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ScienceDirect

Procedia CIRP 119 (2023) 570–575

www.elsevier.com/locate/procedia

33rd CIRP Design Conference

Potential of additively manufactured particle damped compressor blades: A literature review

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Abstract

The high-cycle fatigue of compressors significantly impacts the lifetime of aircraft engines. Excitations in resonance lead to early blade fractures; therefore, vibration reduction measures for blades must be taken. Additively manufactured particle dampers are a suitable measure to suppress vibrations. The focus of this paper is to analyze the applications of additively manufactured particle dampers in compressor blades through a literature review. The design requirements, previous vibration reduction measures for compressor blades and properties of additively manufactured particle dampers are investigated in three studies. In order to evaluate the application of additively manufactured particle dampers in compressor blades, the findings are compared and research demand is derived. The main requirements on compressor blades are stiffness, vibration reduction and wear-resistance. Recent vibration reduction measures are focused on friction dampers. To optimize damping multiple vibration suppression measures shall be used. Few studies exist for additively manufactured particle dampers and some prove their damping improvement in compressor blades. Due to the complicated operation conditions, further studies are needed, which are listed to give researchers an approach for further steps.

Keywords: powder bed fusion of metals using a laser beam (PBF-LB/M), particle damping, Design for additive manufacturing (DfAM), compressor blade, aircraft engine

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1. Introduction

Vibration reduction in compressor blades has employed researchers and developers since the 1950s [1]. Due to the blades' high dynamic loading, vibration can lead to high-cycle fatigue, which is often the cause of engine failure [2]. The compressor development goes towards higher velocities, pressure ratios and larger engines, resulting in even more significant blade loadings [3]. In addition, the requirements for the lifetime and security of modern aircraft engines are continuously rising. Therefore, many researchers are still working to find better solutions for blade vibration minimization [4–6]. The excitation spectrum is vast and the avoidance of resonances is impossible [7]. Thus, new damping concepts are needed to design that offer high damping over a wide range.

Additive manufacturing offers new design freedoms for producing components with inner effects [8–10]. The layer-by-layer coating of powder and selective melting in the powder bed fusion of metals using a laser beam (PBF-LB/M) enables the integration of internal cavities filled with unfused powder particles. When the metal powder is retained in the component, a so-called particle damping effect appears due to energy dissipation caused by friction and impact between powder particles themselves and the cavity wall, which can reduce vibrations significantly [11, 12]. In the literature, few studies exist to design guidelines for additively manufactured particle dampers. Some works characterize the effect in components. However, less information is given regarding its design and application in compressor blades. Therefore, this paper hypothesizes that many research questions are still open and need to be answered to enable a new compressor blade design

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10.1016/j.procir.2023.02.151

filled with additively manufactured particle dampers.

This paper aims to determine the application potential, gather the research questions and derive further demand for studies from developing a new innovative compressor blade design for additive manufacturing. The work will be done by a literature review described in section 2. First, requirements on the design for additively manufactured particle dampers in compressor blades are analyzed in section 3.1. Then, previously used vibration reduction measures are summarized in section 3.2. After that, relevant properties and design guidelines of additively manufactured particle dampers are presented in section 3.3. Finally, the potential evaluation of additively manufactured particle dampers in compressor blades, as well as the research demand with open questions for the application of a new design, is described in section 4 to enable to set distinguish focus on the most important lack of knowledge for further studies. The paper ends up with a conclusion about the achieved results.

2. Methodology for this study

The main objective of this study is to determine the application possibilities of additively manufactured particle dampers in compressor blades, which is a complicated topic and difficult to answer in a single step. Therefore, this objective is subdivided into three subgoals according to the basic principle of problem decomposition [13]. First, the design requirements on a compressor blade are defined to get the specifications for integrating particle dampers. Second, previous vibration suppression measures are reviewed to find a potential application gap for particle dampers. Third, the properties of additively manufactured particle dampers relevant to the specifications are summarized. In order to solve these subgoals, literature reviews are performed. Finally, combining the findings results in an evaluation of additively manufactured particle damped compressor blades and derives open research demand from answering the primary goal.

