Computer-aided engineering of centrifugal peening equipment

S A MEGUID, BSc(Eng), MSc(Eng), PhD and M S KLAIR, BSc(Eng), MSc(Eng), PhD
Applied Mechanics Group, School of Mechanical Engineering, Cranfield Institute of Technology

SYNOPSIS Within the impact treatment industry, it is recognised that the wheel-assembly is the heart of any centrifugal peening installation and as such is the prime factor which determines the operating costs and efficiency. The wheel-assembly also represents the main problem area and therefore justifies a closer examination. The objective of the present computer-aided engineering investigation is to develop a more efficient design of the assembly, thus resulting in (i) an improved structural integrity of the critical components, and (ii) a design which can be simply and cheaply manufactured and assembled.

1 INTRODUCTION AND JUSTIFICATION

Shot-peening is a cold-working process used mainly to improve the fatigue life and corrosion resistance of metallic components. The result is accomplished by bombarding the surface of the component with small spherical shots of hardened cast-steel, conditioned cut-wire or glass-beads at a relatively high velocity. After contact between the shot and a target has ceased, a small plastic indentation will have been made causing stretching of the top layers of the exposed surface. The outcome of this treatment is two-fold: (i) the cold-working of the exposed surface layers, and (ii) the introduction of compressive residual stresses at and near the treated surface. Both of these effects are highly effective in preventing premature failure under conditions of cyclic loadings, since fatigue failure generally propagates from the free surface of a component and starts in a zone which is subjected to tensile stresses, see, e.g., Refs. [1] to [4].

One of the techniques currently employed in treating relatively large areas and ensuring complete and uniform coverage utilises centrifugal peening equipment in which a rotating bladed-wheel imparts part of its rotational energy into providing the media with the linear momentum necessary for the impingement of the treated components. Within the impact treatment industry, it is recognised that the wheel-assembly is the heart of any centrifugal peening installation and as such is the prime factor which determines the operating costs and efficiency. The wheel-assembly also represents the main problem area and therefore justifies a closer examination.

The present computer-aided engineering investigation is divided into three main parts: (i) conceptual designs of the wheel-assembly, (ii) structural stress analysis and dynamic response studies, and (iii) computer-integrated manufacturing.

2 COMPUTER-AIDED DESIGN

Fig. 1 illustrates the essential features of a typical centrifugal peening equipment. In this type of installation it is normal to feed the media by gravity through a feed spout to a distributor known as the impeller. The media stream is then picked by the rotating blades and is accelerated to the required final exist impinging velocity. The wheel is the heart of any centrifugal peening installation and as such is the prime factor which determines the operating costs and efficiency of the system.

2.1 Design Constraints and Requirements

The following design constraints were imposed on the current design of the wheel-assembly:

(i) Range of yield strength of target materials: 200 - 1000 MPa.
(ii) Minimum surface area to be peened: 65 mm x 800 mm.
(iii) Permissible input power: 25 kW.
(iv) Mass flow-rate: 4 Kg/s.

2.2 Conceptual Designs

A first attempt was made using a single-disc configuration in which eight dovetailed straight blades were secured in position using clamping screws as illustrated in Fig. 2. In order to commence the design process, an initial estimate of the dimensions of the single disc together with the attached blades was made. The above design suffers from the following shortcomings: (i) lack of rigidity of blade fixing, (ii) increased turbulence to the jet stream, which has the effect of carrying an excess of shot into the wheel-hood casing, thus causing undue wear of the protective lining, (iii) inefficient use of blades (only one side can be utilised), (iv) damage caused by escaping shots to blade clamping arrangement. In view of the above, it is believed that a single disc design can be utilised in applications requiring relatively small size wheel (<250mm dia). In this case, it is possible to integrate disc, blades and distributor in one unit during the manufacturing process and thus eliminate both lack of rigidity and possible damage to the clamping arrangement of the blades. In view of the present design constraints, a single disc design was not pursued further.

As an alternative to the above design, a double-disc eight-bladed relatively rigid wheel
arrangement is proposed. The details of the design are given in Fig. 3; it contains two discs separated by four positioning spacer bars. As a result of the improved guidance to the flow of media, a reduction in turbulence is expected.

