Development of a sensor for performance studies of the CFM56-3 engine

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November 2017

Abstract

The high pressure compressor is one of the main focus when performing maintenance to a turbofan engine. To study the performance of this component, it is important to know the temperature and pressure values at its inlet and exit. For this thesis, a sensor capable of measuring these variables for the CFM56-3 engine was developed and produced for station 25, the one before the high pressure compressor. With this data and using the Gasturb^{TM} software, performance calculations were done which led to two studies. The first one is related to the blade tip clearance influence on the performance of the high pressure compressor. Its effect on four performance parameters was analysed, the overall compressor efficiency, the pressure ratio, the polytropic efficiency and the corrected mass flow. To present the results the dimensionless tip clearance was used. The results obtained were erroneous, which led to the conclusion that to study this variable an approach which includes more variables of the compressor is necessary. The second study performed analysed the influence of having a sensor as the one previously mentioned, on the performance calculations of the high pressure compressor. The developer of Gasturb^{TM} Joachim Kurzke, and CFM suggest alternative solutions when the thermodynamic values at station 25 are not measured. These solutions are compared with the results obtained using the sensor, by calculating the four variables aforementioned and evaluating their differences. The results led to some suspicion on the CFM correlation and support the development of similar sensors to properly study the high pressure compressor.

Keywords: Turbofan engine, High pressure compressor, Temperature sensor, Pressure sensor, Tip clearance, Gasturb^{TM}

1. Introduction

1.1. Context

Due to the risk involved in flying and to its intense conditions, maintenance is a very important part of the life of an aircraft. Engines are the area of maintenance of a commercial aircraft with higher costs. According to a study from the International Air Transport Association (IATA) in 2015, engine maintenance costs represent 40% of the direct maintenance cost [1].

Minimizing the maintenance costs of aircraft engines is an important issue for airline companies. In order to implement a proper maintenance, it is necessary to understand how each component of the engine is performing. Then it is possible to relate this performance to the maintenance procedures performed, consequently enhancing them, which leads to a reduction of time and costs. To study the performance of an engine, maintenance centers use test beds to measure their thermodynamic data, simulating flight conditions. This is possible by placing sensors on different stations of the engine, commonly known as the instrumentation of an engine. A proper instrumentation is essential for a useful performance study, since more knowledge on each component of the engine is available. To understand the conditions of each component separately, thermodynamic measurements between the components are required.

This work was developed in collaboration with TAP Maintenance and Engineering (TAP ME), the maintenance department of TAP Portugal. It is focused on one of the most intervened engines in TAP ME, the CFM56-3. The study is aimed at the high pressure compressor (HPC), considered one of the most important components of a turbofan engine [2]. In TAP ME's test bed, the CFM56-3 engine does not have an adequate instrumentation before the HPC (station 25), which is a substantial limitation for a performance study of this component. Thus, the first objective of this work is to describe the production of an adequate sensor for station 25 of the CFM56-3 engine, capable of measuring temperature and pressure, the T_{25}/P_{25} sensor. With these sensor it is possible to study the efficiency of the HPC and consequently, improve the maintenance procedures performed by TAP ME on this component, which will ultimately lead to financial and time savings. This work was focused on one of the variables relevant on the HPC performance, the tip clearance, which is defined as the distance between the compressor blades and the casing around it.

1.2. Outline

This work consists of five chapters, including the current one, the introduction. On chapter 2 the background to this work is presented, describing turbofan maintenance procedures. The chapter finishes with a review of literature related to experimental studies centered on the blade tip clearance.

Chapter 3 is composed by two parts. The first one consists of the description of the development and production of the new T_{25}/P_{25} sensor. The second part of the chapter is focused on the HPC performance calculations accomplished using Gasturb^{TM} a software specialized on the study of gas turbines.

For this work two studies were developed, and their results are presented on chapter 4. The first one was focused on studying the influence of the tip clearance on the performance of the HPC. The second study was focused on understanding the relevance of the T_{25}/P_{25} sensor produced, on the calculation of the performance parameters. In the future, this study will help decide if similar sensors are worth developing for other engines. Therefore, the values obtained for the performance parameters, with the sensor and without it, were compared. Additionally, it was also studied the quality of a correlation provided by CFM, the manufacturer of the CFM56-3 engine, to use in case the T_{25} is unknown.

On the final chapter the conclusions of the study are presented and suggestions for future work are given.