Several methods for conducting a literature review are present in the literature [14–16]. For this paper, the process steps from Templier and Paré [15] are used basically and extended by a discussion and reporting procedure from [14, 16]. The quality assessment is excluded in this study because only peer-reviewed articles are considered and assumed as qualitatively equal. The process is conducted stepwise and iterative. In the first step, the purpose and research questions of the literature review are formulated. In step 2, relevant data are collected by a search through the literature over the platform Scopus® of Elsevier B.V. Here, a search strategy and procedure are defined and restrictions to the search are set in the sections below. The search procedure is conducted over keyword or backward references search. After that, the identified articles are screened by an inclusion criterion to select relevant studies to the three topics in step 3. The information to answer the research questions is gathered from the studies in step 4 and aggregated to receive a new contribution to knowledge in step 5. The findings are discussed and reported in this paper in the last step.

3. Literature review

3.1. Requirements on compressor blades

This section aims to gather all relevant requirements on compressor blades that impact the design of additively manufactured particle dampers. Therefore, previous vibration studies are reviewed. The search is performed as a keyword search in the title, abstract and keywords section of articles by the query:

TITLE-ABS-KEY ("aerofoil" OR "airfoil" OR "compressor blade" OR "turbine blade") AND TITLE-ABS-KEY ("modal analysis" OR "vibration characteris*") ANDNOT TITLE-ABS-KEY ("wind" OR "gas" OR "steam" OR "water" OR "tidal").

In order to limit the search, open-access and English-written articles are only included. With this, 48 documents were found and screened with the inclusion criterion to get information about tests, vibration characteristics and assumptions for loads of compressor blades.

The primary function of a compressor blade is to convert kinetic energy supplied by the rotational speed of the rotor into the energy of gas by increasing its pressure [3]. The blades are exposed to static and dynamic loads in a low-temperature, corrosive environment [17]. Furthermore, blade rubbing and erosion can occur [18].

The main static loads are caused by the centrifugal force due to rotation and the stationary air pressure distribution in the flow surrounding the blade, which occurs due to the flow deflection in the radial direction [19]. The blade's centrifugal force depends on the rotational speed of the rotor, which is maximum while take-off with about 9561 min^{-1} [3]. Therefore, due to the centrifugal force, constant tensile stress occurs in the blade [18]. Furthermore, the superimposed aerodynamic and centrifugal forces result in maximum stresses in the edge and middle of the blade root [20], which can cause cracks and low-cycle fatigue [17]. Nevertheless, static stresses alone are relatively low compared to the yield and fatigue strength of the material [18].

Dynamic loads appear from many sources in a compressor blade and cause vibrations. The primary excitation results from aerodynamic forces when the inlet air collides with the blade [18]. In addition, the flow can introduce excitation via irregularities and local pressure gradients [19], such as wakes [7]. The blade-disk connection can also introduce forces in the blade, for example, via eccentricities [21] or vibrations from adjacent components [21]. Due to excitations, compressor blades are exposed to oscillating bending and torsional loads [18], which can result in high stresses at the leading edge, the rear edge [3] or in the middle of the blade root [18]. These stresses may lead to rapid crack initiation [18] and high-cycle fatigue. Typical crack sizes range from 40 microns to several centimetres [7]. In order to optimize a compressor blade regarding stresses and high-cycle fatigue, mass, stiffness and damping can be adapted. The vibration characteristics of a blade are determined by the natural frequency, mode shape and damping, which significantly affect the blade's lifetime [22]. The natural frequency ranges for the first mode from 380 [23] to 2360 Hz [7], depending on the used geometry. For up to the sixth mode, the natural frequency can increase up to 13,000 Hz

[7]. The natural frequency of the blade varies over centrifugal force and airflow pressure. The rotational speed leads to higher bending stiffness due to tensile stresses [3, 24], so natural frequency increases depending on the temperature and mode shape by 1.7 to 21 % [24]. Contrarily, the airflow pressure causes bending and reduces natural frequencies for bending modes while increasing natural frequencies for torsional modes [3]. The first mode shape is described as a bending mode (see Fig. 1), typically followed by a torsional mode [3]. Then, mixed mode shapes from bending and torsion occur [3]. The bending mode results in maximum stress in the blade root above the locking ground, while the torsional mode causes maximum stress in the middle of the airfoil section [24].