Two further designs of blade configuration were examined. The first utilizes curved blades in which the tips are curved towards the direction of rotation, thus resulting in an increase in the impingement velocity of the media in comparison with the straight blade arrangement. This curved type of blade configuration has been used in the single disc arrangement by some manufacturers. However, it was found that the financial savings resulting from the power reduction are insignificant when compared with the increased production and maintenance costs of both the blades and the supporting disc.

The second utilizes tubular blade arrangement. In this case, the path taken by the shot is more concentrated than that of a corresponding flat bladed-wheel, thus resulting in a higher degree of directional accuracy. The presence of these tubes restricts the mass flow rate capability of the system. Preliminary tests revealed that the resulting peened area is longer and of a much reduced width in comparison with that obtained by the flat bladed-wheel arrangement. For these reasons, along with the expectation of high manufacturing costs, this design alternative was not considered further.

In the double-disc design, however, the media is fed by gravity through a feed spout to the core of a matched impeller fastened to the drive shaft, shown in Fig. 4. As the media enters the centre of the impeller, it is rotated around and is subjected to centrifugal forces. These forces accelerate the media through the appropriate slot in the impeller into the opening of a control cage. An appropriate clearance between the rotating impeller and the stationary cage is provided to retain the rest of the media within the impeller.

The choice of the appropriate angular velocity of the bladed-wheel and the impeller is dictated by the need to produce a suitable impact velocity capable of inducing localised plasticity and maintaining the surface integrity of the exposed target materials. Detailed calculations, as provided in Ref. [3], reveal that the appropriate angular velocity is 3000 rev/min.

3 COMPUTER-AIDED ANALYSIS

3.1 Structural Stress Analysis

The critical components of the double-disc design were transferred to the analysis section of the package using the same data base. As a result of structural stress analysis and dynamic response studies the geometries of these components were modified. The following section provides a brief account of the results obtained for both the "original" and "modified" designs.

3.1.1 Geometry Definition, Model Preparation and Model Checking

The solid modelling facility of SDRC (GEOMOD) enabled the three-dimensional definition of the examined models. In view of the axisymmetric nature of the impeller, only one eighth of its geometry was considered. The mesh system used for the computation is shown in Fig. 5. For the original design, a total of 320 elements interconnected at 525 nodal points were used and 563 elements with 803 nodal points were used for the modified design. In both cases, 8-noded solid brick elements were used. Similarly, a sector of the wheel-hub was modelled and discretised. Fig. 6 shows the mesh used for the modified wheel-hub. Twenty-noded parabolic brick elements were used to mesh the sector and a total of 240 elements and 1533 nodal points were used. The applied loads and imposed restraints for all components considered in the study are provided in Ref. [3].
Grid distortions of the originally proposed and modified designs of the impeller are shown in Figs. 5(a) and 5(b) and several observations can be made. The throat of the initial design of the impeller bulges outward with a maximum radial deformation of 0.527 x 10^{-4} mm, while the base experiences very little deformation as indicated by the solid lines of Fig. 5(a). Fig. 5(b) shows a more pronounced distortion in the modified design. In this case, the maximum deformation resulting from the assumed loads was 2.7 x 10^{-3} mm (indicated in figure). The increase in the maximum deformation is caused by the proposed reduction in the dimensions of the current design of the impeller. It is worth pointing out that the proposed reduction in the dimensions has resulted in an increase in the maximum equivalent stress level (from 3.7MPa to 4.6MPa).

The structural stress analysis results of the wheel-hub indicate that maximum equivalent stresses occur around the bolt hole. The results also indicate that the maximum stress level of the modified wheel-hub is 16.7MPa in comparison with 29.15MPa in the originally proposed design. It must be pointed out that in this case the reduction in the stress level was due to the reduction in flange thickness from 20mm to 10mm. As a result of this modification, a reduction in total weight of 40% was achieved.

3.2 Dynamic Response Studies

In addition to the conventional approach of Rayleigh, the finite element method was adopted in the determination of the first bending mode of the modified wheel-assembly. In the F.E. computations, the assembly, which is shown schematically in Fig. 7(a), was reduced to 34 one-dimensional beam elements with appropriate lumped mass and supporting spring elements, as depicted by Fig. 7(b).

