Design of an automated aerodynamic guide vane mechanism for a micro compressor

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Abstract

The behaviour of centrifugal compressors is sensitive to several parameters that influence their performance. One way used to enhance the performance of compressors involves a set of automated, variable vanes (IGVs) for compressor inlet flow control. If correctly controlled, those vanes allow increasing the operating range of those compressors. This work aimed to find an accurate small-scale guide vane control mechanism. Through experiments, comparison with CFD results and theoretical analysis of error sources, it was detected in this work, that the mechanisms present in the industry are not sufficiently accurate in controlling the angle of IGVs, once entered in the small scale domain. An advanced design involving direct drive mechanism, which eliminates most of the mechanical error of the previous designs present in the IGV adjustment, and controlled from an Arduíno, was designed, manufactured and tested experimentally. After comparison with the CFD results, it was obtained an absolute mean error reduction in the IGVs adjustment of 30.75%, compared to the results obtained from the previous automated geared mechanism.

Keywords: Guide vane mechanism, small scale, mechanical design, control , flow angle

1. Introduction

In the world of turbomachinery, famous companies like Rolls Royce or Pratt and Whitney have vast experience in the engine manufacturing for large scale applications. As a result, manufacturing of small-scale turbomachines components is often neglected by large industries.

The Laboratory for Applied Mechanical Design (LAMD) focuses on the design and experimental investigation of small scale turbomachines. One of the laboratory's tests stands is used to assess the performance of a small scale turbo compressor developed by LAMD. It includes variable Inlet Guide Vanes (IGVs), located in front of the compressor. These have the purpose of directing the fluid-flow to the compressor (Fig.1), at the appropriate angle to ensure the most efficient operation. In small scale applications, even manufacturing tolerances play an essential role in the angular adjustment of IGVs. The control mechanism of IGVs needs to be even more accurate compared to larger-scale applications in order to be able to perform tests and obtain results used in the subsequent design of centrifugal micro compressors.

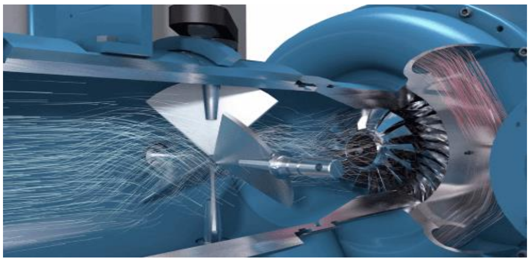


Figure 1: Purpose of IGVs in centrifugal compressors operations [1]

At LAMD, there is a set of small-scale IGVs that require accurate control and repeatability of results. In order to control this set of IGVs, an automated geared mechanism has been designed and realised. It has been found in Aeschbacher's work [2] that this mechanism was insufficient in terms of accuracy and repeatability. In order to achieve more precise control in terms of accuracy, repeatability and adjustability, a manual mechanism was built that meets the quality criteria, namely allows more precise control in the adjustment of the blade angle.

The challenge of this work is to redesign a system that can combine the accuracy of the manual mechanism with automated control. In order to achieve this goal, the following procedure was followed: problem analysis, solution finding and design of the new mechanism.

2. Background

2.1. IGV theory

Depending on the type of compressors for which its use is intended, IGVs can be fixed or variable and are located in front of the impeller eye. This project uses variable IGVs in order to enhance the operating range.

The performance of a compressor can be assessed using a map of the compressor that associates the variables of pressure ratio and volume or mass flow rate (Fig.2). The surge line bounds this map at low flow rates and the choke limit at high flow rates. The surge line reflects the operating points where the pressure ratio is too high for the volume of fluid flowing. This phenomenon causes the fluid to no longer adheres to the suction side of the compressor blades, leading to the reversal of the fluid flow direction, and thus the discharge process is disturbed. For instance, surge can lead to the complete breakdown of steady flow in the compressor. When the volumetric flow rate of the fluid is too high for the pressure ratio, and the velocity of the fluid can not be increased further, it means that a choke situation is reached.

In a well designed compressor, the maximum volumetric flow is limited by the cross-section at the inlet, where transonic conditions are reached [2]. Thus, the range of operation between the surge and choke limit defines the operating range of a compressor. It is at this point that the use of IGVs comes in since they allow manipulating the map of the compressor, increasing the range of operations [3].

