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Discharge Tube Design for Reciprocating Compressor – How to Do it Right the First Time and Quickly

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ABSTRACT

In order to remain competitive in compressors business by improving quality and reducing launching deadlines, the companies face everyday new challenges related to research and development of compressors. Thus, the application of numerical simulations becomes crucial to design success due to the possibility and viability of virtual models evaluations in most engineering areas. In addition to product optimization, these numerical tools are also capable of provide manufacturing solutions, propose assembly methods and evaluate target deviations due to geometric tolerances and material properties variability. This strategy significantly increases the probability of project success by avoiding redesigns and unanticipated problems during manufacturing and applications (design it right the first time). Furthermore, the union of Finite Element Method and Design for Six Sigma becomes an effective tool which, combined with powerful hardware and numerical resources, allows the development of designs each day more robust. Specifically in this article, it will be presented some methods currently used in designing compressors discharge tubes based on finite element models, component robustness analysis, geometric deviations evaluation and even the knowledge about manufacturing, simulating machines and tools used to produce the tubes. The validation of numerical results with experimental data is critical to the credibility of the methodology used.

1. INTRODUCTION

Most of household and small commercial refrigeration applications use hermetic reciprocating compressors, which functionality are based on gas compression by crank and connecting rod system. Due to non-linear displacement of piston and connecting rod, it is impossible to balance the compressor only with counterweights, so the compressor kit (composed basically by crankcase, crankshaft, connecting rod, piston, manifold and electrical motor) is suspended by springs and connected to the shell through a discharge tube in order to reduce kit vibration transferred to the shell. Figure 1 shows a schematic view of a compressor without the housing top so it is possible to see the discharge tube system (composed by discharge tube, discharge connector and discharge tube terminal, where the tube is assembled on the kit). Sometimes, the system uses a dumping spring to reduce vibration.

2. THE DESIGN WORKFLOW

Figure 2 describes a complete development workflow of a product or component. It can be noticed that there is more than one way to reach a product design. Following a good methodology it is possible to efficiently achieve and overmatch project targets, saving costs and reducing launching time. Sometimes, however, loops may occur and it is necessary to redesign components in production phase or, even worse, when the compressor is already operating in field.

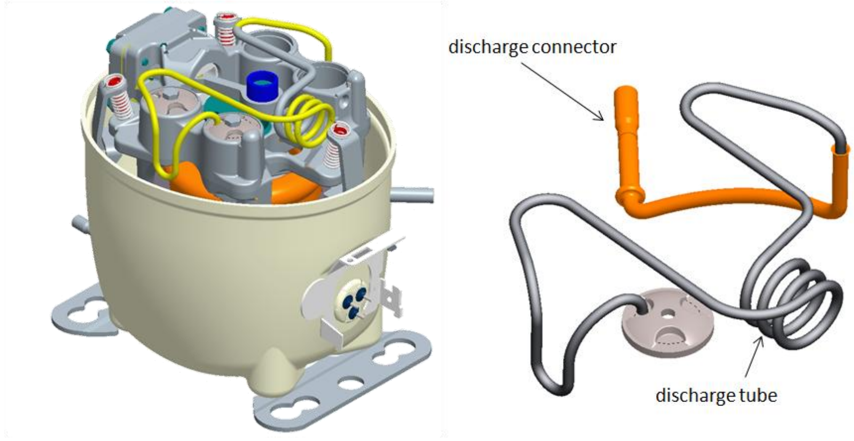


Figure 1: The discharge tube system assembled on the compressor (left) and the discharge tube system in details (right)

