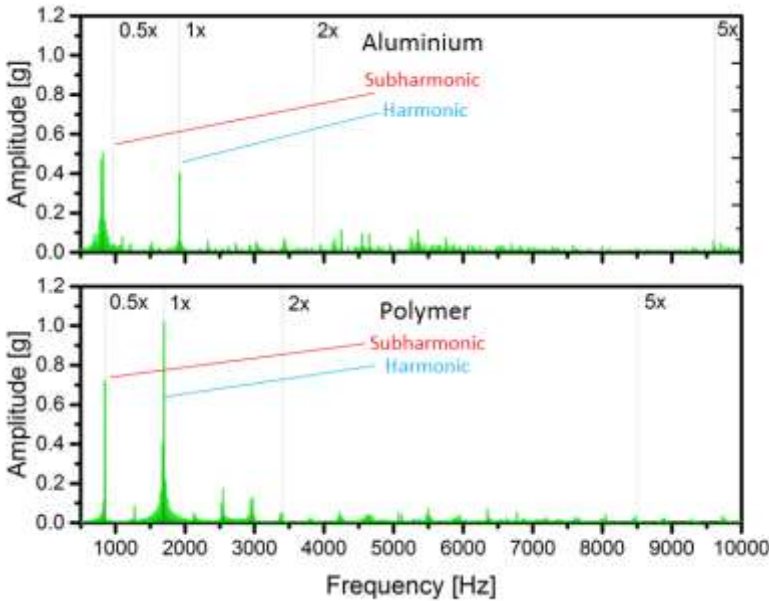


Fig. 9. Vibration amplitude spectra (in the X-direction) of the turbocharger, obtained at a rotational speed of 100,000 rpm for two different compressor wheels at a throttle level of 60%

Due to the oil whip instability and a suspected local disruption of the airflow in the compressor of the turbocharger (that is, the compressor stall), a decision was made to analyse the vibration acceleration signals measured in the Z-direction. These phenomena are often accompanied by a rise in the vibration level in this direction. Figs. 10 and 11, respectively,

show the vibration spectra which were measured in the Z-direction during the tests of the two discs conducted under different operating conditions.

In the case of the aluminium disc, component 1X is dominant in the FFT amplitude-frequency spectrum (Fig. 10) having the following values: 0.45 g (without throttling) and 0.69 g (with throttling). The 0.5X component is visible but its value is about half that of the 1X component. As for the experiment conducted without throttling the flow, the 0.75X component can be observed, which is not associated with the compressor stall. The increased vibration amplitudes that occur at frequencies of 3,000 and 4,900 Hz are related to the eigenfrequencies of the test stand. After the flow was throttled at the compressor outlet, an increase in the amplitude of vibrations associated with the 5X component was observed (blades) and, as in the case of vibrations registered in the X-direction, the subharmonic linked to the functioning of the bearings moved towards lower frequencies (to 0.4X), indicating that the oil whip instability had occurred. Other components likewise appeared (at different frequencies), which may indicate that the compressor stall phenomenon occurred.

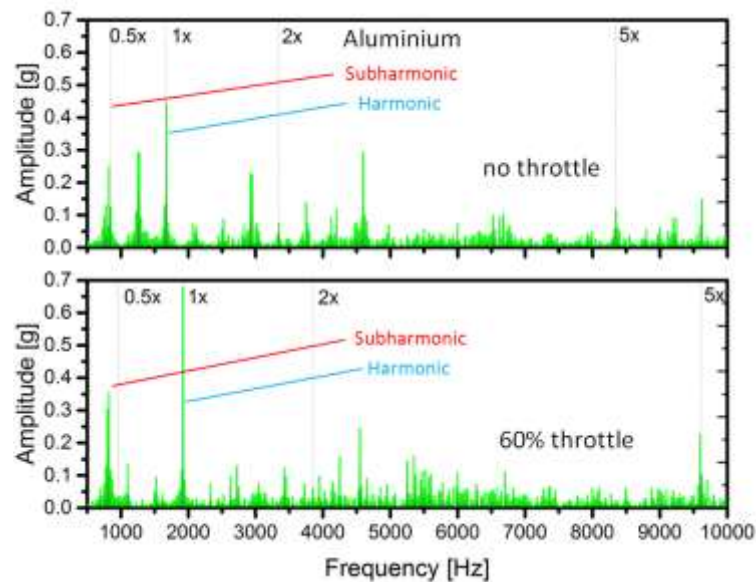


Fig. 10. Vibration amplitude spectra (in the Z-direction) of the turbocharger, obtained at a rotational speed of 100,000 rpm for an aluminium compressor wheel under different operating conditions

