Concurrent and Simultaneous Engineering Applied to Design Hermetic Refrigeration Compressor

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The objective of this work is to present the main topics related to design and manufacture the housing of a hermetic compressor for household refrigeration. The product development cycle was made in a concurrent and simultaneous engineering environment, and based on an integrated CAE/CAD/CAM system. The emphasis will be on: surface modeling due to the complexity of the component shape; geometric restrictions considered for designing the component; use of the finite element method for engineering analysis; tool design based on the components created during the designing phase; automatic generation of NC programs; use of DNC (Direct Numerical Control) to download programs to CNC machines.

INTRODUCTION

Today's rapidly changing technology combined with fast communication is shortening the overall product life cycle. To keep pace with technology, the development phase of new products needs to be completed faster than ever before.

Until recently, the industries used the traditional serial engineering cycle for developing their products. The development followed a linear path, with each step beginning only after the latest has been completed. Engineers worked in isolated departments, and the designs were thrown over the wall that divided the product design from the manufacture. Changes often required coming back to conceptual design and increase in cost as time went on.

In order to shortening the product development cycle, and to be more cost effective, the industries are to changing from the traditional serial engineering cycle to the concurrent engineering. In this cycle, suitable for the 1990s life style [01], the team approach all the aspects of product development simultaneously contrary to the traditional serial method. Most changes come in the early stages when they are easily an unexpensively made. Fewer prototypes are needed, and the ones that are built often require only fine-tuning. The end result: a product that takes less time to develop, has higher quality, and less cost since expensive changes and prototypes are virtually eliminated [02].

The objective of this paper is to present the main topics related to developing the design of a new housing for a hermetic refrigeration compressor. The product development cycle was made in a concurrent engineering environment, and based on an integrated CAE/CAD/CAM system. This kind of approach allowed to reach the project stated goals within schedule.

BACKGROUND

The compressor housing is the primary noise radiator for a hermetic refrigeration compressor [03]. There are two possible ways to decrease such housing radiation. One involves reducing the amount of energy reaching the inner part of the shell. The second approach is to improve the housing by reducing its structural response to dynamic excitation.

The sound energy can reach the housing through the following paths: suspension springs, discharge tube, oil reservoir and...
refrigerant gas [04,05,06]. It is difficult to identify the noise sources, particularly in high frequency ranges. Sometimes, the noise source is well known, but there are other related aspects like energy efficiency, and so it is very hard to counteract the noise source. Therefore, to improve the compressor noise level by reducing the energy reaching the shell is a hard task.

In general, the housing responds in two distinct ways to the energy that reaches it [07]. For excitations below the first natural frequency, the housing vibrates as a rigid body, without deformation from its static shape. Sound problems in this frequency range are usually associated with large forces, for example those produced by a acoustic resonance of the refrigerant-oil mist within the housing cavity. Once a natural frequency is excited, the second form of housing radiation begins. At these frequencies the housing deforms from its static shape into other shapes, described by resonance modes. These modes require less energy to resonate and, therefore, account for most of the compressor sound problems. Two methods are generally available to reduce the mechanical response of the housing: increasing damping our higher stiffness. Since introducing damping in light metallic structures, like compressor housing, still has practical restrictions, the better option is to increase the stiffness.

**CHARACTERISTIC OF THE PROJECT**

The main goal of the project was to improve the role of the housing in the reduction of the global noise level radiated by the compressor. To be effective the changes in the housing should decrease the noise radiation in the range of 1600-3000 Hz. The chosen way to reach the objective, was to change the housing shape increasing its stiffness. This means that we had to shift the first resonance frequency of the housing to beyond 3000 Hz.

In changing the shape of the housing, there were some geometric restrictions that had to be obeyed. The main restrictions were related with the external dimensions of the housing. The compressors are used in refrigerators, freezers, etc, where the space for its location is already defined. In this manner, to avoid troubles to the manufacturers, the external dimensions of the compressor should be kept, nearly unchanged at least for its height, length and the distance A-A' (A-A' is the smallest distance between the top of compressor and refrigerator bottom, showed at figure 1). Since only the housing would be modified, the changes should also be consistent with the other components of the compressor. Mainly for the parts that are also standard for other existing models, such as the base plate and the support plate of the electrical starting device. The figure 2 shows the old housing and its main components.

The manufacturing process of the housing is stamping. The stamping tool is complex in its characteristics: size, shape and dimensional tolerances. Stamping requires a high tool investment, and long time is needed to build the tool, even the prototype one. The changes in the product, after the tool has been manufactured, have a big impact over the economic and chronological development of the project. Therefore, the use of a reliability engineering analysis tool, during the conception phase, would be fundamental for the success of the project.

**DEVELOPMENT OF THE PROJECT**

The methodology of concurrent engineering was used to develop the project. Several sectors of the company (Research and Development, Industrial Product Engineering, Sales, Process Engineering, Tool Shop, Industrial Design, Quality and Procurement) were involved since the beginning of the project. In this way, more suggestions were analysed during the conception phase of the product. This procedure decreased the number of changes in the product after the conception phase.