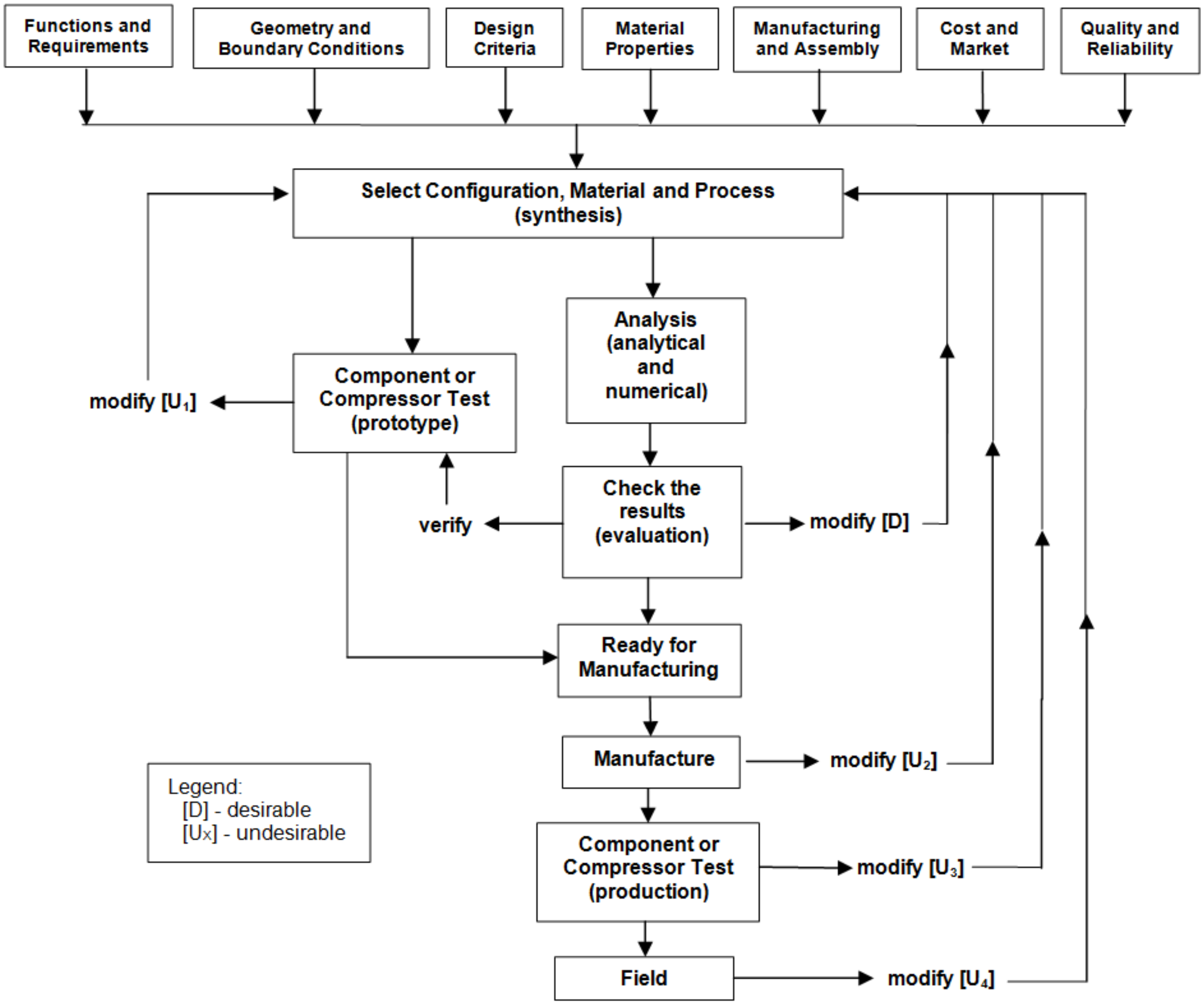


Figure 2: The design workflow (adapted from Bortoli and Silva, 2012)

From the workflow described in figure 2 it can be easily concluded that, in order to reduce component or product launching time, design efforts must be concentrated in two strategies:

- Reduce modifications in prototypes development phase, assigned as U_1. All other modifications (U_2, U_3 and U_4) should be avoided and the only acceptable modifications remain in the configuration analysis phase, which is based on analytical and numerical models. Factor of 10 rule, well known especially in FMEA, estimates the necessary increase of costs to fix a design problem in each project phase (see Figure 3). This rule is a great motivation to avoid undesirable design modifications due to financial and lead time impact.

- Increase analysis accuracy by performing more complete (all design important aspects should be considered) and validated numerical simulations so, in addition to reducing evaluation time, solutions may be more precise and robust. The ideal situation is obtaining deep knowledge about component so no physical tests are required to confirm numerical results.