2. Background

2.1. HPC maintenance

The four variables considered by TAP ME to have a greater influence on the HPC performance are the blade chord, the blade tip clearance, seal teeth clearance and the compressor discharge pressure (CDP) seal. The one analysed in more depth in this work is the tip clearance, defined as the gap between the surrounding casing and the compressor rotor blades. This gap is essential to avoid rubbing between the compressor blades and its casing, which would cause an increase in friction and great damage. Tip clearance represents a very serious problem in turbomachinery, due to its negative impact on the efficiency of a compressor [2]. To minimize this, the tip clearance should be kept as small as possible. However, due to vibrations or to the possibility of a variation higher than expected of the blade's size due to thermal variations, this is quite a risk. The thermal variations, occur due to the different engine's operating conditions, during a flight. Therefore, it is advisable by manufacturers, to provide a liberal clearance in order to avoid rubbing [2].

To perform the blade tip clearance maintenance procedure for the HPC, two processes are necessary. Firstly, the compressor outside casing diameter is measured and its medium value is determined. Subtracting this value by the tip clearance intended, the blade height required is defined. Secondly, to set the blade height, a high speed grinding (HSG) machine is used. It grinds the blade tips of the rotor while it is being spun at high speed, which may reach the value of 7000 rpm. This equipment is provided with measuring systems, which ensure a considerably high degree of accuracy, with diameter tolerances that can be held to 0.025 mm [3].

Two examples of the HPC casing diameter measurements are presented in Figure 1 and 2.

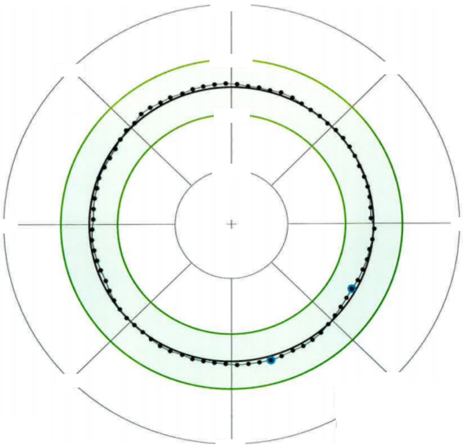

Figure 1: Example of an HPC casing with a regular surface (scale deleted for confidentiality reasons) [4]

The first figure represents a casing with a regular diameter, since all the points measured are close to the medium diameter line. This line is the one on the middle of the green zone of the figures. Figure 2 has several points considerably distant from the medium diameter. Considering that for these two engines, the tip clearance defined on TAP ME's workshop would be the same, the distance between the medium diameter of the casing and the tip of the blades would also be the same. However, due to irregularity of the casing of Figure 2, the real tip clearance would be different, which could lead to different efficiencies obtained for the two HPCs. The engine of Figure 2 would likely be the one with a smaller efficiency, since it has a higher tip clear-

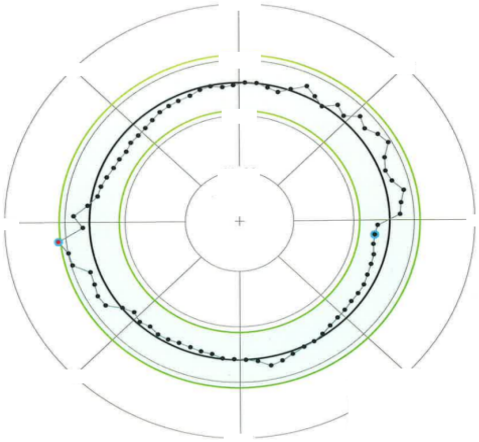

Figure 2: Example of an HPC casing with an irregular surface (scale deleted for confidentiality reasons) [4]

ance. The ideal would be to repair the casing of this engine, which can be done through a process named skin cut repair. However, this process is expensive, which is why it is not currently used at TAP ME. If, through tip clearance studies such as the one of this work, it would be concluded that this process would increase significantly the efficiency of the HPC, then the investment on the skin cut repair procedure could compensate despite of its high financial price.

2.2. Literature Review

According to authors in the area, the blade tip clearance and the blade chord are considered two of the main variables influencing the efficiency of an axial compressor [5]. The objective of this work is to study the influence of the tip clearance on the HPC. Therefore, below it is described how researchers perform experimental studies related to the impact of the tip clearance on the performance of axial compressors. This review was helpful to chose the approach used on this work.

Experimental studies on tip clearance flow have been extensively carried out in the past sixty years [6]. Two recent papers from Danish et al. [6] and Dong et al. [7], from 2016 and 2014, respectively, present a review of the experimental tip clearance studies performed over the years, which was the basis for this section.

One relevant assumption encountered was the use of only the three first stages of an axial compressor, since these three are considered to have a significantly higher importance on the performance of a compressor than the remaining stages [5].