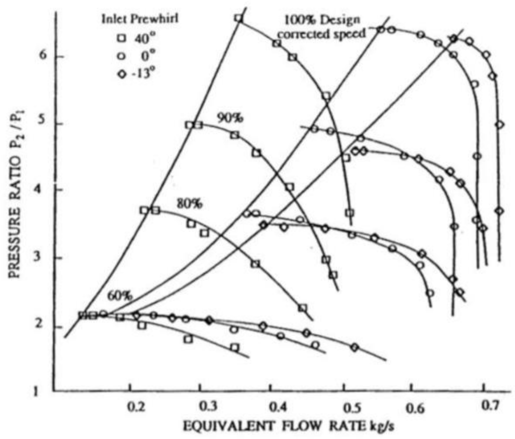


Figure 2: Compressor map representing the IGVs influence in the impeller stalling [4]

Placed in front of the first stage of the impeller, the different angle at which IGVs are adjusted allows the creation of a pre whirl, which is the phenomenon of adding a tangential component to the inlet air.

By using IGVs, the absolute velocity of the fluid at the leading edge of the impeller can deviate angularly. The fluid flow is directed according to the attack angle of the IGVs. Therefore, the performance of the compressor stage varies by inducing this pre-swirl for a given rotational speed and mass flow rate [5]. The IGV effect in compressors work can be seen through the most fundamental and famous equation in turbomachinery, the Euler equation:

$$w_{compressor} = u_2 c_{u2} - u_1 c_{u1} =$$
$$= \frac{1}{2}((u_2^2 - u_1^2) + (c_2^2 - c_1^2) + (w_1^2 - w_2^2)) \qquad 1)$$

where the term defined by the quadratic difference of rotational speeds, u, represents the working input to the fluid by a loss-free centrifugal effect due to the change in rotational speed. c_1 and c_2 are the absolute velocities of the fluid at the inlet and outlet respectively. w_1 and w_2 are the relative velocities of the fluid with respect to the blade at the inlet and outlet respectively. From this equation, it can be noted that the creation of a negative (with opposite direction to the impeller rotation) pre swirl results in the creation of higher work by the compressor (Fig.3) [6].

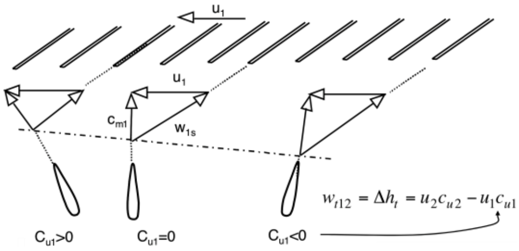


Figure 3: Influence of IGV angle on output work of a centrifugal compressor (figure from ITSM University of Stuttgart)

2.2. Guide Vane Mechanisms

The final goal of a control mechanism is to ensure that the error between the operator-adjusted angle and the final blade angle is as low as possible. The IGV control mechanisms used in the industry consist of: airfoil profile that makes up the vanes, connecting shaft, control unit in the form of levers, actuators (motors) and controllers.

2.2.1. Guide vane air foils

IGVs have blades shaped according to a chosen aerodynamic profile. Depending on the airfoil profile of the vanes, the operating range of the angular adjustment mechanism differs. The maximum possible range of flow angles is determined by the separation angle of the airfoil. Once this angle is passed, the blades no longer direct the fluid, and their use ceases to make sense, due to flow separation.

Consequently, an important factor when designing the vanes that make up a mechanism is the choice of the airfoil. Depending on the shape of the vanes chosen, the system losses due to the use of IGVs can be reduced if an airfoil profile with a low drag coefficient is chosen. In Pillet's work [7], several NACA airfoils have been examined. For the mechanism subject to this project, a symmetrical NACA 0012 airfoil was chosen (Fig.4).The operating range of this airfoil profile is between -16º and +16º, values that serve as a reference for the operating range of the vanes.

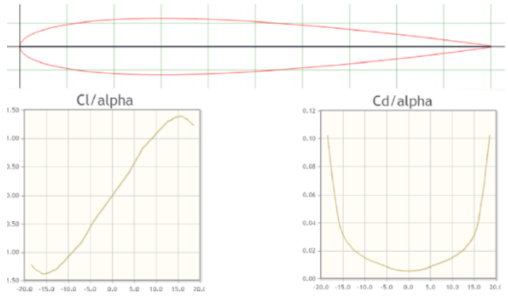


Figure 4: NACA 0012 Airfoil with its lift and drag coefficient curves [7]

2.2.2. Control mechanism

A survey was carried out of the solutions used in the industry to control IGVs. The designs found can be split up as variants of four kinds: lever mechanism, geared mechanism, manual mechanism and direct drive mechanism.