Fig. 7(c) shows the modal shape for the first bending mode for the modified design. The results indicate that the first natural frequency of the assembly is 7440 rev/min which is well above the running speed of the machine. This agrees with the "hand-calculation" using Rayleigh's method (9800 rev/min).

The proposed modified geometries of the wheel-assembly were also subjected to similar dynamic response studies. The results indicate that no vibration problems will be experienced (\( \omega_n = 8040 \) rev/min) either at or near the running speed of the machine which is 3000 rev/min.

4 COMPUTER-INTEGRATED MANUFACTURING

4.1 Choice of Materials

Our choice of material for the manufacture of the wheel assembly was based upon the following:

(i) strength and rigidity considerations
(ii) resistance to wear
(iii) economic considerations
(iv) ease of manufacture and good machinability
(v) low specific gravity for reduced centrifugal forces
(vi) reduced porosity during casting

The vast majority of the wheel parts (blades, impeller, control cage and spacers) described earlier are manufactured from a family of alloys known as "hard irons". These alloys are generally white cast-irons containing 15-30% chromium, 1.5-3% carbon and up to 3% molybdenum. High-chromium cast irons are used extensively in many varied industrial applications requiring a high level of wear resistance.

4.2 Development of NC Machining Programs

The same data base was transferred to the McAuto Unigraphics system through a IGES file to develop NC machining programs for the drive shaft and the discs.

The drive shaft requires a combination of rough, finish turning and groove cutting operations. In view of its symmetry about the axis of rotation, only one-half of the geometry was considered. The rough turning tool path as generated by the manufacturing operations Module of the McAuto Unigraphics system is illustrated in Fig. 8(a). Within the rough turning program, there is also provision to leave an amount of stock on the different diameters and finish turning as the subsequent finish turning operation. It is also necessary to define a clearance envelope, which consists of perpendicular axes, outside which the tool can move freely without danger of colliding with chucks, centres, jigs and fixtures, etc. In this case, the tool moves from the change position to the edge of the clearance envelope at a rapid feed-rate (200 mm/min) to ensure minimum wastage of time. The depth of cut is then indexed and the tool traverses along the shaft. This procedure is then repeated until only the prescribed amount of stock remains on the appropriate diameters. In the finishing cut, which is illustrated in Fig. 8(b), the tool is instructed to profile the geometry in a single pass. The finishing tool was then used to machine the two circlip grooves and the screwthread undercut as indicated in Fig. 8(c).

The geometry of the grooves in the disc is made up of two pocket milling operations set to different depths of cut. In order to illustrate the milling operation, only the tool path required to form one groove in the disc is shown in Fig. 9. Obviously, other grooves can be milled similarly. The depth of cut is set to 2 mm and the estimated time to produce one groove is 5 minutes.

5 CONCLUSIONS

This study demonstrates the efficient utilisation of computer-aided engineering in the design of the critical components of the wheel-assembly. Throughout the investigation, integration between the different aspects of the design has been maintained. Both structural stress analysis and dynamic response studies were carried out and substantial reductions in weight has been achieved without sacrificing the mechanical integrity of the assembly. The results also reveal that the dynamic response of the assembly would be enhanced by the introduction of the modified geometries. Computer-integrated manufacturing using the same data base was also performed on one of the components of the wheel-assembly using the McAuto Unigraphics manufacturing module. Both, turning and milling NC machining programs were used in conjunction with CNC machines to produce the components.
Fig 4  Layout of the wheel-assembly

Fig 5  Discretised structure and deformed shape of a sector of impeller using SDRC interactive 3-D Enhanced Mesh Generation (EMG) facility:
(a) original design, (b) modified design

Fig 6  Discretised structure of a sector of modified wheel-hub using SDRC interactive three-dimensional Mapped Mesh Generation (MMG) facility

Fig 7  (a) Schematic representation of the wheel-assembly showing the different sections used in the dynamic analysis
(b) Finite element discretisation of the assembly
(c) Modal shape corresponding to the first bending mode
Fig 6
(a) CiK machine tool paths for roughing cut of shaft
(b) CNC machine tool path for finishing cut of shaft
(c) CNC machine tool path for circlip-grooves and screwthread undercut

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support given by the Department of Trade and Industry, U.K., Ref. No. MEE/68/044.

REFERENCES