In order to handle the tip clearance variable specifically, some of the authors used the dimensionless tip clearance, d, defined as the ratio between the absolute tip clearance, t and the blade height, H_b. This relation is represented by equation 1 [7].

$$d = \frac{t}{H_b} \tag{1}$$

The use of this variable is suggested by several researchers as Saravanamutto et al. [5], and Dong et al. [7]. However, the dimensionless tip clearance was not the only variable found to study this problem. Actually, there is an alternative approach further applied than this, which is the ratio between the tip clearance, t, and the chord, c, the tip clearance-chord ratio, τ, introduced on equation 2.

$$\tau = \frac{t}{c} \tag{2}$$

This solution is adopted by Lakshminarayana and Horlock [8] who on their study used the ratio between tip clearance and chord, therefore, studying, together, two of the main variables that influence an axial compressor's performance.

In summary, there are two main variables used to study the tip clearance, the dimensionless tip clearance and the tip clearance-chord ratio. This last one is the most popular due to addition of the chord variable, which is related to the profile losses, one of main causes of decline of the compressor's performance [6]. As parameters for characterizing the compressor performance, four variables were found to be the most commonly adopted, compressor isentropic efficiency, pressure ratio, polytropic efficiency and corrected mass flow. This last is considered to have a similar behaviour to the compressor efficiency, therefore it is not analysed on this work [9].

3. Sensor production and calculations

3.1. Sensor design

In order to measure the temperature and pressure at station 25, TAP ME had a sensor manufactured by CFM. However, in the past years, the sensor has not been used due to its inoperability during the majority of tests, because the sensor breaks very easily. The main problem of that sensor is the pressure tube, responsible for connecting the sensor to the engine support. The tube is quite rigid, which makes it difficult to assemble and disassemble [10]. This is specially a problem because its placement on the engine requires many bendings of the tube. Therefore, TAP ME decided to produce the sensor itself, instead of being dependent on the one from CFM which was not practical to use.

Firstly, to work on the design and production of this new sensor, it was necessary to understand what are the conditions that it will be subjected to. Station 25 is characterized by values of total temperature commonly between 370 and 395 K, and in a range of 220 to 240 kPa for total pressure [11]. Then, the design of the sensor was done, which is presented in Figure 3 in computer-aided design (CAD) format, with its components numbered. This design was composed by four main components, which are described below.

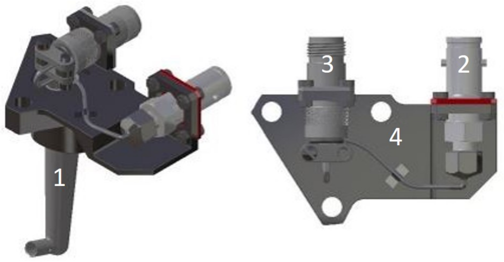

Figure 3: New sensor designed in CAD with its components numbered [10]

1. Probe, which has a thermocouple and a pressure tube inside of it and exposes them to contact with the flow. The thermocouple measures the total temperature value. The pressure tube receives the flow and guides it to the test bed, where the total pressure can be measured.

2. Pressure connector which guides the air from a pressure tube to the test bed.

3. Temperature plug that receives the thermocouple electrical wires and makes a connection to a socket on the test bed.

4. Central support of the sensor that connects all the other components.

The first three components were ordered from outside of TAP ME. Component four, which has the objective of connecting the other parts, was manufactured in TAP ME. The other components have predetermined dimensions, because they are standard components produced by external manufacturers. However, component four was entirely produced and developed in TAP ME, which implies it did not have limitations on dimensions, being the only part that can be adjusted to fit the available engine space.

This solution is an improvement to the one before since it does not rely on long tubes directly attached to the sensor, as the previous sensor did. The tubes, which will be hereafter named test bed connections, are inserted separately after the positioning of the sensor, so there is no need to apply torsion and bending on them. The attachment occurs on component two and three, pressure and temperature connections, respectively.

3.2. 3D printing

Due to confidentiality issues, TAP does not possess the technical drawings of the engine, which makes it difficult to know the exact dimensions of its components [10]. The solution used was to measure manually the dimensions needed. Therefore, the exact measurements of the engine are not known, and since the space where the sensor is placed is tight, it means the dimensions of the sensor are a critical factor. The largest issue was if the two plugs would be aligned with the two corresponding openings where they fit on the engine. To build the sensor it would be necessary to invest financial capital and an important amount of time, so it would not make sense to do it without being completely certain if it would fit into the engine. To have that assurance the most effective approach and chosen solution was to use a 3D printer to test the CAD.