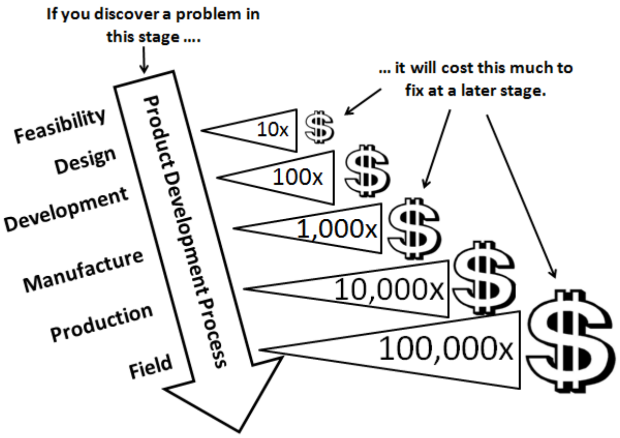


Figure 3: Factor of 10 rule (adapted from Carlson, 2012)

3. INPUTS FOR THE DISCHARGE TUBE DESIGN

A crucial requirement to achieve success is to clearly specify design inputs, classified as: functions and requirements, geometry and boundary conditions, design criteria, material properties, manufacturing and assembly, cost and market, quality and reliability. Precise inputs do not necessarily guarantee the final correct design, but inconsistent inputs will surely imply turbulent development, with high probability of results below expectations when it comes to design scope, cost preview and lead time.

3.1 Function and requirements

The main function of a discharge tube is to conduct gas from manifold to shell, so it must resist the maximum internal pressures and temperatures that refrigerant fluid works. Furthermore, discharge tube must be sufficiently flexible so as not jeopardizing compressor external vibration. This flexibility characteristic also brings benefits to reliability during transportation and compressor expected operating life. Compressor operation frequency range and discharge tube natural frequency must be mismatched, so it is especially challenging to design a flexible discharge tube with high natural frequencies in operating conditions for variable capacity compressors. Besides that, during compressor stop, kit displacement causes discharge tube loads to increase (no impact is allowed between tube and shell or other components during start-stop or transportation), so significant structural strength is required. The flexibility is reached for long tubes with lower diameter and thickness, what may cause an increase in refrigerant pressure drop inside discharge tube, negatively affecting compressor power consumption and minimum starting voltage. Raw material cost is also an important issue, so configurations should preferentially have lower mass. Therefore, several requirements (sometimes opposing to each other) must be simultaneously met, and it becomes an even more complex task to design the discharge tube when considering assembly and manufacturing process features.

3.2 Geometry and boundary conditions

Discharge tube is usually the last component to be designed in compressor, so it must fit inside the shell remaining volume even with several geometrical boundary conditions. Manufacturing, assembly and brazing are critical to component quality, so those processes must be allowed in the discharge tube configuration. Compliance with space restrictions is also required during operation, start/stop and transport, in order to avoid components impact that may cause noise, structural damage or kit misalignment.

3.3 Design criteria

Main design criteria to the discharge tube approval are minimum bending radius (related to tube diameter), fatigue strength limit, yield strength limit, compressor operating frequency, curvature geometric deviations, minimum distance between components, material properties variation and brazing parameters. It can be evaluated using FEM in static and dynamic simulations.

3.4 Material properties

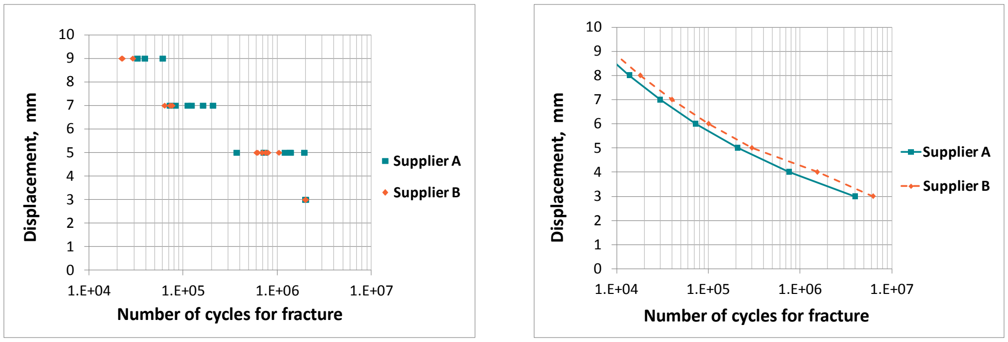
Uncertainties about mechanical properties and its deviations are considered extremely challenging in an attempt to achieve a robust design because even the most sophisticated numerical simulation tools (three dimensional model with refined mesh for nonlinear analysis with finite elements method) are not affective if material characterization is simply based on generic tables from basic engineering books or database available on internet. Bortoli and Silva (2012) indicate ways to perform Monte Carlo statistical analysis based on stochastic behavior of mechanical properties of some materials.