Wear occurs in an aircraft engine due to erosion and blade rubbing. A compressor can suck hard particles, e.g. sand, that cause abrasive wear at the blade's surface [21]. As a result, geometry deviation can occur [7] that changes natural frequencies and results in rapid growth stresses [7], crack generation [18] and premature failure [21]. The casing of a compressor can be deformed due to external loads and blades can rub at its inner surface [19]. The gap between the casing and blade increases, resulting in changed flow conditions and mechanical overload of the blade up to fracture [19].

A compressor blade's weight directly impacts aviation's fuel consumption [25]. Therefore, in order to increase efficiency, weight reduction is a current area of research [26].

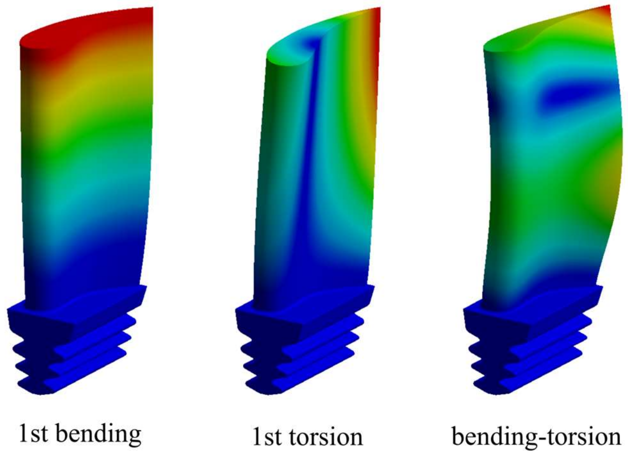

Fig. 1. Vibration modes for a compressor blade, in colour the vibration amplitudes, according to [19].

3.2. Measures for passive vibration suppression

The research on better vibration suppression measures for aero-engine components is ongoing because blades have a small amount of material damping with about 0.02 % and the aerodynamic damping of approx. 0.3 % is also relatively low for sufficient vibration reduction [27]. Therefore, passive vibration suppression measures have received much attention due to the absence of external power [28–30]. In this section, passive vibration suppression measures in compressor blades are reviewed to identify an open application gap for additively manufactured particle dampers. A keyword search with the following query is conducted:

TITLE-ABS-KEY("damp*") AND TITLE-ABS-KEY("compressor blade*" OR "turbine blade" OR "airfoil" OR "aerofoil") ANDNOT TITLE-ABS-KEY("tidal" OR "wind" OR "gas" OR "steam" OR "water").

To limit the search, only English-written and open-access articles are included. With this, 138 articles were found and screened via the inclusion criterion to thematize a vibration suppression measure. Excluded are all articles which only simulate aerodynamic damping.

The passive measures tuning, vibration absorber and damping are applied in compressor blades. Tuning is an approach to shift natural frequencies out of the critical excitation range by adjusting the blade's geometry [21]. However, due to the extensive possible frequency range, resonances are unavoidable and conflicts can be generated between tuning and optimal aerodynamic design. Tuned vibration absorbers are typically used to minimize flutter instabilities [31]. They consist of a small mass attached to a blade via a spring and damper system. The stiffness and mass of the additional elements are tuned so that their resonance meets the excitation frequency [31]. A tuned vibration absorber can reduce the vibration amplitude by a factor of 0.3 to 1.5 [31]. Nevertheless, they can only minimize one resonance and the effect depends on the blade's position [31].

Damping in compressor blades can be increased by friction damping, which is widely used in the aero-engine sector [32]. Friction damping dissipates energy in the form of heat by using the relative motion of contact interfaces [33]. In Fig. 2, some of the most typical damping measures are listed. The friction dampers can be integrated into the blade design by shrouds, blade connections or blade roots. Using multiple friction contact elements improves the overall damping [6]. In addition, friction dampers increase stiffness and damping [33], are economical [33], have a simple structure and are insensitive to temperature variation [29]. Nevertheless, the gained friction effect depends significantly on the contacts' normal force and gap size, which can vary over the operation [5]. In addition, friction dampers can only efficiently minimize vibrations tangential to the contact surfaces [28].