In total three 3D models had to be produced, since the first two did not fit properly on the engine. The two failed tests were due to the temperature plug, component three, not having enough space on its respective opening of the engine, to attach its respective test bed connection. After altering dimensions of the design CAD, the third 3D model was successfully assembled on the engine. This indicated that the design T_{25}/P_{25} sensor was acceptable to move to the next step, the individual production of its parts.

As mentioned previously, component 1, the probe, was used from the previous sensor, so it did not need to be acquired. Components two and three, the pressure connector and temperature plug, were ordered to their respective suppliers. The last component, the central support, was done in one of TAP's workshops, with a modern computer numerical control machine (CNC). The material used for its production was stainless steel.

With this part concluded, the next step was to assemble the components together.

3.3. Assembly of the sensor

The mounting of the sensor parts included several steps. Firstly, the thermocouple wires and the pressure tube were positioned inside the probe, component 1. The thermocouple used was type K which can read temperature values from 5 K to 1645 K, therefore its range includes the temperature values expected at station 25. The electrical connection was done using two pins and two sockets [12].

The following step was to connect the different components. The connection between the central support and the probe was accomplished through welding. The process used was Tungsten Inert Gas (TIG). The remaining connections were done with screws. The sensor production was then concluded, with the final version of the sensor presented in Figure 4. Additionally, it was then necessary to have connections to the test bed. The former connections from the CFM sensor were reused to provide adequate connections to components two and three.

Figure 4: Concluded sensor - Front view

3.4. Sensor quality tests

To verify the quality of the temperature measured on the sensor, through the thermocouple, a calibration test was done in a TAP facility specialised in this sort of tests. If the test revealed a different value from the real one, troubleshooting of the sensor could be done before moving to a test with an engine, on the test bed. The test consisted on putting the tip of the sensor on a tank with silicone oil which is controlled to be at 393.0 K. For a better understanding of how these test proceeds, the work of Benedict [12] is recommended. The sensor proved to be accurate, by measuring exactly 393.0 K. No similar test was available to calibrate pressure so it was decided to proceed to the following test.

The second test with the T_{25}/P_{25} sensor had the objective of evaluating if the new sensor could be properly installed on the engine. This was tested on an engine in TAP ME's workshop. An issue was found caused by the tip of the temperature plug that was protruding too much. However, the problem was solved by cutting a very small part of the tip of this component, by approximately 5 mm. Then the positioning was attempted again with good results. Subsequently, the final necessary test was possible, the test with an engine on TAP ME's test bed.

On this test, a problem occurred, the temperature value read was 328.0 K. However, the value of temperature acquired should be between 370 and 390 K, as mentioned on section 3.1. The measurement was certainly incorrect and the error was quite high. The pressure read was 33.0 psi, or 231.6 kPa, which is a value on the expected range. Therefore, it was concluded that only the temperature measurement was incorrect.

To perform troubleshooting of the sensor, it is necessary to understand how the thermocouple circuit works. The thermocouple is composed by two metals of different materials, which are welded on one end. Each metal produces a different electrical potential that varies according to changes in temperature. This rate of change is different for each of the metals in the thermocouple, so a thermocouple produces a voltage that increases with temperature. This is described as the Sebeck effect [12].

The problem was occurring on the coupling between the temperature plug of the sensor and its respective test bed connection. On this coupling, the continuity of the materials has to be kept to ensure a proper reading of the measurements. The connection is done by sockets and pins, therefore the pins have to connect to sockets of the same material to keep the continuity. However, the material of the sockets was switched, generating a voltage which is read on the test bed. This value will translate the temperature in the temperature plug of the sensor, not the one on the flow. As stated by Benedict, problems similar to these occur quite often when working with thermocouples, extra attention has to be given to the connections [12].

The second calibration test was done with the sensor and the test bed connections, the source of the problem. The result was 372.8 K for 373 K of reference on the silicone oil tank. This meant the sensor and its connections were apt to measure temperature, and the problem was fixed.

In total, the new T_{25}/P_{25} sensor was used two times on CFM56-3 engines on TAP ME's test bed. The measurements carried out by the sensor are presented in Table 1. The temperature and pressure values presented on this table are the corrected values, which take into account the ambient conditions of temperature and pressure, so a more appropriate comparison can be done between the tests. On Table 1, engine 1 is the engine tested with an unsuccessful measurement, where the thermocouple problem was discovered and the value read was 328.04 K. Engine 2 was the second measured engine with the sensor, which presented positive results, with a temperature value of 374.14 K, inside the range of temperatures expected. It is possible to observe that the temperature values are quite different, this was due to the issue of the sensor during the test of engine 1. For the pressure measurement, both results were on the expected range. Unfortunately, it was not possible to test the sensor in more engines, but the test of engine 2 provides confidence on the quality of the sensor.