All the development of the project was based on an integrated CAE/CAD/CAM system. Below, are presented details of the use of this system in the different phases of the project. These phases were done simultaneously, and with high exchange of information.
Design of the product

The solid model is the fundamental link for the integration of the CAE/CAD/CAM systems. The model created at the design phase, represents the basic input for the development of the other activities of the system, as for example, engineering analysis using the finite element method, automatic coding to CNC machines, or to build a sample on resin by a rapid prototyping systems [08,09]. This integration increases the design efficiency for the model will be built only once. The solid model is also, an excellent communication vehicle for the project team in the environment of concurrent engineering, because it makes easy to visualize and to understand the model, since the preliminary phases of conception [10].

The increase of the design quality is another important aspect associated with the use of solid models. With solid modeling a higher consistency of the design interpretation is achieved, which otherwise would generally be only identified at the manufacturing stage. Since the database contains only the information of a specific solid model, the uniqueness of the information is guaranteed. There is also the advantage of having a better control on the design changes that have to be introduced on the original model. Clearance analysis and assembly checking with other components is another advantage of the solid modeling technique.

From the solid model, other useful information can be obtained for the project, such as volumes, areas, weight, moments of inertia, and center of gravity. Detailing the design is a slow phase of the project, and sometimes it may take more time than the solid modeling phase itself. It is estimated that the time for the detailing phase is reduced by 50% if the detailing is made based on a solid model then if based on a CAD bi-dimensional drawing. From the solid modeling technique it is also much easier to get perspectives and exploded views. With an integrated system the detailing phase may be unnecessary for some phases, such as finite element analysis and automatic programming for CNC machines.

The housing of a hermetic compressor can only be represented by a set of complex surfaces, i.e., a surface that cannot be represented by primitives such as straight lines, cylinders, blocks, spheres, or cones [11]. All the models created and analysed were obtained by using the Bezier surfaces. The methodology used throughout the project, is described below. The first step was to generate curves which had to conciliate the geometrical restrictions of the product, and also had to result in a favorable shape that produced an increase of the shell stiffness. The second step was to build the paths on which occurred the transitions of the curves. And the last step was to build the surface which contained the curves and the paths. The major difficulty was to get a smooth and coherent transition between the several surfaces that form the shell. Several times the shading process was used to detect possible failures on the surface, which would not have been identified by the conventional representation by lines. The change on a surface, even small modifications, implied in rebuilding the whole surface, making use only of the curves and paths. It is important to mention that the surface that form the shell, may be converted in solids, if desired.

Engineering analysis of the product

The use of engineering analysis tools, based on electronic prototypes, are the most adequate for product development. These tools are flexible, and of fast response, speeding up the development and optimization of the product. Therefore, more options can be analysed and tested, with less cost and reduced time, when compared important when building actual prototypes is expensive and time demanding.

The engineering tool generally used to calculate numerically the resonance frequency and vibration modes of the structures is the finite element method (FEM). Among all the information needed to build the finite element model, the most troublesome, in order to get
A rapid solution, is the generation of the mesh. Luckily, the capacity of the CAD systems to generate meshes over the models created in the system, is continuously increasing. Therefore, the mesh can be created faster by the CAD system if compared to manual mesh generation, or, using the limited mesh generator of the finite element solvers. Other advantages associated with CAD/FEM integration are: avoidance of rebuilding the model by some other way, that would be a duplication of work; and, the uniqueness of the information is guaranteed for the projected and analysed model.

In this study, the finite element mesh was built on models created by using surfaces of the CAD system. Although the mesh generator available in the system is able to make an automatic mesh on the surface, this approach was avoided because it would be restricted to the use of triangular elements only. To get a good solution using this kind of elements, a great mesh density is needed, i.e., a great number of elements. The consequence of using great mesh density is to increase the time processing of the computer to find the solution. The solution was then, to use quadrangular elements where they were possible. The consequence was that the patches of the surface had to be arranged to allow the use of the mesh generator. It is only possible to generate the mesh with quadrangular elements when the patch has at least, four edges (vide figure 3). Therefore, the mesh was created patch by patch, supplying the quantity of divisions on each edge. To reduce the computer processing time, the housing symmetry was used. The figure 4 shows a mesh of a finite element model to represent a housing shape. After the meshing process was completed, the model data was stored in a file, that was the input data to the finite element solver.

To calculate the resonance frequencies and shape modes of the model, a in-house developed finite element solver was used [12,13]. This solver was previously tested, and validated experimentally. The solver checked the mesh created on the CAD, and fixed it when necessary. The solver also automatically applied the boundary conditions. The results were analysed on line on graphic video terminal, where it was possible to see the animation of the shape modes and getting the values of the resonance frequencies. After the analysis, if the results were not adequate, it was necessary to go back to the conception phase. This procedure was repeated successively until reaching the desired value for the frequencies, which fulfill the goals of the project.