2.2.2.1. Lever mechanism

This design uses a rotating ring and a lever mechanism to actuate the vanes. An actuator turns the ring that is linked to the levers. One of the major problems of this type of mechanism, when applied to reduced scale machines, is the loss of precision due to the presence of joints, which reduce accuracy. By using it in small-scale applications, the effect of the presence of clearance in the joints gains more relevance in the overall adjustment accuracy of the system.

2.2.2.2. Geared mechanism

This type of mechanism involves the presence of a crown gear, responsible for the transmission of movement, is emphasised. Bevel gears are placed on the shafts in which the vanes are manufactured, which are associated with the crown gear that acts as a planetary gear. One of the problems with this design, especially when in small-scale applications is the angular backlash (i.e. the play that exists in the gear train). This problem is caused by the gap between the gear teeth and the tooth thickness that leads to inaccuracy in the blade angle adjustment movement. It follows that once dealing with small-scale applications, this factor acquires more relevance, due to the ratio between the adjustment range and the backlash of the gear train.

2.2.2.3. Manual mechanism

In this design, each blade is mounted on a shaft with an indicator arm. Consequently, each blade angle can be adjusted directly with a cursor manually by the operator without slack as there are no intermediate mechanisms. This type of design allows giving accuracy to the adjustment mechanism insofar as the accuracy of the angle is only influenced by the manufacturing tolerances of the parts involved in the control of the same. Since it is manual and not automated as the other mechanisms, it is not suitable for performing test cycles. This happens because the repeatability of the tests is very dependent on the adjustment made by the operator.

2.2.2.4. Direct Drive mechanism

In this design, each vane is directly connected to the actuator and can therefore be controlled independently. As a result, the motion transmission mechanism of the actuator for the vanes that are not directly connected (passive axes) is suppressed. A further advantage is the rapid response rate of the system and the ease of replacing damaged parts in the system. Such happens due to the lack of interaction between the different moving parts of the system. In this sense, one of the disadvantages of the mechanisms described in the previous sections is solved.

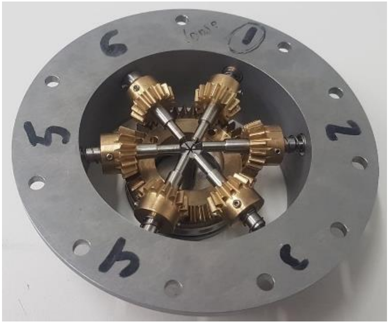
This design, by replacing mechanical elements for the electrical ones, allows having better control of the angle adjusted for each blade, as there are no passive shafts in the system. Its use is compatible with small-scale applications as it does not involve the manufacture of small moving parts in the system. As a result, the manufacturing tolerances of the parts, the resolution and accuracy of the actuator are the only influencing factors in the accuracy of the system.

3. Methodology and Analysis

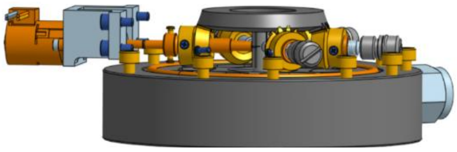
The focus of this project is on problem analysis, solution finding and design. theoretical and experimental evaluation and quantification of the two available mechanism (automated geared mechanism and manual) was performed in the problem analysis stage.

3.1. Automated Geared Mechanism

An analysis of the current automated system [Fig.5 a) and b)] detected some problems that contributed to the system's failure to comply with its requirements.



a) Crown Gear System



b) Connection between active shaft and passive shafts

Figure 5: Automated Geared Mechanism of LAMD

3.1.1. Stepper Motor

Stepper motors are actuators that can provide high accuracy through low step angle resolution. SPG1518M0504-102 is the motor stepper that was used as an actuator of the mechanism. Regarding the accuracy of the same:

- The reduction of 102.5 allows that for every 102.5 turns the end shaft of the gearbox will do one turn;
- The minimum angle possible to control in this stepper motor is 0,176º;
- Step accuracy reflects a possible deviation of **± 0,01232º (7%);**
- To mantain the accuracy of the stepper motor the torque required by the system should not

exceed the stepper motor holding torque (Fig.6).