As for the polymer disc, after analysing the spectrum shown in Fig. 11, it was discovered that there was no oil whip instability. However, the 0.75X component was dominant and its value exceeded 0.5 g. During throttling, there was no increase in the rotational speed as in the case of the aluminium disc, which may be a sign of inefficient operation of the blades. When the flow was throttled, an increase in the amplitudes of vibrations was visible at the following frequencies: 2,500, 3,000 and 3,500 Hz. In both cases, an increase in vibration level was observed at a frequency of 6,400 Hz (which is one of the eigenfrequencies of the test stand).

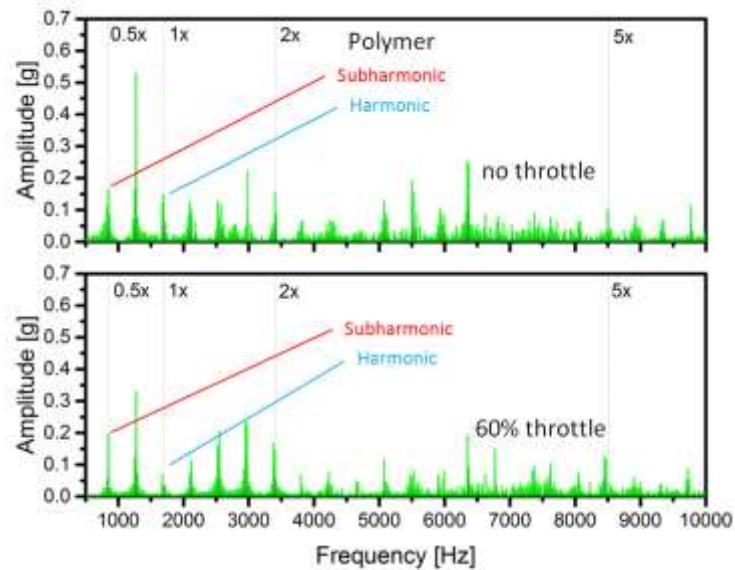


Fig. 11. Vibration amplitude spectra (in the Z-direction) of the turbocharger, obtained at a rotational speed of 100,000 rpm for a polymer compressor wheel under different operating conditions

## 5. CONCLUSIONS

The aim of this work was to carry out an experimental study to assess the dynamic performance of the machine using rotating elements manufactured in a conventional manner or by precise 3D printing technology. The disc used in the tests was manufactured using MJP technology.

The experimental research was conducted under conditions of reduced temperatures using compressed air as the supply air. Accelerometers were used to measure vibration amplitudes in two directions (X and Z). The research was carried out at speeds between 10,000 and 105,000 rpm. The results of run-up tests as well as a detailed vibration analysis of the turbocharger at elevated levels of vibration and selected rotational speeds are presented. About the rotational speeds that did not exceed 90,000 rpm, the use of the polymer disc had a positive impact on the dynamic performance of the machine. At higher speeds, the stall condition was observed regardless of the type of disc used. As for the polymer disc, a decrease in the operating efficiency of the compressor was observed at speeds greater than 100,000 rpm, which may have been caused by deformation of the blades. In addition, the results obtained in the axial direction of the turbocharger show that in the case of the aluminium disc, during throttling of the flow, the oil whip instability phenomenon was observed, and its occurrence confirmed. This phenomenon did not occur when the polymer disc was being used.

Future research will focus on flow optimisation using the manufacturing technology described herein. A destructive test will also be performed.

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Received 17.03.2020; accepted in revised form 19.05.2020



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