Safety, health, and ergonomics of metalworkers engaged in manual grinding and finishing operations

Developing a prototype solution to reduce vibrations to their hands and arms

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The FORSAL (FOnderia Robotizzata per la SAlute dei Lavoratori [Foundry robotics for worker health]) project is part of the Veneto region's Smart Manufacturing framework, which makes use of the enabling technologies of micro/nano electronics (interactive robotic tooling management systems), advanced materials (high-performance light alloys for prototype production and custom-made tooling materials for the aforementioned processes), and advanced production systems (the introduction of robotic systems into foundries). Active ageing is the key driver for innovation here.

The project's key goals are to study inclusive and human-centred workspaces and organization, and to design innovative solutions for building machinery and equipment with safety, environmental protection, energy saving and efficiency in mind.

The FORSAL project (ID 10063706), which was approved by the Veneto Region in 2017 to support collaborative R&D activities for developing innovative sustainable technologies for new products and services (action 1.1.4), has successfully designed and prototyped a system that reduces the vibrations transmitted to operators by the grinders used for the finishing processes on foundry castings.

This article introduces the ergonomic issues related to grinding operations, and then focuses on the design and validation of a vibration reduction system that can also be used outside the foundry environment.

Fig. 1. Angle grinder used in foundries.

The material removing and finishing processes of foundry products involve specialized operators who use tools, such as angle and axial grinders, to manually perform quite complex movements to reach all areas of the metal parts to be finished. Since these operations cannot yet be delegated to traditional robots or to cobots (collaborative robots) due to the high levels of dexterity and dimensional precision required, and since no available exoskeletons fully meet the current efficiency and quality requirements, the FORSAL project focused on finding solutions to immediately improve working conditions, specifically in terms of safety, health and comfort. The project concentrated on the two main elements that cause operator fatigue: the vibrations and the weight of the instrument to be supported.

We analysed commercial grinders currently being used by the SAFAS Foundry. With the health of its workers at heart, SAFAS became a partner in the project to share its experience and facilities to support the analysis, design and validation of a vibration reduction system for commercial grinding and finishing tools.

A multi-thematic analysis (of the ergonomics, mechanical design, vibro-acoustic conditions, tool morphology and performance, tooling dimensions, and finished product quality requirements) was necessary to subsequently define the requirements for an innovative customized system for the specific tools. The materials, methodology and validation paths identified by the analysis can be applied to a wide range of grinding and finishing tools.

To objectively quantify the extent of vibrations transmitted to the operator's hand and arm during grinding operations, instrumentation from the University of Padua (UniPD) was utilized to take and process acceleration measurements for various types of tools used at the SAFAS foundry. The measurements revealed that the Fein type angle grinder, model MSfov852-1 (shown below), transmitted the greatest stresses to the operators. This grinder was therefore chosen as a test case for vibration reduction system.

Ergonomic study of the grinding and finishing process

To create the innovation and facilitate the operators' activities it was necessary to first study the ergonomics of the current situation and to identify objective criteria to measure the comfort of use so that these working conditions and, consequently, the quality of production could be improved.

BNP was the FORSAL project partner that studied the current situation in the steel foundry sector with specific reference to SAFAS with the purpose of identifying a starting point for developing a new solution as well as the requirements it had to meet.

The first task concerned behavioural observation and analysis in the field. In particular, BNP assessed the present state of grinding operations and identified the potential criticalities. Key aspects considered in the analysis were: correct posture, biomechanical risk, the different types of tool handles, their weights, and the length of time the operator had to maintain the positions.

Semi-structured interviews were conducted to obtain the operators' point of view and to focus on the key ergonomic design elements of the tools. Using videos, photos, pictures, and interviews, BNP also analysed body positioning as a function of the type of tool in use and its grip, as described in the table below. The same criteria were used to verify the improvements resulting from the prototype solution designed and created through this project.

Design of the vibration reduction system

A solution was designed using an integrated CAD (computer aided design) and CAE (computer aided engineering) system to attenuate the vibrations transmitted to an operator's hand and arm by the grinder shown in Fig. 1, which is used for surface finishing operations.

The design, developed synergically by all the FORSAL project partners, focused specifically on devising a vibration reduction system consisting of two fundamental elements: a front handle isolated from the grinder body by means of elastomeric anti-vibration mounts, and a device designed to partially decouple the grinder body from its rear handle, again using elastomeric anti-vibration mounts.