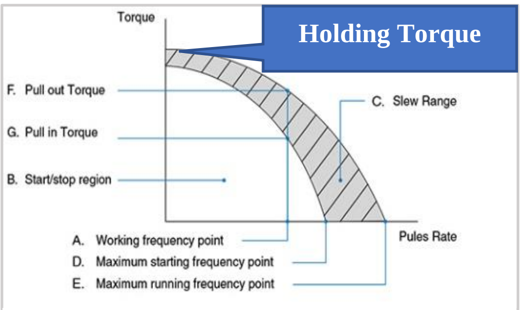


Figure 6: Generic example of a Nema stepper motor torque vs speed chart [8]

3.1.2. Gear Train Angular Backlash

The backlash of the gear train used in this design is another problem that leads to loss of precision in blades angle adjustment. Backlash is the maximum angle through which any part of a mechanism may be moved in one direction without applying considerable force or motion to the next part in mechanical sequence. Experimental tests allowed the quantification of the error from the gear train (Fig.7).

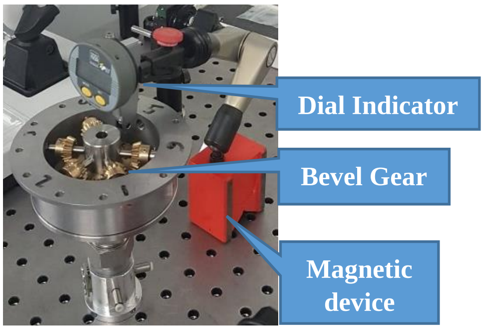


Figure 7: Scheme of the test setup used to measure the backlash of the gear train

3.1.3. Calibrator Tool

Calibrator plays a significant role in the functioning of the automated geared mechanism as it allows fixing the initial position of the IGVs. It is responsible for ensuring that the initial position of the vanes is at 0º of the referential. Due to the tolerances required to leave in the material for machining and manufacture thereof, calibrator becomes a source of error in blades adjustment, failing to ensure that the initial position of the vanes is 0º. Schreiber [9], quantified the uncertainty

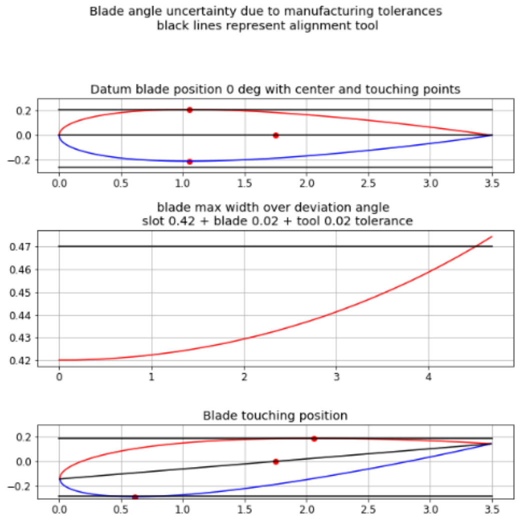


Figure 8: Deviation in blade adjustment caused by the calibrator and manufacturing tolerances

adjacent to the use of the calibrator tool in the calibration of the automated mechanism (Fig.8). Table 1 shows the summary of the quantification of the sources of error of the automated geared system, result of the analysis performed.

Table 1: Summary of the maximum error quantification of the sources in the automated system

Source	Max Error Angle (º)	% of Total Error
Manufacturing Tolerances	Included in calibrator calculation	----
Backlash Gear Train	±1,742	43,10
Calibrator	+4,5	55,66
Actuator Accuracy	+0,10032	1,24

The manufacturing tolerances error is included in the initial calibrator error when adjusting the blade position to 0º. The calibrator and backlash are responsible for most of the system error and should be suppressed in the future mechanism.

3.1.4. Experiment with Automated Mechanism

Also a experimental evaluation of the automated geared mechanism was performed. Aeschenbacher's CFD results [1] were used for comparison (Fig.9).

In order to evaluate the mechanism accuracy, the mean of the absolute experimental deviation of the mechanism between the adjusted angle and the fluid flow angle was calculated. The result was **3.05°**. This value resulted from the mean of the flow angle deviations observed for the radial positions measured in the tests and served as a measure of the precision of the mechanism. The theoretical evaluation was confined to estimating the maximum possible error coming from each element that constitutes the mechanism.

