Computer-Aided Design of Centrifugal Peening Equipment Using Solid Modelling

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ABSTRACT

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-wheels 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 also represents the main problem area and therefore justifies a closer examination. It is believed that there exists a number of interesting areas where it was considered that some computer-aided design investigations could be attempted in order to provide a more efficient design of the wheel assembly, thus resulting in (i) an improved structural integrity of the critical components, (ii) a design which can be simply and cheaply assembled and (iii) lower overall cost.

Throughout the design process, the Computer-Aided Engineering facilities available at Cranfield Institute of Technology were fully utilised to achieve the most effective design. All 3-D models of the components, which make up the assembly, have been developed using SDRC*(GEOMOD) solid modelling facility. The detailed components were then assembled, in the system assembly section of the package, and interference checks were made.
In this study, the McAuto system was also utilised to generate all 2-D engineering drawings of the components and hence the layout of the assembly. This was followed by considering the detailed design of each component which included dimensioning, tolerancing and surface finish requirements.

1. **INTERACTIVE COMPUTER MODELLING**

Computer-aided design (CAD) is a technique in which man and machine are blended into a problem solving team, intimately coupling the best characteristics of each. The result of this combination works better than either man or machine would work alone, and by using a multi-discipline approach it offers the advantage of integrated team work.

A common form of 3-D interactive computer modelling capability found in many CAD systems is wire-frame modelling. This enables the definition of only the edges of an object. In this case, the object is transparent; thus anything but the simplest model is very difficult to interpret visually. A partial solution to this problem is the removal of all hidden lines from the object. Hence, the resultant model is view dependent and without the corresponding surfaces and volumes. It is, therefore, well short of satisfying the requirements of true engineering design.

An improvement on the wire-frame definition is surface modelling. In this case, the appropriate bounding surfaces are attached to the external edges of an object. In reality, however, the object still lacks substance and sectioning the model will only reveal the edge definition of the cut surfaces. Consequently, mass and inertia properties calculations are not possible.

The current state of the art in 3-D CAD is 'solid modelling' which provides a full solid 3-D definition of objects, generating in effect a computerised equivalent of real-life model. The complete model is constructed from basic solid primitives in combination with boolean operations such as addition, subtraction and intersection. Using the appropriate combination of solid primitives, one can readily construct components or assemblies and generate the appropriate designs.

In SDRC-GEOMOD colour assignment by individual bodies or assembly of bodies together with shading by sensible positioning of light source can yield a highly informative picture.

Being to scale, the model can yield line drawings that can be readily dimensioned and annotated as detailed manufacturing drawings, also technical illustrations can similarly be produced. Further details regarding the different CAD systems can be obtained from Refs. [1] to [4].

Increasingly, solid modelling is becoming an important part of engineer's everyday life. There are many areas where the latest technology has not yet been applied; one such area is the design of centrifugal peening equipment. In this study, the SDRC (GEOMOD) system was utilised to generate the conceptual design of different components. The detailed design of each component which includes dimensioning, tolerancing and surface finish requirements was performed using the McAuto Unigraphics system. The different components were then re-assembled, in both systems and the appropriate interference checks were made.
2. CENTRIFUGAL PEENING EQUIPMENT

The first patent for "..., cutting, grinding, etc......" by blasting with steam, water and compressed air was filed by Tilghman [5] in 1870. This patent included methods of using direct pressure, suction (syphon system) and partial vacuum. In the same year, Tilghman filed a patent [6] covering, projection of abrasives by means of centrifugal force. He visualised the use of a wheel in which the abrasive was thrown by "slider" action and by a "batter" technique as shown in Fig. 1.

The growth of the process over the early years was fitful; it was mainly looked upon as merely a useful cleaning method. However, in 1927 Herbert [7] devised equipment that was described as "cloudburst" of steel balls against a metal surface for the purpose of hardening the exposed regions. No mention was made, by Herbert, of the possible improvement to the fatigue resistance of the treated components. Indeed, it was Weibel in 1935 who recognised the value of the shot-peening treatment in connection with fatigue resistance of highly stressed components. There has been ever since, considerable research and investigations into the field of shot-peening and its effects on fatigue, corrosion fatigue and stress corrosion cracking, see for instance, Refs. [8] to [13] and the references listed in them. In these publications very little emphasis, if any, was devoted to the design of centrifugal peening equipment and its effect upon the performance of the treatment. It was therefore thought desirable to undertake the present investigation.

Fig. 2 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 exit 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. The wheel also represents the main problem area and therefore justifies a closer examination. It is believed that there exists a number of interesting areas where it was considered that some computer-aided design investigations could be attempted in order to provide a more efficient design of the wheel assembly, thus resulting in: (i) a lower overall cost, (ii) an improved structural integrity of the critical components, (iii) an enhanced overall dynamic performance of the assembly and (iv) a design which can be simply and cheaply assembled and easily maintained.