Table 1: Values measured with the new T_{25}/P_{25} sensor

Measurement	Engine 1	Engine 2
Corrected temperature (K)	328.04	374.14
Corrected pressure (kPa)	231.62	231.99

3.5. Performance calculations

The Gasturb^{TM} software, is a program capable of evaluating the thermodynamic cycle of common gas turbines in a user-friendly way [9]. On the present work, this software was used to perform the comparison between the performance of different engines, through a tool named Model Based Test Analysis (MBTA). To work with this tool it is necessary to have a model engine as benchmark. A model already existed in TAP ME for the CFM56-3 engine, which could be used. However, this model was done with data from the CFM56-3 engine working at the CFM56-3B2 rate and the data available for this work was from engines tested at CFM56-3C conditions. Therefore, it was necessary to extrapolate the data from this model to the CFM56-3C conditions. This process was done with success and thermodynamic equations were used to understand if the efficiencies obtained on this model were adequate, helping to confirm the quality of the solution obtained.

4. Results

Two sets of results are presented in this chapter. The first set, presented in section 4.1, is focused on the tip clearance of the HPC blades, considering how it affects the behaviour of this component. The second set of results is related to the T_{25}/P_{25} sensor produced, and is presented in section 4.2. The objective is to understand the relevance of the measurements accomplished with the sensor, on the HPC efficiency calculations. To achieve this, five scenarios of different measurement possibilities are compared.

4.1. Tip clearance influence on the High Pressure Compressor

For this study the results obtained from the Gasturb^{TM} calculations are used. Seven CFM56-3 engines are taken into consideration here. For each engine, three variables regarding the HPC component are studied, HPC efficiency, polytropic efficiency and pressure ratio. In this section these variables are correlated to the HPC values of tip clearance.

As stated in section 2.2, the first three stages of the HPC are considered the most relevant and some experimental studies just consider these on their work. Therefore, only the results for these stages are presented and analysed in this chapter.

In Figure 5, the effect of the tip clearance of the first stage on the HPC efficiency is presented. However, for the blade tip clearance, the values known are for each stage and the HPC overall efficiency represents the entire compressor, not each stage. Thus, the results obtained would not be conclusive. Therefore, the approach chosen was to use the polytropic efficiency which is related to the efficiency of each compressor stage.

The following charts were done with the seven engines in study and resorting to a second degree polynomial function to correlate their values.

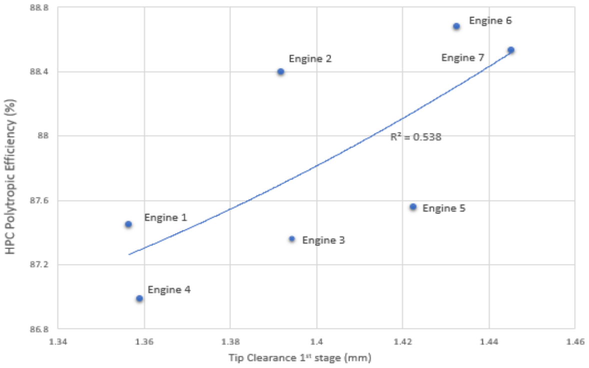

Figure 5: Effect of the first stage tip clearance on the polytropic efficiency

The curve obtained in this figure presents an opposite trend to the expected one. The efficiency is increasing with the tip clearance, which is an odd result, since with a greater tip clearance, the losses are higher leading to a lower HPC efficiency. The correlation coefficient obtained was 0.54, which indicates that this correlation is inadequate. In Figure 6 the same analysis is done, for the second stage of the HPC.

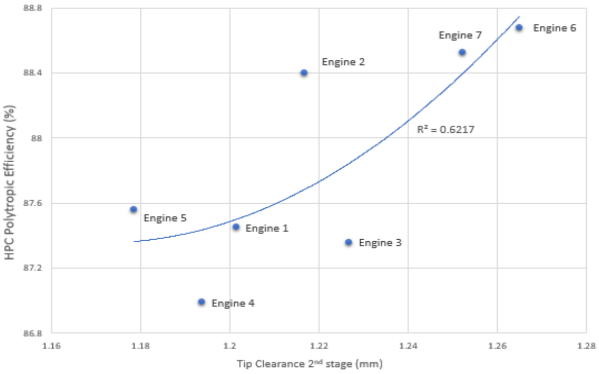

Figure 6: Effect of the second stage tip clearance on the polytropic efficiency

This curve is similar to the one from Figure 5, with the polytropic efficiency increasing with the tip clearance, which is a result different from the expected. The correlation coefficient is slightly higher than the one before, with a value of 0.62, which is still a low value. However, the result is different in Figure 7, where the analysis of the third stage is done.