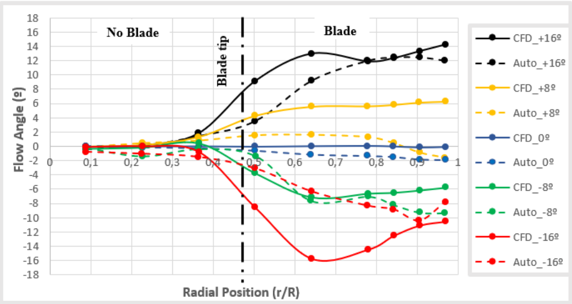


Figure 9: Deviation between automated mechanism and CFD angle profiles

3.2. Manual Mechanism

In the manual mechanism, the accuracy of blade adjustment operations depends on manufacturing tolerances and operator accuracy. In this stage, the parts involved in the control of IGVs and its manufacturing tolerances were analysed. The quantification of the possible error coming from the eye of the operator could not be fully aligned with the scale on the mechanism when adjusting the angle of IGVs was also calculated (Fig.10).

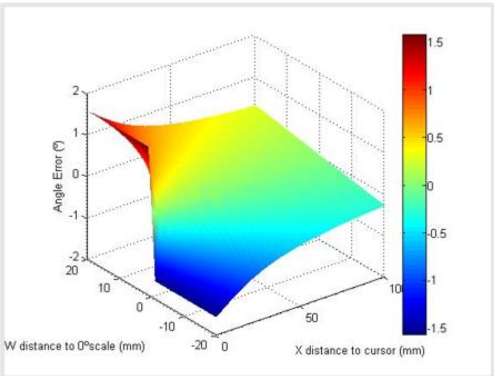


Figure 10: Possible error coming from operator precision to perform the task of adjust blades angle

Table 2 shows the summary of the quantification of the sources of error of the manual system, result of the analysis performed.

Table2: Summary of the error quantification of the sources in the manual system

Source	Max Error Angle (º)	% of Total Error
Manufacturing Tolerances	±0,075	4,48
Operator Dependent	± 1,6	95,52

3.1.3. Experiment with Manual Mechanism

The experimental evaluation of the results of the manual mechanism, through comparison with the CFD results, obtained the mean experimental absolute deviation of **1.75º**. This value reflected an improvement in accuracy compared to the automated geared system, through a **reduction in mean absolute deviation of 43%** (Fig. 11). However, due to the dependence of the operator, this mechanism is not suitable for the performance of test cycles, due to the challenge of obtaining test repeatability.

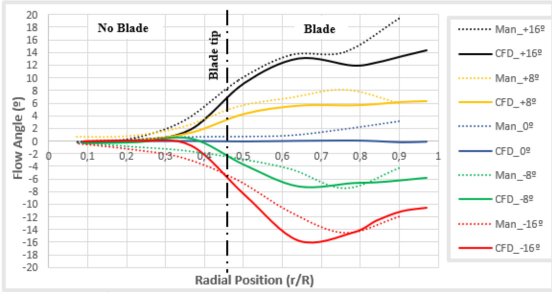


Figure 11: Deviation between manual mechanism and CFD angle profiles

3.3. Analysis Conclusions

Once both systems were analysed and evaluated, the advantages and disadvantages of each system could be summarised. The findings were considered in the subsequent stage of the solution finding work.

Table3: Summary of pros and cons of manual and automated system

Mechanism	Positive	Negative
Manual	✓ No calibrator tool ✓ Mechanical Accuracy (just dependent of small manufacturing tolerances)	✓ Operator dependent ✓ Bad repeatability ✓ No remote control ✓ No usage in test cycles
Automated	✓ Repeatibility ✓ Remote Control ✓ Stepper Motor	✓ Calibrator ✓ Mechanical Accuracy ✓ Precise Assembly (Stepper motor can't have enough accuracy because the torque required by the gear train is too high)

4. Solution Finding

4.1. Project Requirements

Requirements are part of the specifics of the project. They are a set of guidelines that the project must respect in order to be fully functional and meet the needs for which it is designed. Regarding the requirements of the project:

I. The IGV mechanism must be an independent module that will be fixed on the volute of the compressor;
II. The mechanism must allow controlling the blades angle between -16º and +16º (range of angles in which the airfoil chosen for the vanes does not stall);
III. The mechanism must be completely sealed;
IV. The step angle of the vanes must be lower than 0.5º to have precise control of the compressor map.

4.2. Methodology

The next step of the project involved the finding of the final solution. Once the existing problems with the mechanisms used in the laboratory were identified, and the project requirements were presented, it was essential to develop a method (Fig.12) that would allow a solution to be found that could overcome the flaws of the previous mechanism.