Material characterization becomes an even more important matter when manufacturing depends on different raw material suppliers around the world. Figure 4 shows tube samples (copper tube) from two suppliers, bending fatigue test device and component failure after fatigue test.

(a) samples (b) equipment (c) failure

Figure 4: Experimental procedure to evaluate bending fatigue for tubes

Fatigue properties characterization usually takes long time, because a lot of samples must be tested in order to obtain the necessary accuracy and confidence levels. Figure 5 (a) shows a dispersion of points from fatigue tests conducted for two different suppliers. Figure 5 (b) represents the same data after a statistical treatment through of inverse power law model, and Weibull distribution for 99% reliability with 90% of confidence bound. It was also considered the suspension data (when an expected failure after a pre-defined number of cycles does not occur) through likelihood method.



(a) (b)

Figure 5: Fatigue curves for two discharge tube suppliers

Figure 6 exposes typical fatigue curves for common tube materials, but no reliability or confidence bound is specified (subtended 50%).

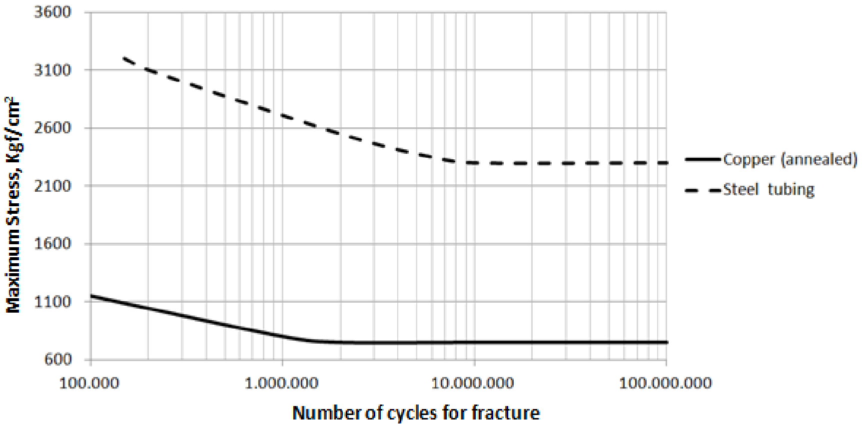


Figure 6: Typical fatigue curve for tube materials

3.5 Manufacturing and assembly

For manufacturing process and component assembly evaluations, it is necessary to perform tests using real components so final effects can be observed. Figure 7 describes a fatigue test performed in discharge connector configurations from two different manufacturing processes.

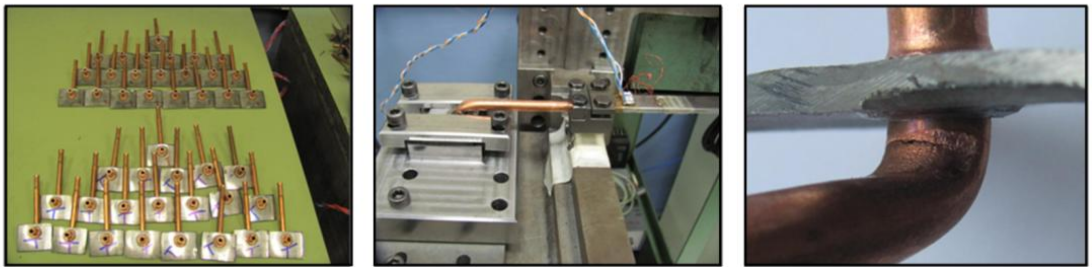
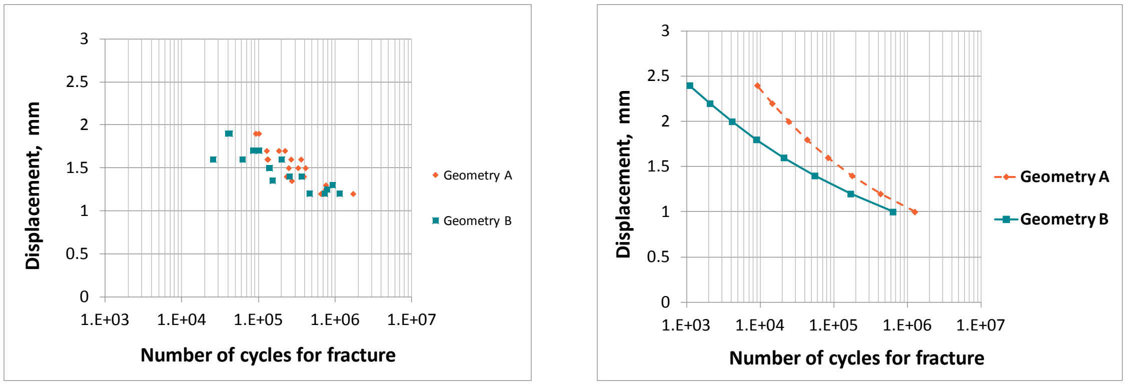

