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Generator Design: A Study of Optimized Airflow

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Generator Design: A Study of Optimized Airflow

Honors Research/Senior Design Project 4900:490

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Executive Summary

Problem

The core goal of this project was to prototype, test, and evaluate a new type of fan for the Safran Electrical & Power air-cooled generators and motors. When these machines run, they create a lot of heat from electrical and mechanical energy. If the parts become too hot, they can fail, so this heat needs to be released. Therefore, a cooling process is incorporated into the generator design by air-cooled process. The current design of the generators under investigation incorporate a fan that has been the same for the past 50 years without ever being analyzed for optimization or major design changes. The base fan is first created from a sand casting. It is then machined and modified for each generator in this project. The idea of a new fan being made for these two generators arose when they were not adhering to design requirements. A base mixed-flow fan was created to test on multiple generators. Upon creating a prototype, it will be tested to prove if it can increase the air flow, decrease temperatures, and increase power and life of the machines.

Results

The test was run with the test procedure outlined in the later pages. There were six tests ran total on two different fans. They all proved to be successful and achieve the main objectives for this project. The summary of results can be views in Table 10 where each test is outlined with its success criteria. The data taken was the most important in order to compare one fan directly with the other. Data such as temperatures throughout the generator, rotational speed, mass flow, pressures, vibrations and more were taken during the tests on the generator. Figure 11 outlines the Fan Curve graph which illustrates the mass flow vs static pressure. The graph has both fans overlaid on each other to show that the mixed-flow fan can produce a higher mass flow rate through the generator. For the self-cooled configurations 1&3, Figure 12 shows the bearing temperature vs the rotational speed. The bearing temperature was chosen because that was the most important area of interest. The temperature gap between the legacy and mixed-flow fan increases as speed increases. The fan only becomes more powerful the faster is goes. Lastly, Figure 13 represents the data for configurations 2&4 when hot air is added at the intake of the generator. Even under these extreme conditions, the mixed-flow fan manages to reduce the temperatures internally better than the legacy fan.

Conclusions

Both fans successfully completed all configurations without failure. The generator was able to hold RPM and all loads applied except for some minor deviations. Overall, the new mixed-flow fan performed better than the legacy fan. The new fan was able to decrease the DE bearing liner temperature for all configurations. Mass flow was also improved with the new fan.

Though the results for both Generator A & B were positive improvements, there are some things that the mixed-flow fan is having difficulty competing with the legacy fan design. They legacy design has not only been around so long because it works, but because of how easily manufactured, inexpensive and light weight its design is. The mixed-flow fan is opposite of all of these things. It is more expensive, heavier, and creates a much more difficult manufacturing process. Because of these things, the fan was not chosen for either generator for the future. The requirements were instead altered to overcome the issues being seen. Not always do positive result tests come with the finalization of a new design. The benefits of the mixed-flow fan just did not outweigh those of the legacy fan.

Broader Implication of Work

The skills that were gained through engineering school and the co-op experience were implemented throughout this project. It was a full circle experience in which design, manufacturing, testing, and reporting were included. Prioritization and project schedule were both critical aspects to the success of this project as they were on a tight time frame to complete. This research will benefit Safran in the future because if they are able to increase power and decrease heat in their air-cooled machines, they can also decrease the overall size of their generators. Saving weight in any aspect saves money.

Recommendations

The current fan is still being used because of the economical process and simplicity of the design it is being manufactured as. After completion of this project, a couple of issues holding it back from production is the cost and the weight. Optimizing the fan design to limit material will both decrease the cost and the weight of the fan. Second, in the tests performed, the prototype fan was not designed to conform to the shape of the already existing air inlet. If the shape of the fan is more specific toward each generator, the performance would increase because the air would have the most direct route.

