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Research Article

Vibration Testing of 3D-Printed Turbine Blades: Precautions and the Application of Scale Factors in Design

Buschaiah Karolla[1], Mudda Nirish[2, *], Rega Rajendra[1]

[1]Mechanical Engineering Department, University College of Engineering (A), Osmania University, Hyderabad, India
[2]R&D Center, MIC Labs, Measure India Corporation Private Limited, Rampally, Hyderabad, India

Abstract

Testing of components and systems is a specialized discipline that often involves complex instrumentation schemes, dedicated test rigs, and meticulous interpretation of results after assessing measurement accuracies. Turbine blades, especially those made of super alloys like Nimonic, have been subjected to vibration testing for over seven decades for research, design validation, and quality control. In recent years, advancements in 3D printing have transformed manufacturing processes, evolving from plastic powders and filaments to metal powders, enabling the production of functional components for industrial applications. Small turbine blades have been successfully manufactured using additive manufacturing (AM) techniques, particularly for wind tunnel and vibration testing, to support design and performance evaluation. This paper presents the experimental investigations conducted on a 3D-printed gas turbine stage blade subjected to vibration testing. The study outlines the test methodologies, instrumentation, and data acquisition techniques employed to evaluate the dynamic behavior of the printed blade. Additionally, key precautions necessary to ensure reliable testing and accurate result interpretation are discussed. A significant aspect of this work is the correlation between vibration characteristics of 3D-printed blades and actual steel blades used in gas turbines. The paper explores predictive techniques that facilitate the estimation of dynamic parameters in real turbine blades based on results obtained from 3D-printed prototypes. The findings contribute to the growing understanding of how additive manufacturing can aid in early-stage design validation and provide insights into the feasibility of using 3D-printed components for experimental testing in turbomachinery applications.

Keywords

Additive Manufacturing (3D Printing), Selective Laser Sintering (SLS), Vibration Testing, Turbine Blades, Super Alloy (Nimonic), Dynamic Response

1. Introduction

3D printed arts are becoming common place in the past 5 to 7 years in view of growing confidence among the industry partners for this technology [1]. These parts have demonstrated for normal applications due to their adequate strength and sometimes adequate durability [2]. However, for applications involving dynamic loading, more studies need to be undertaken prior to these parts being accepted on a large scale [3]. Towards improving the confidence level of using 3D printed parts, various tests are undertaken in industry for checking their quality and reliability of performance [4].

*Corresponding author: nirishyadav@gmail.com (Mudda Nirish)

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Vibration testing is one of the moderate to severe requirements for acceptance [5]. For more than 70 years, testing systems and parts especially turbine blades composed of super alloys like Nimonic have been a crucial part of research, design, and quality assurance [6]. This process necessitates sophisticated instrumentation and the interpretation of test results [7]. Since 3D printing has advanced over the last five to eight years, components have been manufactured using plastic powders and filaments, and more recently, metal powders [8]. This has made it possible to fabricate turbine blades for experimental uses including vibration and wind tunnel testing [9]. The vibration properties of turbine blades made conventionally have been the subject of numerous studies [10]. However, little is known about the vibration behavior of 3D-printed blades, especially when comparing them to real steel blades [11]. Using data from 3D-printed plastic or filament-based prototypes to precisely forecast the dynamic response of actual metal turbine blades is the main problem [12]. By giving experimental results on the vibration testing of a 3D-printed gas turbine blade and going over the precautions and procedures needed to extrapolate these findings to real steel blades, this paper fills this knowledge gap [13]. In this paper, vibration tests are detailed with special reference to turbine blades. Except wind turbines and hydro turbines, turbines using steam and gas operate under very high temperatures of 600 ℃ to 1400 ℃ which precludes use of instrumentation on these turbine rotors to carry out measurements. The only way to overcome these limitations is to carry out model tests and projet the results using relationships obtained from Buckingham Pi theorem [14].