Body Position / Type of Tool	Tool Grip
Standing or linear / angular	Neutral / flexion
Leaning (supported) / linear	Neutral
Covering the tool / linear	Neutral / flexion
Covering the tool / angular	Neutral / extension
Inwards / linear	Neutral / flexion
Crouched / linear	Neutral / flexion
Crouched / angular	Neutral / flexion / extension
Force from above / linear	Neutral / flexion
Kneeling / linear	Neutral / flexion
Kneeling / angular	Neutral / extension / flexion

Table 1. Summary of machining postures and tool gripping modes.

Fig. 2. First prototype of the grinder with the vibration reduction system installed.

Fig. 3. FEM model of the grinder coupled to the vibration reduction system.

The geometry and a CAD model of the grinding machine were used to define the shape of the front handle, firstly identifying the potential coupling points between the tool and the new system. The anti-vibration mounts were inserted at these points. The mounts were selected by first identifying a general size using simplified dynamic models and then refining the choice through a numerical investigation based on the finite element model described below. A similar approach was taken to dimension the device that partially decouples the grinder's body from its rear handle. The end result was the prototype shown in Fig. 2.

The numerical study was based on a finite element model (Fig. 3) created to represent the grinder and the vibration reduction system coupled to it. The input data included the force values and acceleration fields obtained from experiments on the grinder during the machining phase and the forces produced by a suitably unbalanced disc-tool, as required by standard EN 60745-2-3:2011+A13:2015 for repeatable tests that reflect typical stress conditions.

The survey relied on three types of analysis:

- a static analysis to identify the stress and strain on the complete system;
- a modal analysis to identify the natural frequencies of the complete system and evaluate them with respect to the force frequencies; and finally
- a harmonic analysis of the amplitude of the vibrations induced on the front and rear handles of the device and then transmitted to the operator's hand and arm.

The results of the analyses (deformations, stresses, and accelerations) were subsequently processed to determine the body's mechanical resistance, its fatigue behaviour, and its efficiency in terms of ergonomic comfort.

Static Analysis

The static analysis was used to determine the stress and deformation on the components of the front and rear handles due to the weight of the grinder, as well as of the maximum force exerted by the operator during grinding activities (Fig. 4).

The static test enabled us to verify the adequate stiffness of the complete system for forces significantly higher than those proposed by the reference standard (45 N), up to a 'feed force' of 70 N verified by SAFAS during operations. Even at this level, the system continues to reduce vibrations by maintaining sufficient gaps between the vibration reduction system and the grinder so as to prevent direct contact between the surfaces of the components thereby attenuating the transmission of the vibrations.

Modal Analysis

The modal analysis was conducted to determine the modes of the system's vibrations (natural frequencies and modal shapes). To describe the human-machine interaction as accurately as possible, we defined the system's constraint conditions by simulating the operator's grip using lumped parameters (masses, springs, and dampers) to generate a representation of the operator's hand (Fig. 5), according to Annex B of standard EN 10068.

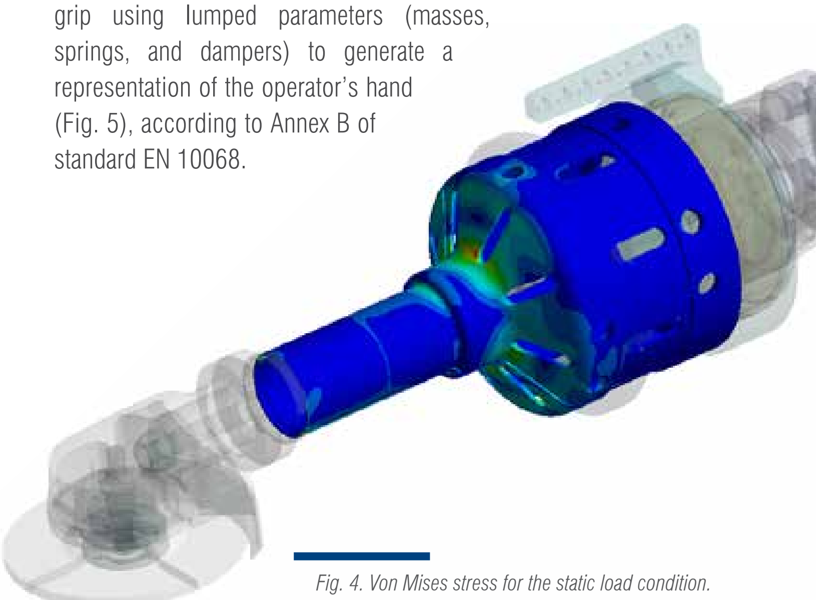

Fig. 4. Von Mises stress for the static load condition.

