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Pulsed laser ablation as a tool for in-situ balancing of rotating parts

M. Stoesslein, D.A. Axinte*, A. Bilbao Guillerna

Rolls-Royce UTC in Manufacturing and On-Wing Technology, Faculty of Engineering, University of Nottingham, UK

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ABSTRACT

The balancing of complex rotating systems is a challenging task as it may require repetitive (dis)assembly to enable mass adjustments; thus, developing methods for in-situ dynamic balancing of rotatives is regarded as a key technology enabler. In this context laser balancing with its high flexibility in adjusting its firing frequency (to match that of the rotating part) and pulse energy (to vary the material removal) could offer significant advantages from both precision and cost point of view.

In this paper, a laser balancing system is developed to continuously remove material from a target part in a controlled and automated manner. The amount of material ablated can be controlled by an influence coefficient, which is related to the change in vibration amplitude for a predefined amount of pulses at a given operational balancing speed, material, and geometry of the rotative part. The proposed system features a three-layered case-driven programmatic approach to optimize single-plane balancing process duration in a fully automated system. This enables the use of prioritization to avoid misfire and therefore, structural damage to the targeted part. Furthermore, the application allows the component to be balanced to all common balancing grades as specified in the ISO 1940/1 standard. Thus, validation trials involved balancing an Inconel 718 rotative to a preliminarily specified balancing grade by extracting the acceleration signals using an IIR peak filter. A computer simulation encompassing the rotor bearing state space system, a model of the laser and the adapted peak detection algorithm, has been developed and used to validate the trials conducted. Henceforth, a maximum deviation from the desired correction position of less than 1 mm has been recorded. Moreover, it has been shown that the detection and correction of imbalances can be reliably achieved by reducing the vibration level of a rotor from G 22.5 to G 19.5.

1. Introduction

Balancing has become an essential part of many manufacturing and maintenance processes in the power turbine, defence, automobile and airplane industry; it contributes to the increase of the life cycle and reliability of rotary components, while also decreasing wear and the overall noise level of the system [1]. Negligence to balance rotatives can lead to malfunctioning, that is the common failure modes being bending of the shaft, fatigue and failure in the bearing of the rotative. Balancing is a standard process in many industries, especially in those related with high-speed applications. Nevertheless, this relies on strict procedures that usually end-up in extensive idle times. Usually a balancing machine first determines the position and the mass of the imbalance. Then the imbalance is either removed in a separate step using removal techniques, or it can be counterbalanced by the addition of mass opposite to the angular location of the imbalance. Of particular difficulty is the addition and removal of small masses, which is a commonly required for fine balancing and is time consuming as it requires manual interaction.

During the last decades the challenges have become ever more complex requiring balancing components/assemblies without disruption to the setups and henceforth, there is a need for in-situ balancing machines capable of detecting imbalances in the magnitude of *G 0.4*. Those advances can mainly be attributed towards the rapid digitalization of machines. In 1974 Schenk pioneered the first computer controlled balancing machine. Consequently, in the early 80 s the first micro-processor based balancing machine revolutionized the market enabling the easy balancing of dynamic unbalances [2].

Engine industries require the balancing of whole assemblies, thus, challenging existing strategies. Hence, there is a need to provide balancing processes capable of both operating with little space for machining equipment and creating no waste, which can damage adjacent components in the assembly during the material removal process [3]. The topic of in-situ balancing has been the area of active research over the past years, especially in

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* Corresponding author.
E-mail address: dragos.axinte@nottingham.ac.uk (D.A. Axinte).

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Nomenclature

Variable	*Description*
m	Mass of the rig (kg)
m_u	Mass of the imbalance (kg)
n_p	Number of laser pulse (-)
m_l	Mass removal per pulse ($\mathrm{kg/n_p}$)
L	Length of the shaft (m)
Z_1	Distance from the ball bearing 1 to the axial position of the imbalance (m)
r	Radius of the imbalance (m)
φ	Radial position of the imbalance (°)
ω	Angular velocity of the rotor (rad/s)
t	Time of the simulation (s)
t_d	Time delay between triggering a pulse and the laser firing (s)
$k_{ixx},\ k_{ixy},\ k_{iyx},\ k_{iyy}$	Bearing i stiffness coefficient in the x-y plane (-)
$c_{ixx},\ c_{ixy},\ c_{iyx},\ c_{iyy}$	Bearing i damping coefficient in the x-y plane (-)
i	1, 2 (-)
k_t	Threshold amplitude for peak identification (-)
$k_{w\ min}$	Minimum period width (rad)
$k_{w\ measured}$	Measured period width (rad)
θ	Position of rotor (rad)
k_1	Constant for signal threshold (-)
k_2	Constant for minimum period width (-)
k_3	Calibration Constant ($\mathrm{m/s^2/n_p}$)
e_{per}	Permissible specific unbalance (-)