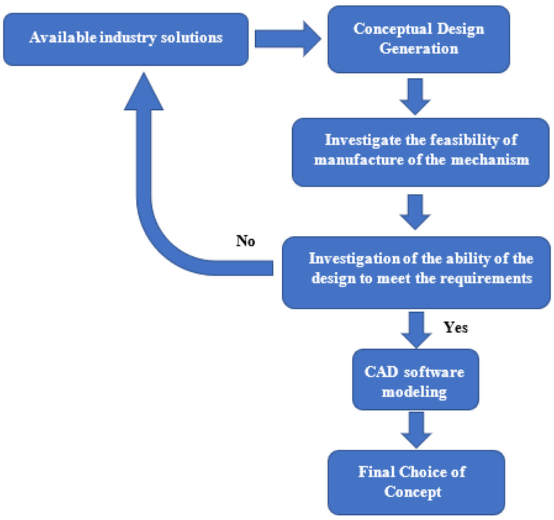


Figure 12: Steps involved in solution finding stage

The starting point for the development of the new mechanism were the solutions available on industry. From the existing design types, the conceptual design was generated. The next step was to investigate the feasibility of the mechanism to be made and produced. It is then checked whether the design can meet the requirements of the project. The search for standard materials and parts that may need to be acquired for the system design takes place next. With the collected material, details are then investigated that serves as a factor in the choice of the final design: theoretical calculation of the accuracy of the mechanism in adjusting the IGV, the relationship between the blade angle and the angle of the actuator and estimated costs in the mechanism's design. After modelling in the CAD software the several possible concepts for the control of IGVs, the final concept of the new mechanism was chosen.

4.3. Final Solution Mechanism

After analysing several designs from the iterative process explained in figure 12, the new design was chosen. The choice of the new design involved a careful selection, and the following factors were considered: manufacture ease, control ease, control of the blade angle, cost, assembly ease, accuracy and stages/possible sources of play.

4.3.1. Direct Drive Mechanism

The final solution is a direct drive mechanism (Fig.13).The new mechanism is based on six vaned shafts, directly connected to the stepper motors through couplings. In this system, there are six steppers motors responsible for controlling the position of the blades. There is also a calibrator tool for each vaned shaft to ensure that the initial position of the blade is 0º.

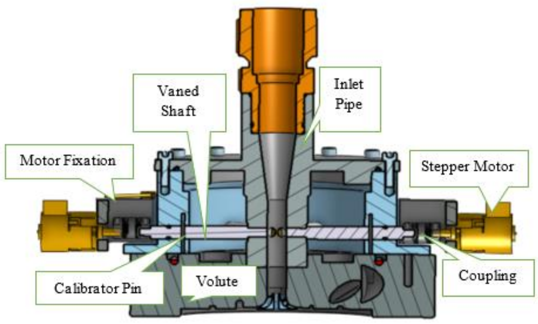


Figure 13: Direct drive final design- Cut View

The accuracy of this mechanism depends on two factors: manufacturing tolerances of the parts involved in calibration task and actuator accuracy.

4.3.1.1. Calibration

The mechanism is calibrated by inserting a Ø1.5mm pin calibrator into the vaned shaft. The use of type H7-g6 adjustment between the pin and the through-hole of the shaft leads to a theoretical maximum error of about ±0.0688º.

4.3.1.2. Actuator

The chosen stepper motor was a *SPG1518M0504-102* biphasic stepper motor, already discussed in section 3.1.1. This way, the maximum error in the accuracy of the mechanism in the adjustment of the blade angle is 0,10032º. Table 3 shows the summary of the quantification of the sources of error of the new system.

Table 3: Summary of inaccuracy sources of new Direct Drive mechanism

Source	Max Error Angle (º)	% of Total Error
Manufacturing Tolerances	±0,0688	40,69
Stepper Motor Accuracy	±0,1003	59,31
Total	±0,1691º ≤ 0,5 (Requirement)	100

5. Design of New Mechanism

Once the concept involved in the final design of the mechanism has been chosen, shown in figure 13, it was necessary at this stage to develop the entire mechanism so that it complied with the all project requirements.