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.

Obviously, the above mentioned design constraints are in addition to the conventional ones of being safe, easy to maintain, reliable and economical to manufacture.
Fig. 1 The first blast wheels patented by Tilghman (1870) (after Refs. 5 and 6): (a) "batter" technique of media propulsion (b) "slider" technique of media propulsion.

Fig. 2 A schematic of the general assembly of a gravity-fed centrifugal peening equipment.
2.2 Conceptual Designs

A fundamental design study based on sound reliable and advanced analytical techniques as well as our experience with the currently available equipment was undertaken. In order to minimise the project risks and ensure mechanical integrity, detailed strength as well as dynamic response calculations were performed on the critical components of the present design.

A first attempt was made using a single-disc configuration in which eight dove-tailed straight blades were secured in position using clamping screws as illustrated in Fig. 3. 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, since only one side can be utilised, and (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. 4; 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 [14].

In this study, the blade of Fig. 5 was secured in position during standstill by the use of rubber or plastic friction pads which are sandwiched between the discs and the blades. They were secured during rotation by the semi-circular positioning grooves allowed for in both discs. It is clear from this design that both sides of blades can be used and consequently improve our utility of the blade material.

Two further designs of blade configuration were examined. The first utilises 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 utilises tubular discharge arrangement [15] shown in Fig. 6. 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. Preliminary tests reveal that the resulting peened area is longer and of a much reduced width in comparison with that obtained
Fig. 3 Three-dimensional solid-modeller representation of eight-bladed single-disc configuration showing a blade secured in appropriate position, dove-tailed grooves and clamping holes with all hidden-lines removed.

by the flat bladed-wheel arrangement. For this reason, this design alternative was not considered further.

In the present design, 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. 7. 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 the control cage of Fig. 8. An appropriate clearance between the rotating impeller and the stationary cage is provided to retain the rest of the media within the impeller.

The angular relationship between the impeller and blades is essential for the accurate delivery of the media to the front of the rotating blades. In this case, a lead angle of 6-8 degrees of the slots in the impeller ahead of the blades is recommended. It is also worth pointing out that in order to prevent erratic feeding of media, the number of the slots in the impeller was matched to that of the blades.
It is clear from the above that, the effect of worn impellers would be to throw abrasives at the trailing edge of the blade or behind it. This disrupts the flow pattern of the media and may cause undue wear of the back of the blade and/or wheel spacer.

The purpose of the control cage in this design is to provide the directional control of the media. The position of the slot in relation to the periphery of the wheel determines both the direction of the discharged media and the region of highly concentrated impingement (known in the industry as "hot-spot").

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.

Fig. 4 Three-dimensional solid-modeller representation of eight-bladed double-disc configuration showing a blade secured in the appropriate groove and spacers with all hidden-lines removed.
Fig. 5  Three-dimensional solid modeller representation of a blade.

Fig. 6  Three-dimensional solid modeller representation of a tubular-discharge arrangements.
The complete and accurate determination of the appropriate velocity (taking into account multiple impact effects, statistical nature of process, strain-hardening and strain-rate effects, surface roughness, etc.) is very complex and the detailed analysis of the problem was considered to be beyond the scope of the present design study.

However, a simplified, yet realistic, approach was adopted. In this approach, an energy balance relating the net kinetic energy of the impinging shot to the plastic work was invoked. The details of the calculations are given in [16]. Detailed theoretical and experimental work on single bladed wheels reveal that the sliding speed is comparable to the normal speed. In this study, the two speeds were taken to be equal. As a result of this approximation and the assumed geometry of the bladed-wheel, an angular velocity of 3000 rev/min was obtained. This velocity would enable the peening of the proposed targets.

The ability to examine a fully defined solid model representation of the wheel assembly is of considerable advantage at the detailed design stage. As a result of comprehensive design calculations, the following solid model representation of the assembly (using the System Assembly facility of GEOMUX) shown in Fig. 9 is proposed. It contains, from left to right, the drive shaft which is keyed to a taper lock bush and fastened to the impeller. The taper lock bush is in turn fitted into a wheel-hub. The wheel-hub is fastened to one side of the bladed-wheels. In the complete assembly, both the control cage and feeding spout will be fixed to the surrounding structure of the machine.

Fig. 10 shows a corresponding 2-D section view of the general assembly of the wheel-assembly with the appropriate dimensions using Unigraphics (MCAuto) system. The recess provided at the impeller wheel-hub intersection plays an important role in its alignment. Accordingly, a good fit in this region is expected. It is also worth pointing out that the presence of a groove at the bottom surface of the impeller allows its accurate positioning and prevents any possible relative rotation between it and the drive shaft during torque transmission.

