A concurrent engineering approach to the development of a scroll compressor

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Abstract

The scroll type of compressor is becoming popular and widely used in refrigeration and air conditioners. But it is time consuming to design and manufacture the compressor since its components are of complex shape and of high precision requirements. This paper presents a concurrent engineering approach to computer-aided design and manufacturing of the compressor. The authors use C++ programming and Pro/ENGINEER as engineering tools to implement the proposed approach and associated design development. A visualised solid model of the compressor was developed. The solid model designed was enhanced by use of an optimisation system. Finite element analysis and an expert system were used to study the model, which is useful for improving the quality of manufacturing and assembly accuracy at the later stages. Manufacturability, process planning and NC tool path code generation are included in the approach. Concurrent engineering concepts were used throughout the design and manufacturing processes. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Conventionally the design and development activities of compressors were performed separately by designers and manufacturing engineers. The designers design compressors or their components using a serial engineering approach to conceptual design and thermodynamic calculations. They perform design analysis and verification using sophisticated computing tools before fabricating and testing a prototype compressor. When it comes to manufacture the product, the manufacturing process is established largely based on experience, intuition and empirical rules. As a result, development of a product takes a long time and ties up expensive manufacturing capacity for non-productive initial processes.

In recent years, the concept of concurrent engineering (CE) has been proposed to overcome such serial design and manufacturing problems [1]. In the practice of CE, product, process and all life cycle issues are considered and reviewed simultaneously throughout all phases of the development cycle. The CE process treats design for manufacturability, assemblability, testability, quality, service, delivery time and cost attributes equally (Fig. 1) and in parallel with product design for performance with particular reference to refrigeration capacity, power consumption, size, weight, noise and reliability. It also provides early visibility for any changes regarding manufacturing, test, quality, and maintenance, etc. CE integrates the expertise from the various engineering disciplines during the actual design phase. When a design is verified, it is already a manufacturable, testable, and serviceable high quality design. The design review is held just to make sure that nothing was missed in the process. The whole focus of CE is on a “right first time” process, rather than on the “redo-until-right” process that is so common in the compressor industry.

A survey of the literature shows that much research work has been done in the CE area. Hartley [2] and Prasad [3] give a comprehensive description on the CE methodology and associated issues. Cheng [4] developed CE environment for product design. Syan and Menon [5] described CE implementation and practice aspects in quite detail. But there is little research on the concurrent design and development of complex-shaped mechanical components, which are very important for general machinery, which is an area that CE can fit well and also challenge the design and manufacturing engineers in many aspects including design analysis, solid modelling (SM), NC machining and inspection.

The authors’ aim is to develop a CE approach to the concurrent design and development of complex-shaped mechanical components for achieving high quality compo-
ments at a low cost in a shorter time. A scroll type of compressor was taken as an example to research the approach. The approach is implemented with Pro/ENGINEER and C++ programming. The work presented is a part of a project being undertaken at Glasgow Caledonian University.

2. Scroll compressors

A typical scroll compressor is shown schematically in Fig. 2 [6,7]. Its principal components include a fixed scroll, an orbiting scroll, a drive shaft, frames, an electric motor, etc. As shown in Fig. 2, the motor is placed at the top and the compressor at the bottom. The orbiting scroll is driven directly by the driving shaft connected with the motor rotor. The working process of this type of compressor is shown in Fig. 3. Two identical scrolls, i.e. the fixed and orbiting ones, whose axes of rotation do not meet each other and are assembled at a relative angle of 180° contact each other at several touch lines and form a series of crescent-shaped chambers. The orbiting scroll rotates around its own axis in a plane motion. In Fig. 3a the gas suction process is just finished, the centre of the orbiting scroll is at 0°. At this position, the gas is trapped within the outer chamber. As the orbiting scroll rotates, the outer chamber becomes smaller and smaller. Fig. 3b shows the centre of the orbiting scroll being at 90°. At this position, the outer chamber is in the suction process, the middle chamber in the compression process and the inner chamber in the discharging process. Fig. 3c and d shows the suction and compression process in progress simultaneously. This working cycle appears periodically.

Obviously, the manufacturing and assembly accuracy of the scrolls must be very high. Firstly, because at the same time the two scrolls may contact each other in the radial direction at several points. The larger the machined clearances and assembly clearances of the two scrolls, the much higher the leakage of the compressed gas will be. Secondly, the working surfaces of the scrolls are inner surfaces, which are more difficult to machine than the outer ones. Thus, this results in larger machining tolerances. As the requirements described above are so strict, the development of this type of compressor needs a relatively long time regarding design, manufacturing and assembly. The costs are high and hence it is ideal for the development process of scroll compressors to adopt the CE approach and tools which can support the whole process simultaneously and comprehensively.