A friction damper can be integrated when the blade has a shroud on the tip to optimize airflow and stability. Adjacent blades can cause friction in contact at the shroud side faces and result in damping. However, the impact is dependent on the variable blade height due to several centrifugal forces [5], angle of contact surfaces [33], excitation force and mode shape while vibration [5]. Another possible design is to create a friction contact surface of adjacent blades at the height of the flow. Pesek et al. [34] found that the vibration amplitude can be reduced and all blades maintained their single mode shapes. The connection between the blade root and the disk is another design which results in friction while vibration and deformation of the blade root [35]. It reduces the vibration amplitude of blades [36], but is very sensitive to small gaps between tenon and mortise [6]. Under-platform dampers are widely used in aero-engine blades [30]. An under-platform damper utilizes an additional element located under the platforms of two adjacent blades, which generates contact surfaces and friction [29]. One possible concept of an under-platform damper consists of a solid metallic damper placed under the platform, frictionless mounted on an elastic beam attached to the disk [4, 28]. When the engine shaft rotates, the centrifugal force elongates the elastic beam and presses the damper under the platform [29]. So, the damper can vibrate with radial motions and stay in contact with the platform [29]. Other concepts exist which leave out the elastic beam and utilize positive locking. Typical shapes of these dampers are wedges [37], cylinders [38] or prisms [23]. The centrifugal force during rotation fits the damper into a cavity under the platform [37]. Here, an elastic constraint between two adjacent blades is generated, which can negatively influence the natural frequencies [23]. Another design comprises a thin, flexible metallic strip attached to the platform [28]. The elasticity of the strip causes deformation at the contact and increases the relative displacement [28]. Under-platform dampers are insensitive to mass, stiffness and excitation amplitude [4]. Nevertheless, the damping characteristics depend on the rotational speed [4] and the normal pressure, which mainly affects the stick or slip state [29].

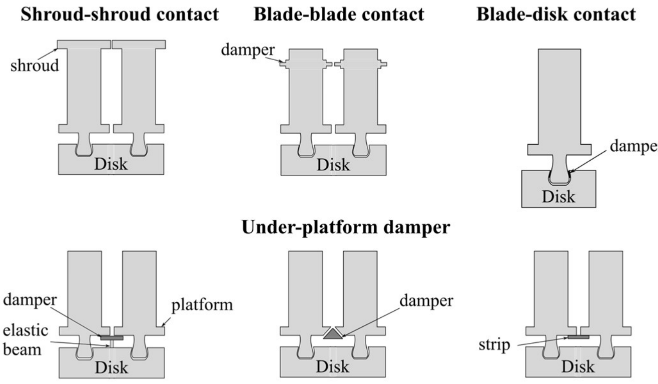

Fig. 2. Summary of the passive vibration suppression measures.

3.3. Additively manufactured particle damped compressor blades

In this section, all relevant properties and design guidelines of additively manufactured particle dampers for the specifications on compressor blades are gathered to evaluate the potential. Therefore, a search is conducted by a keyword search and then a backward references search is performed to find additional articles. The search query is:

TITLE-ABS-KEY ("additive manufactur*" OR "additively manufactur*") AND TITLE-ABS-KEY ("damp*").

To limit the search, only English-written and open-access articles are considered. The search resulted in 103 articles which were then screened by an inclusion criterion to report results for particle damping. Finally, the references in the paper are viewed to expand the search.