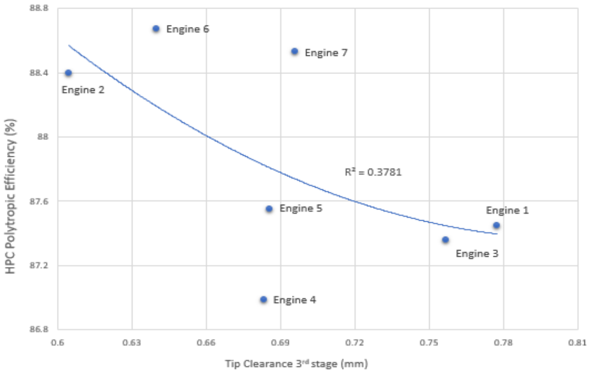

Figure 7: Effect of the third stage tip clearance on the polytropic efficiency

This curve presents the expected result, as the polytropic efficiency is decreasing with the increase of the tip clearance. However, the correlation coefficient is the smallest so far, 0.38. These erroneous results may be occurring because the stages are being studied separately, when they should be studied together, since all three have a substantial impact on the overall compressor. This led to wonder if the approach of studying the stages separately was the best.

A different approach was attempted based on the use of a variable suggested by several authors, the dimensionless tip clearance. This variable consists on dividing the blade tip clearance value by the height of the respective blade, as represented by equation 1. However, the height of the blade is not measured on TAP ME's procedures, therefore, its value is not available for the engines studied. The solution used was to adopt a standard blade height measured from a CFM56-3 engine available on TAP ME's workshops. The values obtained were, 8.92 cm, 6.72 cm, 5.43 cm, for the first, second and third stages, respectively. With these values it is possible to study the dimensionless tip clearance. However, if this is applied to the results from Figures 5, 6, 7, the outcome would be similar since all the values would be divided by the same constant. The approach chosen was to take advantage of the nondimensiolization of tip clearance to combine the three first stages of the HPC.

Essentially, due to the irregular results of Figures 5 to 7, an alternative approach was necessary, which led to the use of the dimensionless tip, mentioned in section 2.2. It was handled to combine the three first stages and evaluate the overall compressor, not just the separate stages. Therefore, the HPC parameter used for this curve was the HPC overall efficiency, instead of the polytropic efficiency.

The result had, again, a different trend than the one expected and the correlation coefficient was much smaller, with 0.01. Therefore, the dimensionless tip clearance is not an adequate solution for this study, as the correlation coefficients suggests, it is worse than the one attempted in Figures 5, 6 and 7. The two approaches used were not successful. Unfortunately, due to lack of measurements of chord of the compressor blades, a third approach that uses the tip clearance-chord ratio, represented by equation 2, was not possible.

After the disappointing results obtained with the HPC efficiencies, it was decided to focus on another parameter used in several tip clearance studies, the HPC pressure ratio. The same four curves were done. In Figure 8, the effect of the tip clearance of the first stage on the HPC pressure ratio is presented.

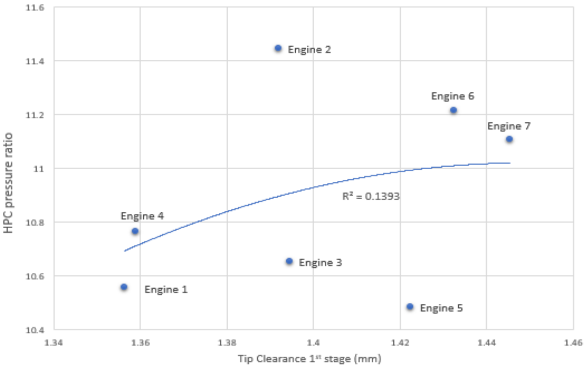

Figure 8: Effect of the first stage tip clearance on the HPC pressure ratio

This outcome is similar to the one of Figure 5, with the efficiency increasing with the tip clearance value. The correlation coefficient obtained was 0.14, which is considerably smaller than the one from the curve of Figure 5. In Figure 9 the same analysis is done for the second stage of the HPC.