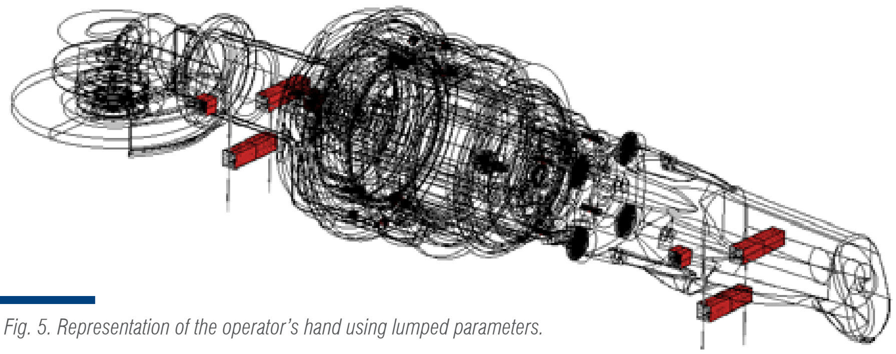

Fig. 5. Representation of the operator's hand using lumped parameters.

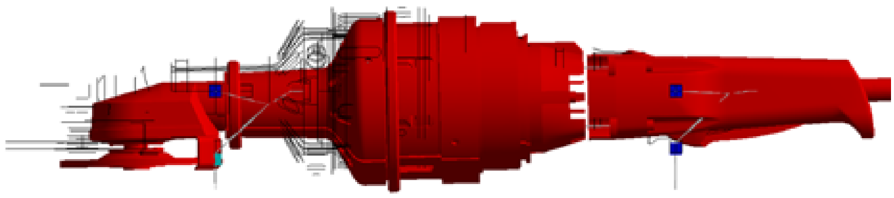

Fig. 6. Representation of the complete system's first vibration mode at a frequency of 1.51 Hz.

When used correctly, the representation of lumped parameters represents the frequency response of the hand in the different grip conditions.

Natural frequencies and modal shapes are the fundamental parameters for designing a structure and/or a component under dynamic load conditions. The minimum design objective required the complete system's natural frequencies to be sufficiently distant from the rotating tool's excitation frequencies to avoid excitations in the device's resonance.

To this end, the stiffness of off-the-shelf anti-vibration mounts was carefully selected, as well as the weight distribution in the front and rear handle components. For instance, Fig. 6 shows the first vibration mode of the complete system.

To effectively reduce the vibrations transmitted to the operator's hand and arm, however, the procedure for selecting the elastic parameters (attributable to the anti-vibration mounts) and the inertial parameters (attributable to the components added to the original grinder) had to be refined to obtain the lowest possible value in the frequency response modules (assuming as input the excitation force and as output the acceleration transmitted to the operators' hands) at the excitation frequency. The harmonic analyses described below enabled us to obtain this result.

Harmonic Analysis

Harmonic analyses are used to describe the behaviour of an object under dynamic load conditions. Resonances can often render critical the resistance of a component that was correctly sized for only static verifications. In the case studied, on the other hand, attention was placed on verifying the device's effectiveness in reducing the vibrations from the handles at the well-known and very slightly variable excitation frequency.

A comparative harmonic analysis was performed to evaluate the ability of the designed device to reduce the amplitude of vibrations transmitted to the handles. The results obtained from the numerical model of the original grinder were compared with the results obtained for the complete system including the vibration reduction devices. The amplitude of force used for the analyses was derived from the indications of standard EN 60745-2-3: for angle grinders with a 125 mm disc, the unbalance value is indicated as being 90 gmm. With the rotational speed of the disc at 8800 RPM, the amplitude of the harmonic excitation is 76.43 N.

These harmonic analyses enabled the absolute effectiveness of the vibration reduction system to be verified and also confirmed that, in conditions of maximum 'feed force', the amplitude of the vibrations is compatible with the residual gaps present between the grinder body and the attached vibration reduction system device.