5.1. Mechanical Design

5.3.1. Structural Analysis to the vanes

As in previous designs, blade is 3.5 mm long and 0.4 mm thick at the maximum. All the six vanes are directly milled on the six shafts, on this new mechanism. The parts of the system that are subject to the highest stresses are also those that require the highest manufacturing accuracy (e.g., Naca 0012 shaft blades). As such, parts need to be manufactured from a high yield stress material. For all these reasons, the components of the mechanism will be made of stainless steel. The chosen material was the same as the previous design, the stainless steel 1.4305, also known as 304, with $S_y = 415$ (MPa) and $S_{ut} = 690$ (MPa). Since the blades that make up the IGVs are the only part of the mechanism subject to stress resulting from interaction with the fluid during operation, were the only elements subject to structural analysis in the mechanism (Fig.14).

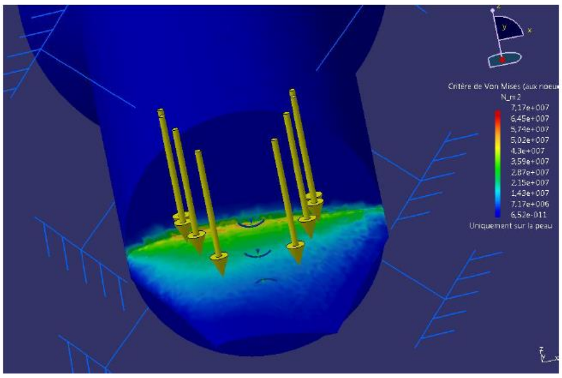


Figure 14: Stress in the vane [7]

The results showed that, even though an axial pressure of 600 bar - the double of the maximum value of the pressure to which they are subjected inside the channel- was applied in the vanes, the maximum stress in the vanes was 72 MPa, a value much lower than the 415 MPa of the material yield stress.

5.3.2. O- Ring Choice

In the design of the chosen solution, one of the main requirements is that the module has to be gas tight. In the task of sealing the designed module, it is important to know how tight the O-ring will be squeezed by the different parts in order to create an effective seal of the entire module. A Normatec catalogue [10] and tables were used depending on the type of application (static or dynamic) for which the O ring is intended, as shown in table 4.

Table 4: Data concerning the existing seal types in the mechanism

O-Ring	Type of seal	Sealing Effect	O ring Type of Stress	Percentage of Flatenning (%)
18.5_1	Static	Piston	Radial	25
14.5_1	Static	Piston	Radial	20
74_3	Static	Flange	Axial	26,67
74_1.5	Static	Flange	Axial	30
3.5_1	Almost Static	Piston	Radial	25

5.3.3. Sizing the Stepper Motor

In this stage, the strategy of checking the capacities of the stepper motor was used, taking into account the torque required for the proper and accurate functioning of the mechanism (table 5).

The necessary condition to check was:

Torque supplied by the motor > torque required by the system during operations

Table 5: Summary of torque required by the system to work properly

	Torque Required	Remaining Torque (Nm)
Motor's Torque	---	0,10
Inertia System	0,00003	0,09997
Friction		
Stepper Motor- Coupling	0,00012	0,09985
Coupling - Shaft	0,00018	0,09967
O ring- Casing	0,00354	0,09613
External Forces		
Lift	0,000177	**0,0960**

5.2. Manufacturing

Following the final design of the new mechanism it was necessary to manufacture it for later assembly and experimental testing. The diagram in figure 15 shows the procedure carried out in this stage of the project. Figure 16 shows the parts manufactured by the ATME workshop.

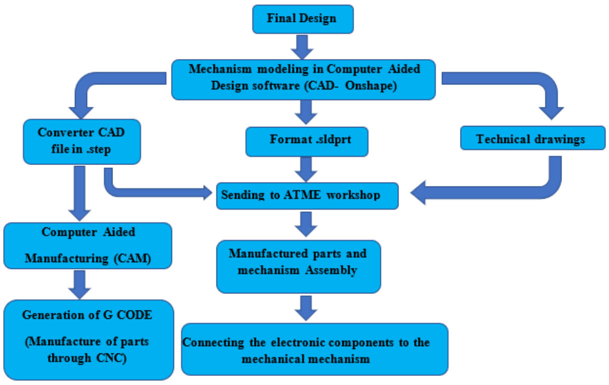


Figure 15: Steps involved in the manufacturing process of the mechanism

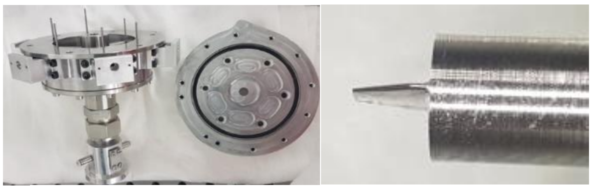


Figure 16: Constituent parts of the new design

5.3. Control of the Mechanism

Once the mechanical design of the mechanism was completed, it was necessary to decide on the electronic configuration of the system to make the entire mechanism functional. Regarding the control of the mechanism, the six stepper motors are controlled via the SMC11-2 controllers. Each of these controllers is connected directly to an Arduíno Mega2560 (the Arduíno Uno did not fit due to an insufficient number of ports for the six controllers). The Arduíno acts as the master, and the input signals [11] (clock, release, direction) are sent to the motor control (Fig.17), in order to place the IGV on the angle adjusted by the operator.