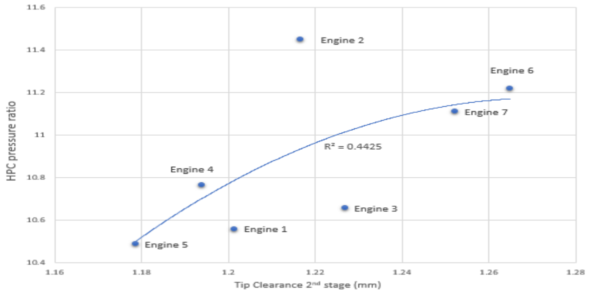

Figure 9: Effect of the second stage tip clearance on the HPC pressure ratio

The curve represents, again, the pressure ratio increasing with the tip clearance and has a correlation coefficient of 0.44. Once more, erroneous results were obtained. Figure 10 is focused on the third stage.

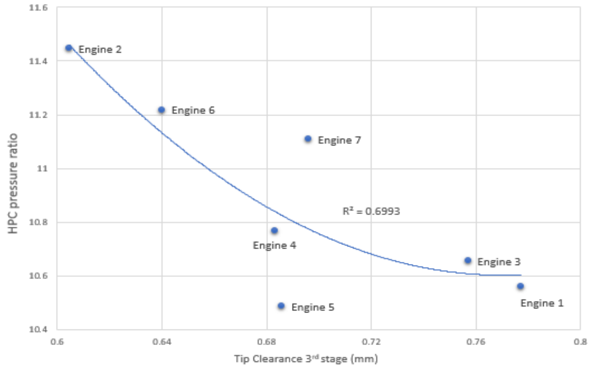

Figure 10: Effect of the third stage tip clearance on the HPC pressure ratio

This curve has a similar behaviour to Figure 7, the pressure ratio decreases with the tip clearance, an expected result. The correlation coefficient is the highest of the entire scope of curves, with a value of 0.70. This different trend for the third stage results is likely to be related to other unaccounted parameters of the HPC that changed besides of the HPC, for example the blade chord.

Lastly, the approach done on with the HPC polytropic efficiency, using the dimensionless tip clearance was adopted for the pressure ratio.

The outcome obtained has a correlation coefficient of 0.3, a considerably low value. This result confirms that the dimensionless tip clearance approach used here is not reliable.

The results obtained from this section, indicate that the third stage seems to have a greater impact on the HPC performance than the others. However, the correlation coefficients of all the curves plotted were too small to make such conclusions. The only possible conclusion is that the two approaches used are not the indicated to study the tip clearance, for the conditions encountered on this work. On the studies referred in section 2.2, when the tip dimensionless clearance was discussed the blade chord was constant. The chord is considered to have a considerable impact on the total losses of the compressor. Therefore, this variable should be constant to enable an independent study of the tip clearance. On the tests from TAP ME the value of this variable is not measured, although it can be assumed that it is not constant. As stated in section 2.2 researchers that dealt with this situation have turned to a different solution, using the tip clearance-chord ratio. Unfortunately, on this work the blade chord values are not available, although, considering the results from section 4.1 it can be understood that it would be the best option to study the tip clearance. By having a ratio combining tip clearance and blade chord the two main variables responsible for axial compressors losses would be studied together.

4.2. T_{25}/P_{25} sensor relevance

In order to complete any performance study of the HPC without a T_{25}/P_{25} sensor developed, Kurzke [9] recommends the use of the values from the model engine. This solution was adopted on the MBTA tests, mentioned in section 3.5, for the stations without instrumentation on TAP ME's test bed. Therefore, it is possible to estimate the efficiencies obtained if the sensor was not developed. Currently, TAP ME has available for the CFM56-5B engine, a T_{25} sensor. This motivated another addition to this study, to understand if just measuring pressure or temperature would result in much difference on the results obtained in Gasturb$^{\text{TM}}$İf that would be the case, it could motivate TAP ME to add a pressure measurement to their current sensor. Additionally, there is another intention for the current study. For station 25, the manufacturer of the engine, CFM International, recommends a correlation to calculate the T_{25} value, when it is not known. This correlation is presented as equation 3 [13]. It assumes a dependence of T_{25}, on the ambient temperature, T_2, and on ΔT_{25} a factor dependent of the low pressure spool rotation, N_1, possible to obtain on a table provided by CFM [11].

$$T_{25} = T_2 + \Delta T_{25}\left(N_1\right) \tag{3}$$

The validity of this solution is tested to understand if it is a reasonable alternative to a sensor. Therefore, the thermodynamic values of five different scenarios are compared. These scenarios are listed below.

- Scenario with the T_{25}/P_{25} sensor.
- Scenario without any sensor, therefore with T_{25} and P_{25} from the Gasturb$^{\text{TM}}$ model.
- Scenario with a T_{25} sensor and P_{25} from the Gasturb$^{\text{TM}}$ model.
- Scenario with a P_{25} sensor and T_{25} from the Gasturb$^{\text{TM}}$ model.
- Scenario with a P_{25} sensor and T_{25} from the CFM correlation.