2. Materials and Methods

The blade which is used in the finite element analyses is manufactured by 3D printing technology in the laboratory as per the same geometry meaning that it is built 1: 1 scale for purposes of scaling studies and to validate the results of finite element analysis (FEA). The geometry of the blade and other details are shown in Figure 1, Figure 2 and the 3D process parameters are given in Table 1 [15].

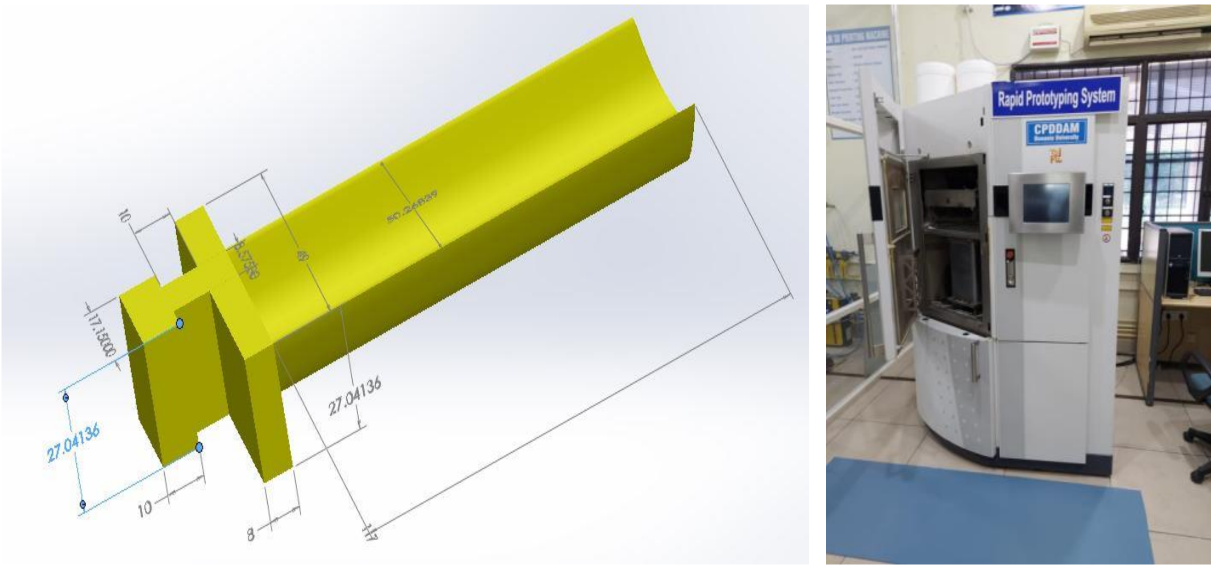

Figure 1. The dimensions of the blade and 3D Printer (Rapid Prototyping Machine, Formiga 100) used for manufacturing the blade (Make: EOS GMBH/Germany).

Table 1. Process parameters for conducting Vibration test used on 3-D printed blade.

Sl. No.	Sensor/Instrument Description	Make	Model No	Serial No
1	Multi-channel Data Acquisition System	Siemens	SCM01	47120433
2	Instrumented Impact Hammer	PCB	086C02	36746
3	Miniature ICP accelerometer	PCB	352C22	LW187836