(a) samples (b) equipment (c) failure

Figure 7: Real components in fatigue tests

From experimental results registered in figure 8 (same description as figure 5) the best manufacturing alternative can be chosen as definitive. Numerical simulations in both configurations can be performed and matched with experimental results for setup calibration, so future experimental tests can be simply replaced by numerical simulations (cheaper and faster).



(a) (b)

Figure 8: Fatigue tests comparing two manufacturing alternatives

3.6 Quality and reliability

Field information, teardown analysis, FMEA and DRBFM are extremely powerful tools present in discharge tube design, but it will not be covered in this paper.

3.7 Cost and market

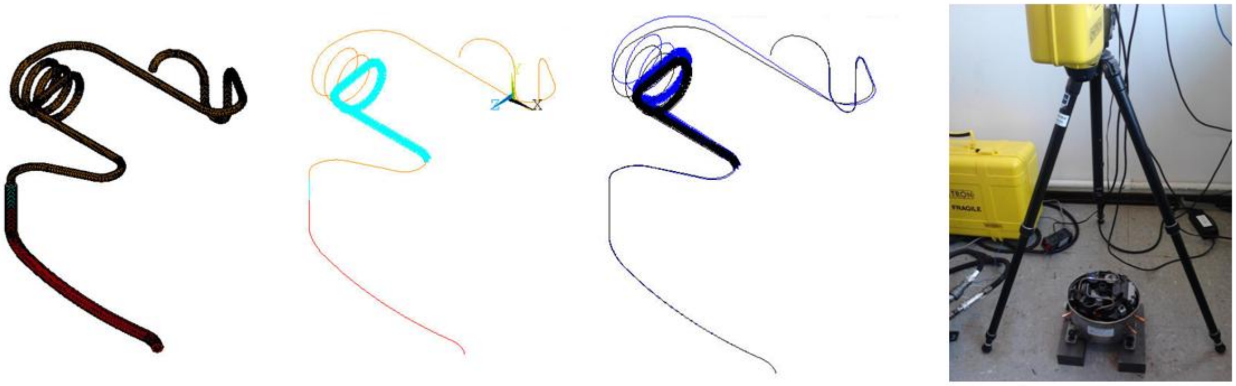
Cost and market aspects will not be covered in this paper.

4. SOME TOOLS TO IMPROVE THE DISCHARGE TUBE DESIGN

Discharge tube design may be based on engineering tools described hereafter.

4.1 FEM

Finite Element Method application on discharge tubes design has been used for a long time, as in researches carried out by Andersen (1980) and Seidel (1986). Puff *et al*. (2006) highlighting success of FEM application in compressors design. Lenz (2010) published a work focused on discharge tube stresses analysis. There is no doubt about FEM power, since it allows multiple analysis considering vibration modes, component stiffness, stress analysis and even manufacturing process simulation. Figure 9 exemplifies a FEM model to discharge tube and discharge connector analysis and first vibration mode post processing.



(a) FEM model (b) dumping spring (c) vibration mode (d) experiment

Figure 9: FEM analysis and validation

A comparison between experimental and numerical results (natural frequency) is depicted in Table 1 considering percentage relative deviation. The experimental result is based on 10 samples. Even though a numerical model using beam elements (considering dumping spring) is considered one of the most simplified, results for first mode frequency are very accurate. It becomes extremely convenient in optimization iterations and Monte Carlo simulations due to its fast solution.

Table 1: Numerical and experimental deviation

Vibration mode	Frequency error [%]
first	0.5
second	4.1
third	3.1

4.2 Optimization procedures

A discharge tube design must consider several functions, requirements and boundary conditions. Since some of them have opposite effects in target functions, optimization procedures are powerful tools to reach efficient solutions in reduced time. Bortoli and Puff (1998) published an optimization methodology to be used in compressors design, including discharge tube. In Figure 10 the development cycle is highlighted where optimization procedure works, automatically performing CAD/CAE modifications loop. CAD/CAE integration is emphasized by Puff *et al*. (2006), what caused an significant shift in optimization procedures performance. The advent of software that works as optimizers and numerical tools integrators enables expressive improvements in this area.