Particle damping is a very effective measure to minimize vibrations. It can be applied in components with less space and local vibration modes and enables the optimization of mass, stiffness and damping [12]. The advantages of particle dampers are their simple structure, low-cost design [39], good utility in harsh and cold environments [40], wear-resistance [39] and reduced weight due to their low packing density [12]. The damping reaches factors of 20 [12] in a wide frequency range of about 500 to 30,000 Hz and up to higher order mode shapes, tested up to the 9th bending mode [41], which leads to an improved component lifetime [41]. The effect of particle damping is nonlinear and influenced by various parameters such as cavity length, width and height [42, 43], natural frequency and mode shape, as well as packing density [44] and excitation force [42, 43]. Particle dampers should be applied where maximum displacement or kinetic energy occurs [45]. For bending mode shapes, it is beneficial to integrate the particle dampers in the neutral fibre to minimize their effect on component stiffness [46]. In addition, few large cavities are beneficial compared to several partitioned cavities [44]. Larger cavity volumes lead to increased damping and packing density [12], with saturation occurring at cavity volumes of 5 % and 1 % damping [44]. Cylindrical cavities lead to more broadband damping than cuboidal shapes [47]. The minimum cross-section of particle dampers is 2x2 mm² [12]. The optimum packing density for particle dampers lies at about 45 % [45], while the PBF-LB/M process results in values of approx. 50 to 60 % [48]. The damping increases when the dimension in the excitation direction is smaller than perpendicular to this [44]. However, the ratio of cavity height to cavity width must not increase by 4 due to direction-dependent damping [44]. In the direction of gravity, cavities shall not be too large because gravitation leads to the reduced motion of particles in lower layers [45, 49]. Particle damping is force and frequency dependent. A low excitation limit must be overcome to release particles from friction and to cause interaction [49], while an upper excitation limit exists because, for a certain magnitude, the particles act like a single mass [12]. The cavities of particle dampers have a negligible influence on the structure damping but change the natural frequencies of a component [12] due to changes in stiffness and mass. For particle dampers, additive manufacturing restrictions have to be considered, such as minimum down-skin angle [12] or support structures [9]. One possibility to meet the manufacturing restrictions is the implementation of lattice structures which additionally increase the mechanical properties and lead to higher fatigue life [26]. Lattice structures shift natural frequencies, e.g. by 5.29 % [26], save mass [26] and reduce costs [50].

Goldin et al. [51] experimentally investigated an additively manufactured particle damped compressor blade under shaker tests. They achieved a vibration amplitude reduction of up to 83 % compared to a fully-fused blade for a relative cavity volume of 1 %. In addition, they found less filled cavities dependent on the used cavity size, complexity and build direction [51]. CT scans and X-ray images were performed before and after the test, which indicates powder structure change and some fused powder caused by heat generation [51]. Moneta et al. [52] proposed a new design for an uncooled turbine blade with a grid of cavities filled with powder, pins and lattice bars, as shown in Fig. 3. Particle damping is superimposed with pins that vibrate independently and bars that transfer vibrations through the structure [52]. They experimentally compared the new design with a baseline design by an impulse test. They found that the natural frequency shift ranges from 4.4 to 7.9 %, and the damping ratio increases by a factor between 20 and 83 [52].

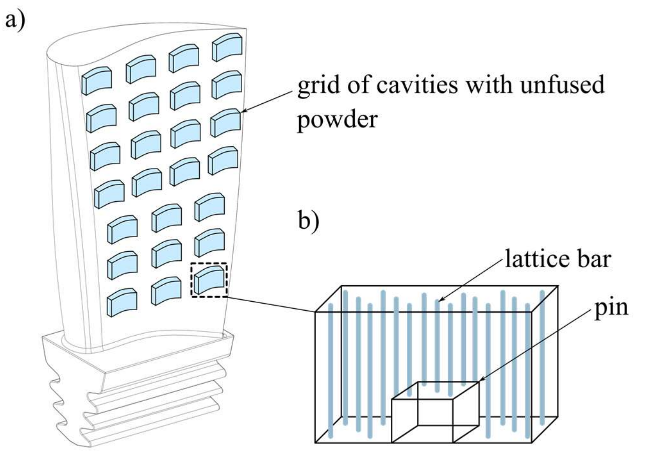

Fig. 3. Design of a) a grid of cavities for particle dampers and b) lattice bars and pins in the cavities for an uncooled turbine blade according to [52].

4. Potential evaluation of additively manufactured particle damped compressor blades and research demand

In the following, the application possibilities of additively manufactured particle dampers are evaluated through the combination of the findings of previous sections. In addition, open research demand is derived from the results.