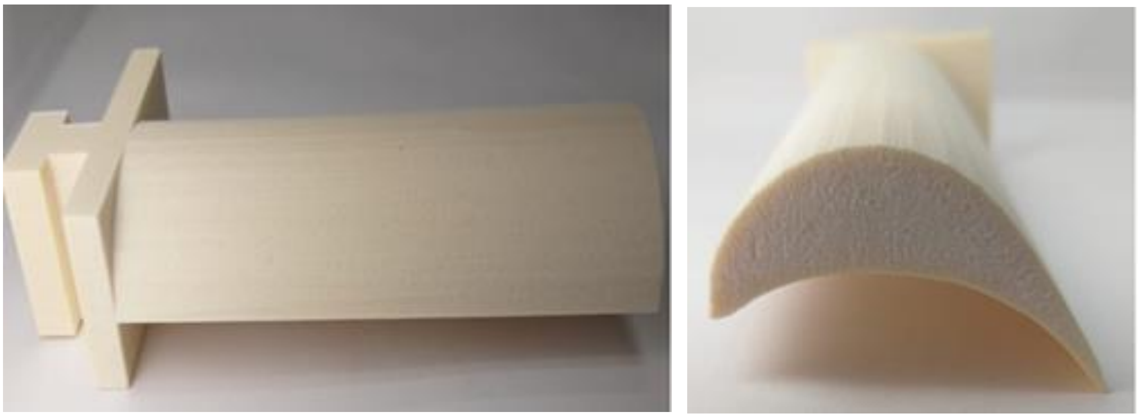

Figure 2. Photo of turbine blade manufactured using 3D printing.

Precautions to be taken in the planning stages are certain precautions to be taken before carrying out the tests. Since 3D printing can be undertaken using various build schemes, it is essential to manufacture another rectangular bar with rectangular cross section termed as calibration beam to obtain properties like Young's modulus and density which are essential parameters in vibration [16]. Care is taken to provide equivalent material portion in this bar corresponding to the base portion of the turbine blade. Text book values are to be avoided in the computations. Prior to the test, it is to be ensured that the vibration sensor (for example accelerometer) weighs less than one-tenth of the weight of the component [17]. This is because, in case of parts made with plastic powders or filaments, the density is low and consequently the weight of the part is low thereby making the above condition difficult to conform to. Clamping of the part must conform to the case actually used in actual usage of steel blades [18]. Since material damping, which is negligible in steel, is not researched adequately, error due to this is difficult to compensate.

3. Results and Discussion

Frequency response function (FRF) measurement is carried on a model of Turbine Blade and Rectangular Beam to find out the Natural Frequencies, the FRF is a characteristic of a system that has a measured response resulting from a known applied input. The equipment used in the present Vibration testing are Instrumented Impact Hammer (Make: PCB Piezotronics), Miniature ICP accelerometer (Make: PCB Piezotronics Model 352C22) also known as "tear-drop" type and Multi-channel Data Acquisition System (Make: Miniature ICP accelerometer, Model SCM01) By making use of Miniature accelerometer shown in Figure 3(a) [19, 20] and the instrumented hammer shown in Figure 3(b), time response and frequency response are obtained, the latter being shown in Figure 4. The data from the measured location were recorded over a frequency bandwidth of 3.2 kHz. Additional data of testing are shown in Figure 5.

Figure 3. Tear drop type of accelerometer (make: PCB Piezotronics, Model 352C22), Instrumented impact hammer and the instrumentation set up comprising of (a) and (b) together with Multi-channel Data Acquisition System.

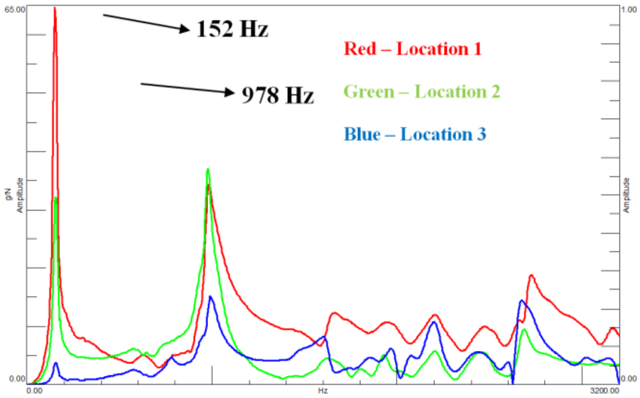

Figure 4. *Natural frequencies of Turbine Blade mounted in a vice.*

Figure 5. *Testing using Impact hammer for giving force and to measure response by an accelerometer.*

Figure 6. *Bending test of cantilever blade.*

A rectangular beam is also manufactured herein termed as calibration beam (as mentioned in precautions) to evaluate Young's modulus E value it using a bending test as shown in Figure 6 [21]. Loads p are varied and deflections δ are measured on the bar using a dial gauge and using the formula E= pl^3 / (3 δ I). It may be emphasized that this test is necessary since E value in a 3D printing structure depends very much on the build scheme adopted and in the present case, build scheme is identical for the blade and calibration bar.