Fatigue Analysis

Using the results obtained from the harmonic analyses, we reconstructed the time stress histories for the points of interest on the grinder body. These temporal histories were further broken down into histories of peaks and valleys that are useful for counting voltage cycles, for example through the rainflow method.

Noting the tension cycles (amplitude and repetitions) present in the time histories, we analysed the S / N curves to calculate the number of limit cycles and each of their contributions to wear and tear, which enabled us to evaluate the overall damage and relative fatigue life of the component. To calculate the latter, we evaluated the alternating Von Mises stresses acting on the anterior handle of the reduction system.

The fatigue analysis highlighted that the front handle is subject to low tension levels, both from the vibrations induced by the standard unbalance, and from the load of the operator's grip (70 N), which is cyclical in nature. In both cases, the amplitude of calculated voltage is below the fatigue limits prescribed by the Eurocode.

Experimental measurements

A first campaign of experimental measurements was conducted at the University of Padua's Department of Management and Engineering (Dipartimento di Tecnica e Gestione dei Sistemi Industriali). A grinder with a disc with an unbalance equal to that described in the standard was used. This made it possible to measure the vibrations transmitted to the grinder handles modified with the vibration reduction system (Fig. 7).

The results obtained showed dramatically different dynamic behaviour by the anti-vibration mounts, both in compression and in shear, from what was expected based

Vibration	Expected performance without the vibration reduction system	Expected performance with the vibration reduction system	Performance obtained with the vibration reduction system
Anterior Longitudinal	1.4 g	0.37 g	0.75 g
Rear Longitudinal	1.5 g	0.79 g	0.85 g
Anterior Transversal	4.2 g	0.81 g	1.1 g
Rear Transversal	3.3 g	0.27 g	0.12 g

Table 2. Average values of the amplitudes of vibrations on the front and rear handles of the grinder.

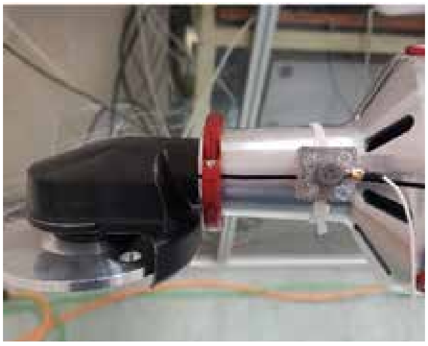

Fig. 7. Location of sensors placed on the handles of the modified grinder (front left and rear right).

on the technical documents provided by the suppliers. In particular, a viscoelastic behaviour emerged that is certainly dependent on the excitation frequency and the amplitude of the deformations. The relevance of the detected discrepancies has imposed a detailed analytical, numerical and experimental analysis which has allowed identifying equivalent stiffness values for the anti-vibration mounts, valid both for the grinder's usage range of frequencies and for the amplitudes of the expected deformations, which can properly describe the mounts altered dynamic behaviour.

Subsequent to appropriately recalibrating the numerical model, a second prototype of the newly modified grinder was created. This showed excellent performance and was also used in field tests in the foundry (see Fig. 8), achieving the results summarized in Table 2.

Conclusions

From an ergonomic point of view, it should be noted that after numerous operators had used the modified grinder for a period of time, they appreciated the reduction in the vibrations transmitted to their hands, while the system's ability to withstand static loads was also deemed adequate. Since the vibration reduction system significantly increases the weight of the grinder, it is intended to be used with a support system, to which operators have adapted easily overall. They have however highlighted critical issues that have led to its redesign by BNP.

Twenty-seven different processing tests were conducted using two distinct types of abrasive disc and placing the grinder in the various positions typically adopted: mainly horizontal or vertical (Fig. 8).

The prototype system that was designed and built satisfied the efficiency and quality requirements and improved working conditions in terms of safety, health, and comfort by eliminating the two main causes of operator fatigue: vibrations and weight to be supported.

The vibration reduction system and its support require further refinement before being industrialized and made available for a wide range of applications and for other application areas. It should be further noted that the grinder can also be connected to the mechanical interface of a collaborative robot by means of the special flange already present in the prototype to extend the benefits of its excellent vibration reduction ability to robotic systems, too.

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Fig. 8. Typical processing tests using the modified grinder.