3. The approach

The CE approach is shown in Fig. 4. Customer requirements are input into a pre-processing module written in
C++, where the performance of the compressor is calculated. The related parameters are derived. Their data files are transferred to the CAD/computer-aided manufacturing (CAM) modules where the following aspects are processed:

- feature-based part-modelling;
- finite element analysis;
- NC tool path codes generation;
- tool path codes verification;
- inspection simulation;
- manufactured results inspection;
- assembly simulation.

In order to optimise the SM, an optimisation system is included. Deformation due to heat, working force and machining force is analysed within the system. The part model, CNC tool path and computer-aided inspection (CAI) can be visually displayed on the system. In the CE concept, the design engineer and manufacturing engineer will check the design and its implementation simultaneously. The manufacturability, testability, assemblability and maintainability will be evaluated. Therefore, the CE approach may foresee production problems before putting the design into the production process.

4. Solid model creation

SM has emerged as a superb tool for component design, especially when there is added value in linking geometry to various forms of structure, thermal, kinematic, dynamic and ergonomic analyses, etc. It is more important that SM can be used as a powerful tool to bridge the gap between the designer and the manufacturing engineers.

To create a compressor solid model, the first stage is to determine the parameters of the scroll and other components of the compressor. The customer’s requirements should be
considered in the first place, such as the capacity of refrigeration, the working conditions and refrigerant type, etc. In many cases, parts of the compressor are bought from suppliers, for instance, electrical motor, bolts and connecting pipes, etc. The dimensions or parameters of these bought parts should be taken into account for the design. The essential of initiating an SM of a scroll compressor design is also to clarify the design task and design specifications. These specifications should be precisely converted to and associated with the compressor’s geometrical data and thermodynamic parameters at an early design stage. For instance, the highest gas temperature, the suction volume per revolution, the highest working temperature and the rotating speed are typical design data or parameters. The computing results can be saved in a data file.

The second stage is to create a constructive solid geometry (CSG) solid model in the Pro/ENGINEER (PART) environment. The scroll curve can be an involute curve of a square, circle or Ackymade. For the ease of manufacturing, the circle involute curve is often used. Because the scroll curve has a wall thickness, the outer surface involute and inner surface involute of a scroll can be represented as

\[ X_o = R [\cos(\omega_o - \alpha) + \omega_o \sin(\omega_o - \alpha)] \]  
\[ Y_o = R [\sin(\omega_o - \alpha) - \omega_o \cos(\omega_o - \alpha)] \]  
\[ Y_i = R [\sin(\omega_i + \alpha) - \omega_i \cos(\omega_i + \alpha)] \]  
\[ X_i = R [\cos(\omega_i + \alpha) + \omega_i \sin(\omega_i + \alpha)] \]  

where \( R \) is the radius of the base circle, \( X \) the co-ordinate of the scroll curve, \( Y \) the co-ordinate of the scroll curve, \( \alpha \) the initial angle of the scroll curve, and \( \omega \) the changeable angle of the scroll curve. Subscripts \( o \) and \( i \) correspond to outer and inner curves, respectively.

The scroll modelling curves can be created using the above four equations automatically as shown in Fig. 5a. In Fig. 5a, a circle at the centre is the basic circle. Based on the scroll curves, the scroll feature model can be generated as shown in Fig. 5b. This is a visual model that can be checked from any viewpoint. Orbiting scroll and fixed scroll components can be built up from this model by adding the necessary features. The fixed scroll model created is shown in Fig. 5c. This is a basic model simplified for finite element method (FEM) analysis. Many geometrical features are not included such as holes, round corner, chamfers, etc.

5. Optimisation

Optimisation quantitatively is to determine a group of parameters according to target requirements from many factors or constraints in the design. In scroll optimisation, the aims are lightweight, high reliability and low cost. In optimising the compressor working process, mathematical models of the process are used to simulate the thermodynamic and dynamic properties. But to optimise the working process only is not enough, because sometimes manufacturing cannot realise the requirements of the optimised design layout in terms of tolerances and dimensions. For instance, if the tolerances of the compressor components are larger than they are required or the clearances of assembly are too large or too small, the improved performance of the optimised compressor will not be achieved. Optimisation for both the
working process of the compressor and its manufacturing process is an important part of the proposed CE approach. The FEM is used to analyse the deformation of the components resulting from the working pressure and high temperatures. An expert system is used to evaluate the process planning and quality of the scroll components. Both of them are two essential parts of the optimisation module.