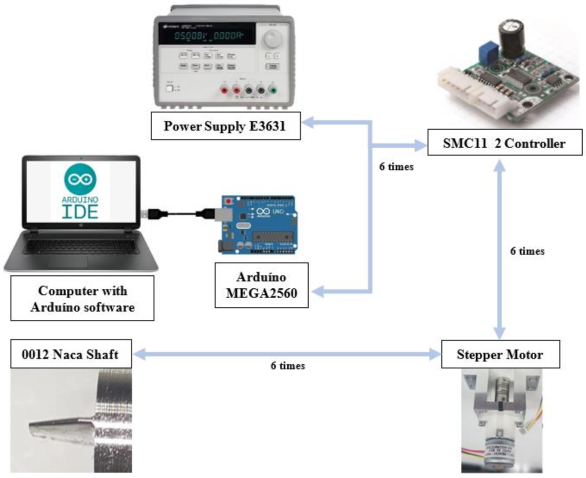


Figure 17: Interaction between electronic components in the functioning of the new mechanism

6. Results

Once the mechanical and electronic design and assembly of the entire mechanism were finished, the last stage of this project included experimental tests with the new mechanism. Tests were performed and results are presented in figure 18.

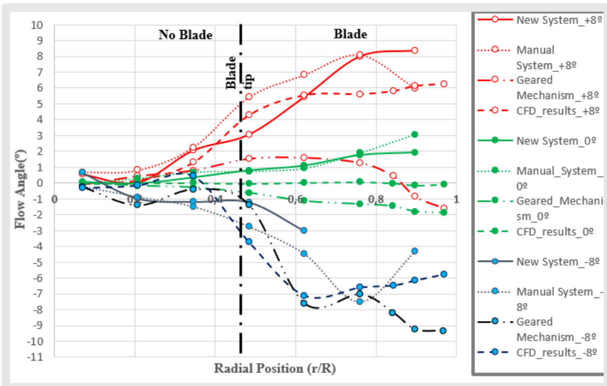


Figure 18: Deviation between tested mechanisms and CFD angle profile with error bars

Based on the flow angle results obtained, it can be concluded that the new mechanism increased the accuracy in the blade angle adjustment, compared to the adjustment made by the automated geared mechanism. For a setting of +8º, the deviation reduction is relevant when comparing the direct drive mechanism with the automated geared mechanism, reaching **72%**.

In an overall analysis, it was possible to conclude that the new mechanism allowed an absolute mean error reduction in the IGVs adjustment of 30.75%, compared to the results obtained for the automated geared mechanism. Regarding the comparison of the new design with the manual mechanism, the results are similar for the tested angles. The new mechanism can furthermore guarantee repeatability of results.

7. Conclusions

The main goal of this work was to redesign an automatic IGV control system, which could meet the requirements regarding the angular adjustment accuracy of IGVs for the design of small-scale compressors. A design involving a direct drive mechanism has been designed, manufactured and partially tested. Better results were obtained compared to the previous automatic mechanism.

The main conclusions of this work can be summarised as it follows:

- In small-scale applications, mechanisms involving gears require accurate and challenging assembly, being difficult to obtain repeatability and accuracy;
- In small-scale applications requiring repeatability of procedures, the electronic error should be preferable to mechanical error which is often a function of the mounting mode of the system and is more dependent on the operator;
- The use of a direct drive mechanism could be implemented on a large scale in future small scale applications, since it does not require a large investment compared to a mechanism that has more mechanical components.
- In order to design efficient compressors, it is necessary to fix the value of numerous variables existing in test rig.

Future work in this field should include improving Arduino code by increasing the accuracy of the resolution in code adjustment, as well as developing an application that can serve as a user interface. A study of ways to minimize test bench variables to achieve better repeatability in test cycles should also be one of the short-term goals for efficient micro compressor design.

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