For the blade, the frequencies response functions shown in Table 2 for the blade obtained from the test are f_1= 152 and f_2 = 872.

Table 2. *Gives the results of the vibration test.*

Results for natural frequencies of the 3D printed turbine blade Natural frequencies of the 3D printed turbine blade Length (L) = 0.117m and Profile area (A) = 4.3794E-4m^2	
Mode No	**Frequency (Hz)**
1	152
2	872

The correctness of the results can be checked approximately by using the fact for a cantilever that f_2/f_1 = 22/3.52= 6.25 which in the case of a blade (not exactly a rectangular parallel piped) with aerofoil cross section is f_2/f_1 = 872/ 152=5.737 which is nearby but for the fact that the blade has stiffening effect. It is observed that higher frequencies could not be obtained due to stiffness of clamping of the blade is very high as observed in the time signal. Due to stiffening due to aerofoil shape measurement of frequencies higher than the two values is not possible as seen in time response (and not frequency response seen in the FRF [22]. Use of scale factors to predict frequencies in steel blade Scale factors enable use of the results of tests on models made of any material to predict the parameters in an actual original prototype of blade. These scale factors can be obtained by making use of the well-known Buckingham Pi theorem. In those cases where a mathematical formula is directly available like in the present case 9 where the blade is almost can be represented as a cantilever beam in the absence of centrifugal and other loads), scale factors can easily be obtained and used [23]. The frequency of a cantilever beam is determined by using the relation (for 1st Mode).

$$f_{m1} = \frac{3.52}{2\pi L^2}\sqrt{\frac{EI}{m}}$$

Where m = ρAL mass/unit length. Now, defining the scale factors for each one of the parameters (except numerical constants like 3.52 above), we get from the basic theory of cantilever vibration, the frequency is given by

$$f = \frac{K}{2\pi L^2}\sqrt{\frac{EI}{m}},$$

Where K - Constant.

After removing the constants, $f_{m1} \propto \frac{1}{L^2}\sqrt{\frac{EI}{m}}$

Defining S as scale factor and subscript denoting the parameter, scale factors for different parameters are:

For length $S_L = \frac{L_2}{L_1}$,

Moment of inertia, $S_I = \frac{I_2}{I_1}$;

Mass/unit length $S_m = \frac{m_2}{m_1}$,

For Young's modulus $S_E = \frac{E_2}{E_1}$.

One may for convenience denote subscript 1 as for 3D printed blade and subscript for steel blade. In the present case, length L, area of cross section of blade and 3D printed part A, are the same and therefore scale factors become equal to 1. E and density are different in original steel and 3D printed part. But m= Density x volume= Density x L x area. Area and L are same in both cases. So, $S_m = \frac{Rho_2}{Rho_1}$.

Therefore, Scale factor for frequencies, $S_{f1} = \frac{1}{(S_L)^2}\sqrt{\frac{S_E}{\mathrm{Sm}}}$.

Applying this formula with the values of S_E = 0.486E9/2.0E9, $S_{rho=}$ =934 / 8100, one gets $S_{f1} = f2\,/f1 = \frac{1}{(1)^2}\sqrt{\frac{S_E}{\mathrm{Sm}}}$ = 930, Therefore, in the steel blade the first mode frequency is 930 Hz.