The choice of the appropriate bearings, as shown in Fig. 10 was dictated by the following: (i) static and dynamic loads imposed upon the system, (ii) possible dynamic unbalance and (iii) gyroscopic effects during rotation. Detailed calculations of the loads imposed upon the bearings are given in Ref. [16]. These calculations reveal that deep groove ball bearings (SKF designation number 6312) with inside and outside diameters being 60 mm and 130 mm, respectively, can be used. These bearings will allow for some axial loads (20% of maximum radial load) [17].

2.3 Computer-Aided Analysis

In view of space limitations, we present here only a summary of the procedures adopted in the Computer-aided analysis of the design.

Due to the complex nature of the critical components which constitute the wheel assembly, it was necessary to undertake a finite element
Fig. 7  
(a) Three-dimensional solid modeller representation of impeller.
(b) Three-dimensional solid modeller representation of a section through the impeller.
Fig. 8 Three-dimensional solid modeller representation of control cage.

investigation. The critical components of the design described in Fig. 9 (discs, impeller and wheel-hub) were transferred from SDRC system design to SDRC pre-processor for subsequent meshing and applying the appropriate loads and restraints.

Fig. 11 (a) shows the discretised two-dimensional model of a segment of the final design of a disc with the appropriate restraints, external and inertia loads. The finite element analysis was carried out using SDRC/SUPERB analysis programme. The results were displayed using the post-processor of SDRC suite of programs.

Fig. 11 (b) shows the maximum principal stress trajectories resulting from the assumed loadings and constraints. It indicates that the highly stressed region of the wheel is at the holes.

The present finite element calculations have resulted in reducing the thickness of the disc from 16 mm to 12 mm without drastically changing its strength.

The above finite element stress analysis was supported by a dynamic response study, and the results were very encouraging.
Fig. 9 Three-dimensional exploded layout of the wheel-assembly using SDRC System Assembly.
Fig. 10 Two-dimensional layout of the wheel-assembly using the McAuto Unigraphics system.
2.4 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 [18].

2.5 Manufacture of Wheel Assembly

In the present design, it was thought appropriate to cast and machine (if necessary) impeller, blades and cage. These parts will be manufactured by the Shell or Koning process which utilises a fine sand coated with thermoplastic resin. This process is ideally suited for the precise definition, excellent dimensional stability and good surface finish requirement.

It is vital that any voids produced by metal contraction during cooling and solidification are excluded from the casting and retained within the feeding reservoir. This would be established by NDT-examination at the pre-production stage. In a cruder test, the casting is broken or slit open to examine internal soundness.

The significance of casting integrity is of vital importance to the life of the wheel-assembly, where the smallest internal defect when exposed is rapidly scoured out by the action of the media. The same comments apply to surface defects and in this case it is highly desirable to produce good surface finish with complete freedom from visible surface defects. Dimensional tolerances are also important to ensure that maintenance and replacement can be carried out quickly and effectively.

Fixing has to be given special attention, since the abrasion-resistant nature of high-chromium irons precludes drilling and tapping. This is overcome by using cast-in steel inserts and cast-in threaded studs.

3. CONCLUSIONS

This study illustrates the utility of the different aspects of CAD in the design of a wheel-assembly for centrifugal peening equipment. These aspects included three-dimensional interactive computer graphics using solid modelling and computer-aided analysis. Our experience indicates that the interactive solid modelling tool allows the designer to conveniently create, manipulate, store, assemble and retrieve solid geometries from the appropriate data base.
Fig. 11 (a) Discretised segment of one of the discs showing imposed restraints and applied loads.

(b) Maximum principal stress trajectories showing highly stressed regions in one of the discs.
It is also worth pointing out that the ability to assemble the different components of the wheel-assembly would ensure that design errors which would be catastrophic at the machining or assembly stage of the manufacture can be pre-empted by simulation of the assembly.

It is evident from this design activity that the use of computer has greatly reduced the time taken between the conception of a design to its manufacture. Working drawings, ready for the machine shop, were developed in a fraction of the time usually associated with this task. These drawings included dimensioning, tolerancing and surface finish requirements.

The relatively arduous operating conditions within the centrifugal shot-peening equipment make the most rigorous demands on those components associated with the propulsion of media. It is believed that these demands are satisfied by the use of high chromium cast irons. The metallurgical versatility of the 25% chromium grade enables it to be used for high level of abrasion resistance and consistency necessary for the manufacture of the critical components of the wheel assembly.

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REFERENCES