Table 2 presents the average difference in percentage, between the performance parameters obtained with the real sensor values, and with the other four scenarios. This average is obtained from the values of six engines tested on TAP ME's test bed. The three HPC performance parameters studied, presented on this table, are the HPC efficiency, the pressure ratio and the polytropic efficiency.

First, analysing the HPC efficiency values from Table 2, it can be understood that the results with the engine Gasturb$^{\text{TM}}$ model are the ones with larger differences, with an average of 2% on the efficiency error.

For the P_{25} sensor and T_{25} sensor scenarios, the averages on the differences are smaller, with 1.24% and 1.40%. These values are quite close, and are smaller than the first scenario. The fourth scenario, with the CFM correlation, presents an average difference of 2.01%, a high value close to the one of the first scenario.

For the pressure ratio, the scenarios with the same pressure value have, obviously, the same results. This is observed on Table 2, where the first and third scenarios have an average difference of efficiency of 2.53%, a considerably high value. The other scenarios do not present any difference to the T_{25}/P_{25} sensor results, since they have the same pressure measurement as the sensor.

Lastly, for the polytropic efficiency, the differences are smaller than the ones obtained for the other two variables. The T_{25}/P_{25} Gasturb$^{\text{TM}}$ model scenario is the one with the highest error, followed by the CFM correlation scenario. The second and third scenarios have an error close to 1% and are, as for the HPC efficiency, quite similar.

In conclusion, in Table 2 where the real scenario, the one where the calculations are performed with the T_{25}/P_{25} sensor, is compared with the others. On these comparisons it is possible to understand that the T_{25}/P_{25} model has the worst average of results, which is not surprising, since it is the scenario with less measured data.

The P_{25} sensor and T_{25} sensor, have smaller differences, typically between 1% and 1.5%, except for the pressure ratio. These errors are still considerably high, justifying the importance of having both variables measured. Additionally, it is not possible to distinguish which measurement, T_{25} or P_{25}, would allow accomplishing a smaller error.

The correlation scenario performed equally or worst than the P_{25} sensor, for all three performance parameters studied, raising some doubts on the correlation's quality.

5. Conclusions

The first part of this work focused on describing the successful production of a sensor capable of measuring temperature and pressure for the CFM56-3 engine, on the station 25. This sensor had its development concluded through 3D models, essential to test the positioning of the sensor on the engine. Afterwards, the sensor was produced and tested with positive results.

After this step, it was possible to study the tip clearance effect on the performance of the HPC. On this study the dimensionless tip clearance was used and the results obtained presented erroneous curves, most of them with an opposite behaviour than the one expected. Therefore, the main conclusion is that for this particular situation, another approach should be carried out, the use of the tip clearance-chord ratio. This variable allows the addressing of the two main blade features accountable for the losses of an axial compressor, the tip clearance and the blade chord.

The final achievement was reached through a study of the relevance of the T_{25}/P_{25} sensor. Four scenarios of alternative measurements were tested, even testing the reliability of a correlation defined by CFM, to replace the T_{25} measurement. This correlation, presented a considerable error and did not prove to be a good option. On the comparison between an isolated temperature measurement and an isolated pressure measurement, it was not possible to compare which one gave the best results, although they both performed better than the CFM correlation. Considering the entire scope of results, it can be concluded that, the investment on the development and production of a temperature and pressure sensor for station 25 is a substantially superior option than its alternatives.

After this work, further research studies could be

Table 2: Difference between the values obtained for three HPC performance parameters with the T_{25}/P_{25} sensor and with the other four scenarios (%)

Absolute average	HPC efficiency	Pressure ratio	Polytropic efficiency
T_{25}/P_{25} Gasturb$^{\text{TM}}$ Model	2.01	2.53	1.62
P_{25} sensor	1.24	0.00	0.98
T_{25} sensor	1.40	2.53	1.08
T_{25} CFM correlation and P_{25} sensor	2.01	0.00	1.43

conducted, such as: increase the number of engines available to execute the two studies performed. Continue the tip clearance study by adopting the tip clearance-chord ratio, which was to found to be adopted by a substantial amount of researchers from this field. Extend the amount of variables studied, focusing at least, on the four variables described in section 2.1, blade chord, tip clearance, seal teeth clearance and CDP seal. They are not independent from each other, therefore they should not be studied independently.

Acknowledgements
I would like to thank TAP Maintenance & Engineering for the opportunity to accomplish the present work with them, and to my family and friends.

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