As the requirements on compressor blades show, they work in a low-temperature, corrosive environment where particle dampers can be applied due to their resistance to these conditions. The loads on a blade result from superimposed static and dynamic loads for which particle dampers have not yet been investigated. Centrifugal forces and static pressures influence the natural frequencies and the particle damping effect, but up to date, mainly bending loads were characterized. The dynamic loads lead to bending and torsion in a frequency range where particle damping significantly reduces vibration. However, the superimposed static and dynamic loads with the high rotational speed in a compressor blade were still not investigated for additively manufactured particle dampers. In addition, erosion and blade rubbing occurs, which can cause wear on the blade surface. The particles also rub on the inner walls of the particle damper, which can lead to further wear and wall thickness loss. The wear is a critical factor for applying particle dampers in compressor blades because releasing cavities and unfused powder can appear, so further studies on the lifetime and wear of particle dampers are needed. Compressor blades aim to reduce weight, which can be addressed via particle dampers and lattice structures. Previous vibration suppression measures are focussed mainly on friction damping via external elements to the blade. This results in the risk of loss in the connection between these elements while particle dampers are included in the blade. In order to optimize damping, multiple vibration suppression measures, for example, under-platform and particle damper, can be applied in a compressor blade. Tuning and vibration absorbers can be realized with additive manufacturing by several inner lattice structures to shift natural frequencies and increase damping.

In order to determine the total value of additively manufactured particle dampers in compressor blades, several studies need to be conducted. The identified research demands are summarized in Table 1. Recently, no design rules for particle dampers in compressor blades exist. So further studies can be addressed to find an optimal design for the cavities and inserted lattice structures. The geometry and position of the cavities can be investigated. This study reveals that cylindrical cavities should be integrated on the blade tip and near the neutral fibre because the deflection is at maximum. The blade's wear needs to be quantified, and a threshold for the minimum distance of cavities to the blade surface has to be given. Further studies should characterize the particle damping effect to make it usable for application in compressor blades. The loadings torsion, tensile and compression are less studied and need to be quantified in the future. The influence of particle rubbing at the inner walls on initiating cracks and surface roughness can be characterized. The impact of different lattice structures in particle dampers still needs to be investigated. In addition, heat treatments, for example, for improved surface hardness and its effect on the particle damper and blade wear, can be conducted. In order to quantify the effect of particle damping in the superimposed loading of a compressor blade, a new test bench has to be designed and built. A similar clamping as in a compressor disk and loadings consisting of centrifugal, compression forces, and excitation must be considered. The erosion should be investigated over several magnitudes. In addition, full-scale durability tests in a compressor close to application conditions lead to better information.

Table 1: Summary of identified research demands

Research demand
Design rules for particle dampers in compressor blades
Characterization of the particle damping effect on torsional, tensile and compression loadings
Influence of particle rubbing at the cavity walls on crack initiation and surface roughness
Impact of lattice structures in particle dampers
Heat treatments of particle dampers
Development and construction of a test bench for particle damped compressor blades
Influence of erosion on particle damped compressor blades
Full-scale durability tests of particle dampers in a compressor

5. Conclusion

In this paper, the application possibilities for a new design of additively manufactured particle damped compressor blades are evaluated by a literature review. First, a requirements analysis determined that compressor blades are under superimposed static and dynamic loads, corrosive and wear environments. Second, recent vibration suppression measures are focussed on friction dampers with external elements. By a combination of several damping measures, vibration reduction could be increased. Additively manufactured particle dampers can be applied in low-temperature and corrosive environments and offer a damping of a factor of 20 in the typical frequency range of compressor blades, as well as weight reduction. However, there needs to be knowledge of the design of additively manufactured particle dampers regarding the superimposed static and dynamic loads of compressor blades, so the potential cannot be evaluated thoroughly. Therefore, the application conditions of compressor blades need further investigation for the design for additive manufacturing of particle dampers. In this study, the most important research demand is derived and listed to give researchers an approach for further steps to develop a new design for compressor blades.

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