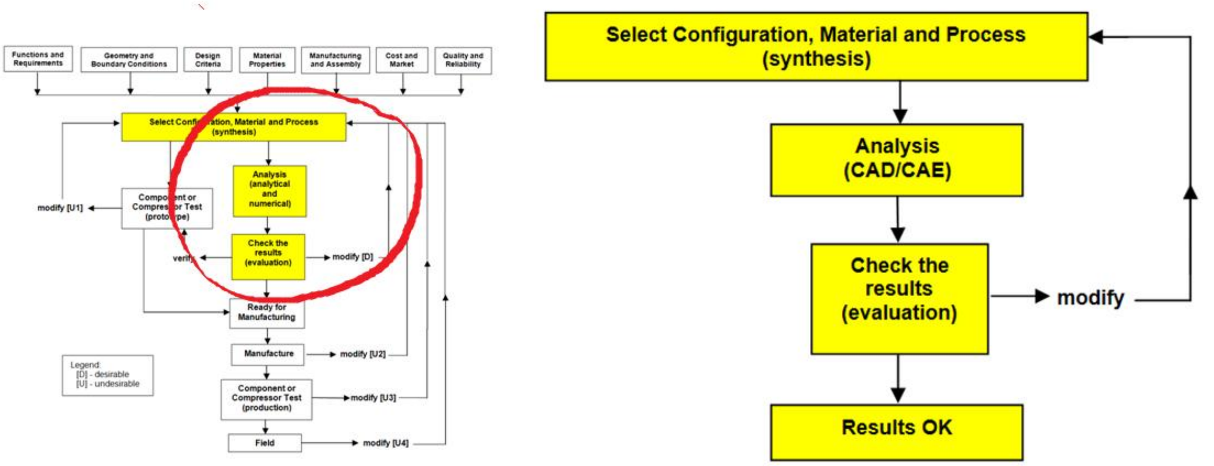


Figure 10: Optimization process on design workflow

4.3 Numerical DOE and Monte Carlo simulation

Subsequently to discharge tube configuration selection based on numerical analysis, its geometrical deviations, material properties variation and assembly procedures must also be checked in order to evaluate the component limits of modal response and ensure that no vibration modes will be excited by operational frequencies even in extreme manufacturing situations.

The most influent parameters on discharge tube structural and modal response can be identified using the FEM by individual numerical analysis or DFSS tools. Supposing an initial list of component characteristics to be evaluated (for example discharge tube diameter and thickness, discharge connector length and discharge tube insertion depth, spring position and components material properties), a numerical DOE easily classifies the top influent among the supposed significant parameters, as shown in figure 11.

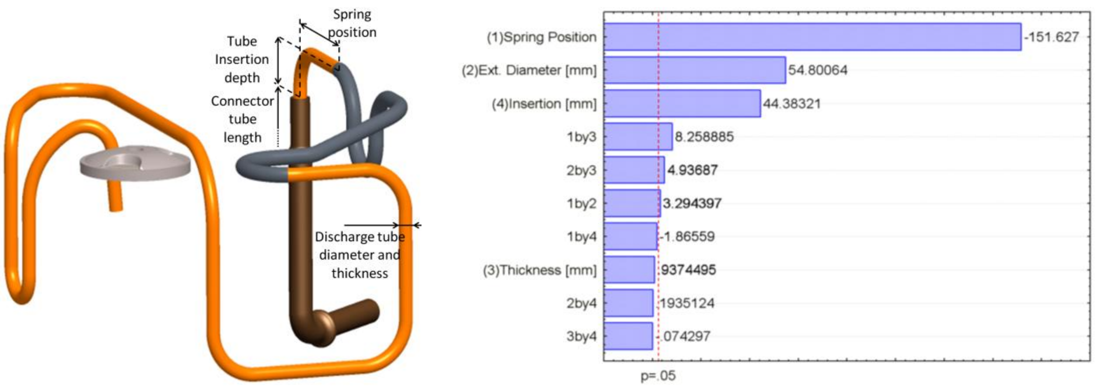


Figure 11: Numerical Pareto chart of standardized effects; variable 1st mode [Hz]

Output coefficients from numerical DOE and sensibility analysis can be used to define geometric tolerances, material properties and assembly specifications, especially for most significant parameters, which are recommended to be treated as critical to quality and should have a special capability control.