regards of Active Magnetic Bearing (AMB) balancing [4]. In particular, the adaptive open loop method introduced by C. R. Knospe et al. [5] showed promising resulting in nearly completely eliminating the rotor midspan vibration within the operating speed ranges. Furthermore, AMB has been used to identify fault conditions in turbomachinery online [6]; this concept has been taken further in designing spindles with AMB embedded in the system [7]. Although AMB offers a method of achieving in-situ balancing online, it requires re-design of the systems to be implemented into (which could be challenging/troublesome for existing installations) [8]. Another method for balancing consists of controlling the current into the windings of an asymmetric spindle motor [9]; however, such methods are possible only if there is access to the controller, which in many cases is not feasible.

In this respect, NASA [10] has come up with a novel approach: spray automated balancing; this is a solution to control material deposition onto a rotating component and therefore, avoid damage to other parts of the assembly due to waste material. Nevertheless, spraying especially needs to ensure high bond strength and appropriate surface finish. However, due to the size of the spraying gun this method is likely to be unsuitable for in-situ balancing where access to balancing areas is restricted due to space being the limiting factor.

A concept that can overcome those issues is laser balancing. The conceptualised idea to use lasers as a removal method for balancing purposes was first discussed in the 60 s [11]. The one of the advantages of using Pulsed Laser Ablation (PLA) is that the laser allows material removal (i.e. balancing) at high rotational speeds with the limiting factor being their pulse duration; i.e. high pulse durations leads to a low fluence, defined as energy per area, on the component and, therefore, little or no material removal. Furthermore, fibre lasers, which can be bent by up to 90°, can be implemented in systems with very little space and, therefore, employed in highly complex systems for in-situ balancing. However, most importantly, when applied correctly the pulsed laser ablation can vaporize material locally; hence, it can access the imbalances of targeted parts without causing damage to nearby components of the assembly [12]. Research has shown that ablation on a range of metallic materials can be conducted with minimal/no thermal alteration of metallurgical properties of the workpiece target material [13] by operating below the damage threshold [14].

Although the idea of pulsed laser ablation balancing for gyroscopic assemblies and small turbines has been commented by industrial technical briefs, there is no scientific article to explain in-depth the working principles, challenges, and the associated systems to enable the implementation of such approach for balancing larger rotating assemblies. This is needed for enabling larger material removal (i.e. surfaces) and not “punctual” balancing as utilized for small rotating parts. This is a very limiting factor especially when large structures need significant volume of material to be removed in particular zones where they will not impart the service performance (e.g. aero engine, power turbines).

The idea of utilizing pulsed lasers for balancing purposes is driven by the need to minimize the balancing operational time, while also achieving low level of imbalance. In [11] Schultz proposes a setup using a triggering signal from a measuring sensor (e.g. accelerometer) to fire the laser in a particular angular position of the rotating part. Furthermore, this setup includes a system to compensate for the delays in firing (a Q-switched) laser by 0.7 ms to counteract for the pulse build up. However, due to the low power output of the laser available and long pulse duration in the ms regime, which does not allow for point ablation at high balancing speeds, Schultz [11] concluded that a laser balancing system would not be economically viable. Furthermore, the reported system was unable to determine the position of the imbalance without interaction of a user, which involved manual calculations of the imbalance position and mass.

A NASA report [15] discussed a method for two-plane balancing of a flexible rotor to reduce operation time and fully automate the process. The paper suggests the use of predefined balancing holes, which would allow the laser to be inserted into the assembly to balance whenever needed without the need to disassemble the system. This could imply that the method has “pre-defined” positions to fire the laser and, therefore, could not be considered a fully flexible approach to perform this task on different part geometries/surfaces without preliminary investigations. Furthermore, this report fails to discuss the controls and methods required for this approach to work.

However, in the early 90 s another attempt on laser balancing, this time with a more material focused view, was reported. This [16] describes a pilot system designed to balance gas turbine engines and features a high power Nd:YAG laser capable of delivering up 50 Joules per 1 ms pulse. The experimental system was capable of automatic balancing, however, the operator was required to select a calibration file for the balancing to work. Although this is by far the most advanced laser balancing system mentioned in literature, the paper fails to describe the mechatronics and control strategies utilized; so, it could hardly be a base for further advancements in the field. Additionally, the implemented controls only account for point ablation, a process at which the laser pulses at the exact location of the imbalance effectively drilling a hole to remove material, which can damage the structural integrity of complex geometry components and lead to reduced life time.

Therefore, although laser balancing could be an interesting academic problem with high applicative impact, up to now limited number academic papers have been reported in relation to this particular field.