5.1. FEM analysis

FEM is a well-established tool and used extensively in the design of engineering components. In the compressor design, its structural integrity has been analysed and evaluated with FEM models for a decade or so. The method was used to analyse the strength of individual components, the dynamic characteristics of the total structure and its separate components, and the temperature distribution in the body block.

Most of the engineers in preparing a finite element analysis are engaged in activities such as selecting elements and using FEM tools to join them together in a meaningful simulation. In order to mesh components easily many commercially available pre- and post-processors for FEM analysis tend to treat mesh generation automatically. Pro/FEM is one of these types of engineering design tools.

Conventional FEM is used to establish a mathematical model of small elements, to find boundary conditions and constraints first, and then to mesh the model to many elements. This procedure is very inconvenient and easy to suffer errors. In the environment developed in the approach, it is much more convenient to carry out the FEM analysis. The FEM procedure is comprised of the following basic steps:

1. Design a part or assembly.
2. While working in the part, meshing should be prepared, which includes:
   - Simplifying the part’s geometry.
   - Adding co-ordinate systems for specifying the vectorial components of loads and constraints.
   - Adding datum points to position loads, mesh constraints, and mass elements.
   - Defining materials.
3. Define the FEM model.
   - Assigning material properties to the model.
   - Specifying a thickness for surface features.
   - Applying loads and constraints to the model.
   - Applying mesh controls to the model.
4. Mesh the model.
5. Output the FEM model to an FEA program for analysis.
6. Display and evaluate the analysis results.

Fig. 6 shows the FEM model with loads and constraints applied. In this figure, pressure acting on the inner surface of scroll is shown and the displacement at the root of the scroll wall is zero. Fig. 7 shows the meshed scroll FEM model. In this model, pentahedron elements were used.

5.2. Expert system

The expert system is an evaluation system for checking the design parameters and keeping the manual intervention to a minimum.

The expert system is helpful for CE because many factors are not possible to be fully clarified by numerical calculations, for instance, the smallest wall thickness, draft angles and corner radii for castings; practical limits on deep drawing, wrinkling and deformation of metal for stamping and forging.

In this expert system module the following database is included:
- Compressor discharge capacity standards.
- Port and flange criteria for connecting pipes.
- Material properties and costs.
- Machining and assembling time analysis.
- Thickness of wall in casting.
- Wrinkling and deformation of various metals in forging.
- Vibration and noise criteria.

Since many of these simulations can be run simultaneously by different specialists, the opportunity exists to
investigate a large number of variations on a theme, and the results studied by the task force well before the design is firmed up. The CE approach is also used in the expert system module. The module can be divided into several parts and used individually, but they can be connected to each other.

Optimisation will produce a compact, lightweight and manufacturable scroll compressor that has lower vibration and noise, shorter implementation time and relatively low cost. The optimal design data can be transferred to the following CAM and CAI functions.

6. CAM and CAI

The components of the scroll compressor have to be machined on CNC machine tools because of their complex shape. To generate CNC tool path codes and to verify it are arduous if the codes are generated manually. In the CE system, Pro/MANUFACTURE can create the tool path codes based on the optimised solid model.

The process planning analysis is carried out in the expert system module, which can analyse the positioning methods and how to fix the components. The offset area clearance is shown which is useful to raster roughing. It removes material by machining a series of contours. A profile is produced around the model and this initial path is offset until the block limit is reached. The CNC tool path codes include rough and finish machining cuts. Rough machining allows a much more consistent depth of material to be left on the job before finishing is undertaken. This means that finishing can be undertaken more efficiently and at higher feed rates with far less risk of tool damage or breakage.

Finish machining is critical as it allows small tools to be used only in areas where the material has been left by the previous larger tools and to clear out corners and other areas where larger tools are precluded. The CAM program allows a tool to follow the contours of the model being machined and so gives more efficient tool paths and smoother surface finish than a raster strategy. For different scroll workblanks the CNC tool path codes are different. If the scroll groove is cast or forged, the rough and finish machining will be determined by the amount of offset area clearance. If the clearance is very small, the rough machining might not be used. The CAM program can be fully simulated on the screen. Visualisation can be at any orientation, which can avoid costly tool machine collisions and show any machining being missed. Fig. 8 schematically shows the simulation of the cutting tool path on the screen. CNC tool path codes can be copied, rotated and mirrored and thus reduce programming time. The codes can be verified on the screen. The CAI operating codes were created in the CE approach. The CAI software compares the part machined against the original 3D CAD model and highlights the differences.

7. Concluding remarks

A CE approach to develop a scroll compressor is presented in this paper. This approach is helpful in developing high quality compressor products in shorter delivery times at lower cost. At the same time of writing the approach and the CE system are to undergo industrial trials to evaluate and validate the approach and the system. This will lead to further refinement of the system based on user experience.

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References