Manufactured prototypes must always be used to validate numerical simulations and also to evaluate other parameters that cannot be investigated with numerical simulations, for example the influence of brazing or welding in the component reliability. Figure 12 describes an experimental DOE result indicating the most influent parameters on determining the discharge tube natural frequency.

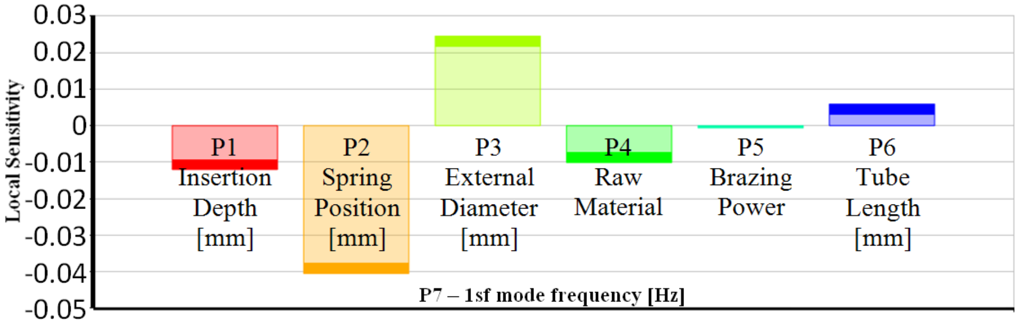


Figure 12: Experimental local sensitivity of influent parameter in discharge tube behavior

Based on a normal distribution assumed for influent parameters or, even better, real data from supplier, factory and assembly line, Monte Carlo simulation is a powerful tool to preview the definitive component behavior after start of production. It takes into account the probability of parameters combination and accurately indicates the percentage of components that may have modal response close to specification limits. Figure 13 compare distributions from a numerical Monte Carlo simulation (based on real data from manufacturing control) and from real components with first mode frequency measured on laboratory. Horizontal axis in figure 13 was divided by samples mean frequency in order to understand distribution deviations.

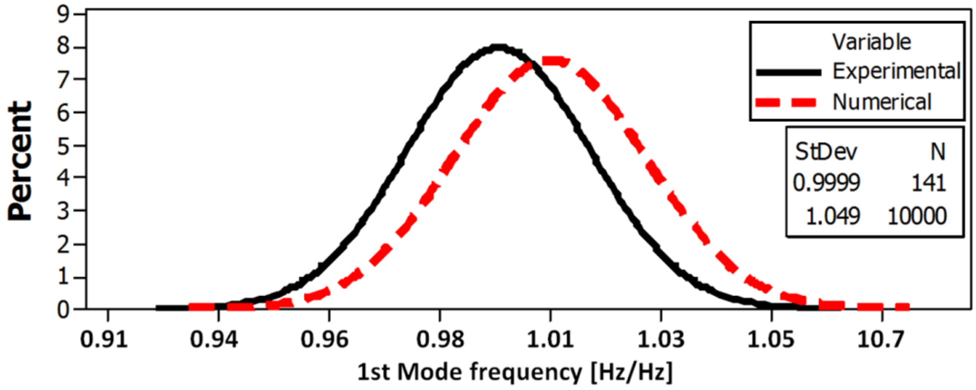


Figure 13: Natural frequency comparison between real compressor and Monte Carlo simulation

4.4 Manufacturing simulation

Anomalies initially unexpected become evident after manufacturing. Besides bending geometrical deviations in discharge tube curves, failures in discharge connector bending may occur due to its relative small curvature radius compared to its external diameter. A classical manufacturing bending method based on tube fixation and bending with cams may be applied, as represented in figure 14.

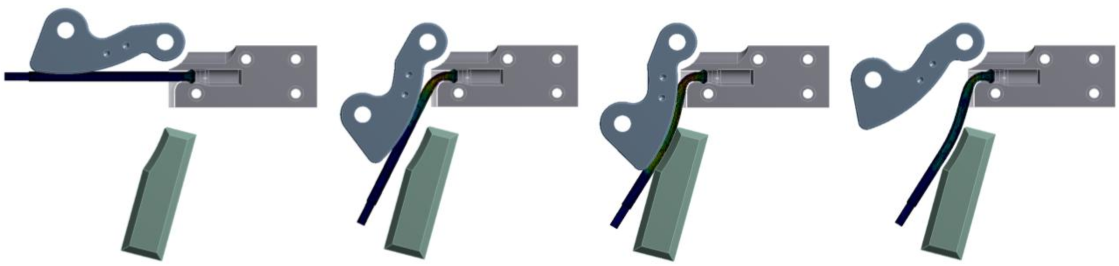


Figure 14: Discharge connector bending simulation steps

Provided adequate elastic-plastic material properties are characterized, this type of numerical simulation is able to verify final geometry, tolerance positions of extremities and roundness deviation on curved sections. Figure 15 represents a section cut from figure 14 last step, pointing out the critical region concerning roundness deviation. Vertical axis in figure 15 was divided by nominal diameter in order to understand the diameter deviation.