The tool design

The compressor housing is formed by the body and the cover. These components are stamped in a progressive tool. The manufacturing process and components assembly began to be studied during the conception phase. During this phase, also a good solution of the product technical function, and its manufacturing process, was searched. Some examples are the study about the shape of the connecting border between the body and the cover, and the maintenance of the stamping tool. Also the sequence of the stamping process began to be studied in the conception phase too.

After the product was defined, but before the detailed design of the product was ready, were began the modeling of the main components of the tool, punches and dies using the CAD system. These components were modeled with the same technique used to develop the product. It is important to say that the housing model was not used in the tool designing. Not even in the tool calibration stage. This happens because the design of the dies and punches have to account for deformation and contractions of the process. The model of the product was used only as a reference to be followed for the tool models. Here it is necessary to mention the importance of exchanging interdepartamental experiences for the development of the models on the CAD system, to increase the productivity.
Manufacturing of the stamping tool

The software to generate automatically the codes to define the tool path to CNC machines is based on surfaces. This software is able to simulate, on the screen of the workstation, the tool motion in near real time to further check the program. Simulation is especially important in complex machining because it helps programmers visualize the part a tool path. The advantage of using the automatic programming is emphasized when the shape of the piece is complex, and to write the program using the usual form depends on the skill of the programmer. Another advantage is to avoid manual adjustment to the tool, guaranteeing its shape when substitute pieces are needed. The codes automatically generated also assure a greater coherence between the design and real tool.

The dies and the punches of the housing stamping tool were manufactured by using CNC machines. The codes to the machines were by using software described before. It used the surfaces created during the design phase of the tools. The greatest difficult found was that sometimes, the surfaces were inadequate for making the path tool, what implied in rebuilding the surfaces. Because of the deficiency of the postprocessors, it was necessary to edit the programs to introduce information about comments and technological information. The use of the CAM reduced 2/3 of the programming time, when compared to the traditional way.

The programs were downloaded to CNC machines by DNC (Direct Numerical Control), which are all connected on the same net. There is also a safe portable equipment, that is able to download the programs directly to CNC machine. It was used when there were any problems with the net.

Manufacturing of the compressor housing

In manufacturing the body, it was necessary to make two adjustments on the tool, to get a good body in terms of the dimensional tolerances. During the first test of the tool, there were problems in the second stamping stage, with excessive lateral deformation of the body. After making some changes in the tool, the deformation decreased, but some remained. Although the important dimensions, like length, height and width were within the specified tolerances. The problem was solved after the inclusion of a calibration die at the fifth stage. The cover tool worked very well since the first test, and it was not necessary any adjustment.

EXPERIMENTAL ANALYSIS

A experimental analysis was made to evaluate the resonance frequencies and the mode shapes of the new housing [14]. A mesh was drawn on a surface of the prototype, and the coordinate of the points were measured. This set of data were used as input to Entek's EMESH and EMODAL softwares to make the analysis. The experimental procedures to perform the modal analysis assumed those well known in the literature [15], and the instrumentation shown in figure 5.

The experimental results agreed well with numeric values predicted by the finite element solver. The first shell resonance frequency was shifted to 80% of the numerically predicted value.

FINAL COMMENTS

The advantages that the integrated CAE/CAD/CAM system within a concurrent engineering environment offered for the development of the new compressor housing project, are shown in three aspects: quality, time and economical benifit. The improvement of quality is directly related with an increase of the quantity of options and suggestions that were analysed to optimize the product. This optimization considered the aspects of
The integration of the system guaranteed a consistent interchange of information among all the departments involved in the project. For example, the finite element analysis was done using the models created on the CAD, and the same happen when making the code to CNC machines.

To analyse better the time spent, the project should be divided in two parts. The first is related with the time that was reduced using a integrated CAE/CAD/CAM system. The best benefit was avoiding to make the work twice, and using the system to anticipate the beginnig of the tasks as soon as possible. For example, to create a mesh to finite element model, due the CAD/FEM integration, it was not necessary to wait for the detailed design. Imagine the time needed to make the detailed design of about 50 models that were analysed, and afterwards, to built the mesh using other finite element pre-processor. The same comments can be made about the CAD/CAM integration, where the NC codes were made over the models created in the tool design phase. The other face shown, was the reduction of the time using concurrent engineering. With all the departments involved since the conception phase of the product, the changes on the product, after it has been defined at first time, decreased.

This method of development of a product reduced the cost, because it avoided great changes on the product, after it has been defined. It reduced costs of re-designing, changes in the tool, and prototypes manufacturing. The other economical aspect is due the overall decrease of the development cycle time. The product can be launched earlier in the market, keeping or increasing the market share.

ACKNOWLEDGMENT

We would like to thank all the personnel in this interdisciplinary project team that developed this work, which is an example of concurrent engineering.

REFERENCES


**FIG. 1 Distance A-A'**
FIG. 2 The main components of the compressor

(a) initial patch  (b) patch changed  (c) mesh

FIG. 3 Generation of quadrangular elements
FIG. 4 A mesh of a finite element model

FIG. 5 Sketch of the instrumentation for experimental modal analysis