4. Conclusion

The study demonstrates that 3D-printed turbine blades may be used for initial vibration testing, providing a quick and affordable prototype method for design validation. The experimental findings show that although 3D-printed blades made of plastic have different dynamic properties than steel blades, the behavior of real turbine components may be predicted with the use of suitable correction factors and techniques. The results highlight how crucial it is to take scale effects, boundary conditions, and material attributes into account when interpreting test results. Vibration tests on a model 3D printed blade is tested for natural frequencies in its fixed condition as obtaining in practice using sophisticated instrumentation after taking some precautions. In view of increasing popularity of 3D printing technologies more such tests can be undertaken for various kinds of machine components. The following experimental results are achieved from the natural frequencies for different lengths of blades under 4 modes; blade length is 100 mm at the natural frequency of the blade is at 1315 (mode 1), 2959 (mode 2), 4704 (mode 3) and 7225 (mode 4). The blade is 117 mm at the natural frequency of the blade is at 973 (mode 1), 2250 (mode 2), 4050 (mode 3) and 5535 (mode 4). The blade is 130 mm at the natural frequency of the blade is at 798 (mode 1), 1855 (mode 2), 3678 (mode 3) and 4633 (mode 4) [24, 25]. For improved vibration analysis accuracy, future research should concentrate on improving prediction models and expanding 3D printing applications to metal-based turbine blades.

Abbreviations

AM	Additive Manufacturing
SLS	Selective Laser Sintering
FEA	Finite Element Analysis
RP	Rapid Prototyping
FRF	Frequency Response Function

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Author Contributions

Buschaiah Karolla: Conceptualization, Investigation, Software, Supervision, Validation, Writing – review & editing

Mudda Nirish: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Writing – original draft, Writing – review & editing

Reag Rajendra: Conceptualization, Data curation, Investigation, Supervision, Validation, Visualization, Writing – review & editing

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Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Appendix I: Graphical Abstract

1. 3D Printing Process: An illustration showing the transition from plastic/metal powder to a 3D-printed turbine blade.
2. Vibration Testing Setup: A schematic of a test rig where the 3D-printed turbine blade is undergoing vibration analysis.
3. Comparison with Steel Blade: A diagram indicating the correlation between test results of the 3D-printed blade and predictions for actual steel blades.

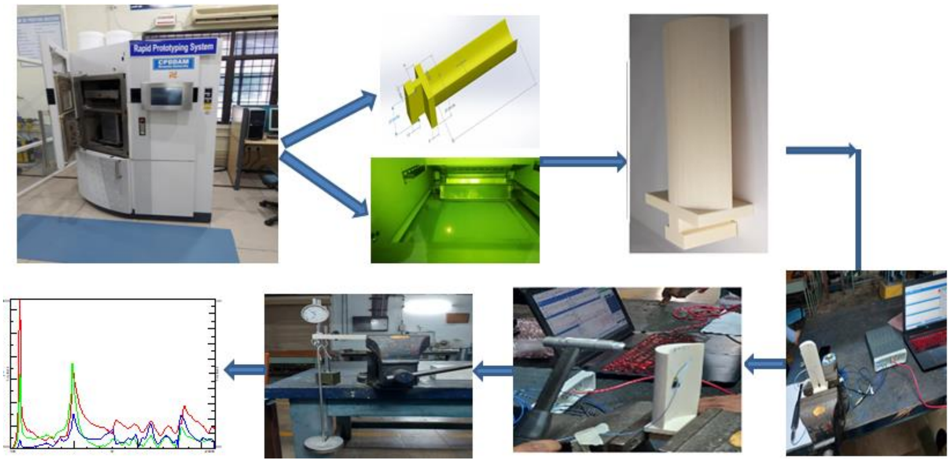

Figure 7. *3D Printing Process.*

Appendix II: Highlights

1. Specialized Testing: Discusses the complexities of component testing, including instrumentation, test rigs, and result interpretation.
2. Turbine Blade Testing: Highlights the long-established practice of vibration testing for turbine blades made of super alloys like Nimonic.
3. Advancement in 3D Printing: Explores the evolution of additive manufacturing from plastic powders and filaments to metal powders in the last 5-8 years.
4. Application of 3D-Printed Blades: Examines the use of 3D-printed turbine blades for wind tunnel and vibration tests.
5. Experimental Investigation: Presents vibration test results of a 3D-printed gas turbine blade.
6. Correlation with Steel Blades: Discusses methods to predict actual steel blade parameters from 3D-printed blade test results.
7. Precautionary Measures: Highlights necessary precautions when conducting vibration tests on 3D-printed blades.

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