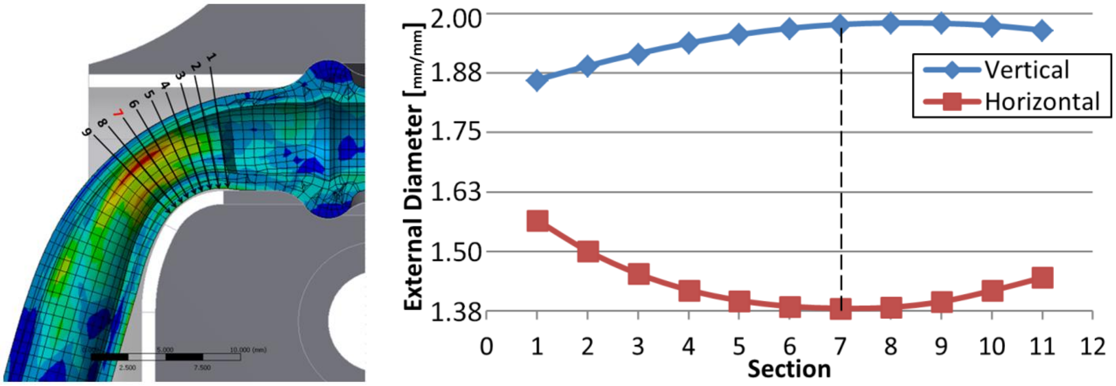


Figure 15: Discharge connector roundness deviation in first curvature

If numerical results are matched with real geometries, as evidenced in figure 16, it can be used to propose a manufacturing improvement in process stages, calibrating addition or even another totally different manufacturing procedure.

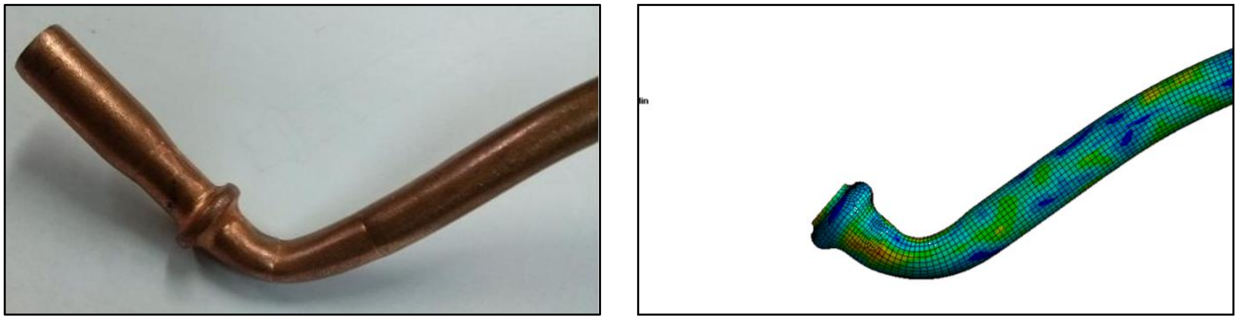


Figure 16: Visual comparison between real component and CAD/CAE model after bending simulation

5. CONCLUSIONS

In order to remain competitive in compressors business by improving quality and reducing launching deadlines, companies should not give up the use of some engineering tools:

- Numerical simulations through Finite Elements Method (FEM)
- Integrated CAD/CAE systems
- Optimization procedures
- Mechanical properties characterization
- Design For Six Sigma (DFSS), such as numerical DOE and Monte Carlo Simulation
- Manufacturing process simulation
- Experimental tests to validate numerical models
- Clear definition concerning projects inputs

NOMENCLATURE

CAD	Computer Aided Design
CAE	Computer Aided Engineering
DFSS	Design For Six Sigma
DOE	Design Of Experiments
DRBFM	Design Review Based on Failure Mode
FEM	Finite Element Method
FMEA	Failure Mode and Effects Analysis

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