Introduction

Safran Electrical & Power have been in the generator business for a significant time with machines dating back 50+ years. There is significant knowledge in the business about the machines and technology within Safran. For each new project the different requirements are taken, and the knowledge passed down is applied to create a new generator for a client. Sometimes though, there is a need for innovation. In this case, a fan adaptation was explored in order to improve the performance of a couple of specific generators. The project that consumed most of the research was a helicopter generator that was having bearing failure before the required flight hours were met. Bearings can fail for many reasons, but in this case, it was thought to be because the grease life was shortened due to high temperatures in the main bearing. The grease life can be extended significantly if the temperatures inside the bearing are decreased, every degree matters. The higher performing fan could help resolve this issue. The main goal of this project was to design, prototype, test, and evaluate a new mixed-flow fan in this generator to prove that it can increase performance, decrease overall temperatures, and increase the airflow. In the following pages the theory behind how a generator functions will be explained along with the details of the research and testing done on the mixed-flow fan.

Background

Generators have been around since 1831 when Michael Faraday created the first transformer (Rigb.org). A seemingly complicated system can be broken down into a few simpler ideas. The basic function of a generator is to convert mechanical energy into electrical energy. Its shaft it driven and attached to a rotor which spins inside of a main stator. The design of the rotor and stator has coils wrapped around stacks of metal sheets which when driven, creates a magnetic field. This electromagnetic induction outputs electricity which can power many types of machines. In the case of this experiment, an aircraft.

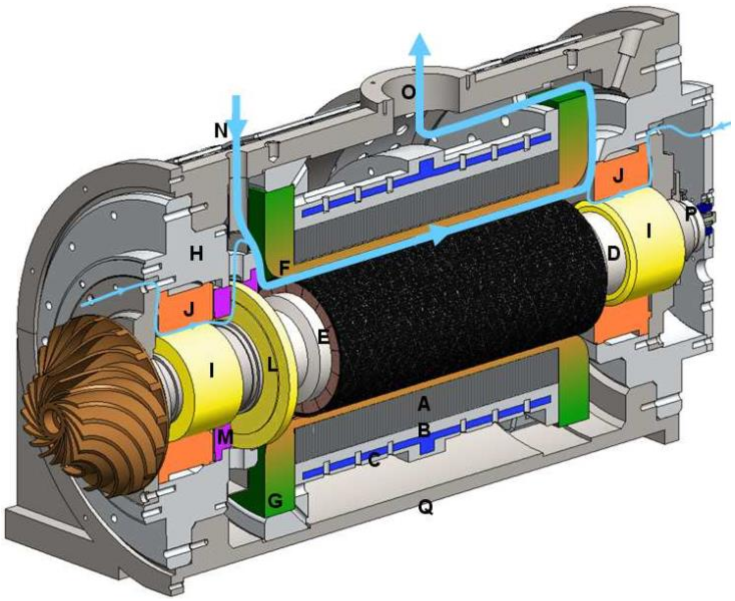


Figure 1: Basic air-cooled motor/generator. (Bianchi)

Figure 1 shows important components to note. They are the centrifugal fan in front, the rotor (E), and the main stator (F). The fan and rotor are on the same shaft and spin together. The air that the fan pulls into the generator is pushed between the small gap of the rotor and main stator. The blue arrows show the path of airflow. In Safran generators, there is typically no side intake or release. The air moves straight from the fan entrance through the end. A lot of energy is created as the rotor is spinning. Between the mechanical movement, the magnetic fields, and the very compact interior, a lot of heat is generating as well as electricity. The design of the fan in Figure 1 is a centrifugal fan. When the air enters the inlet, it is pushed outward by the blades and forced to the outer edge of the fan. When it reaches the edge, it is compressed into the small spaces through the generator. These types of fans are more effective as the air is directed exactly where it needs to go for the best cooling effect.

In contrast to the centrifugal fan, the design of the axial fan Safran uses in these two generators very different. This generator fan has been based off of the fan inside of a vacuum many years ago and has been used ever since. The four bladed axial fan pushes and compresses air from the inlet to the entire surface below. It is less effective than the mixed-flow fan because it does not give the air a best path for the most adequate cooling. Some of the air is directed into areas where it is not needed or is recirculated.

Figure 2: Original four-bladed axial fan design

For each generator, it begins manufacturing from a base sand casted fan. Its interfaces and blades are then machined based on the interior space and assembly structure of the specific generator. The simple design and manufacturing process make these fans economical and light weight. These benefits have made it difficult to rationalize a redesign of the fans, until there was significant reason to be concerned about the performance of the generators. The two generators examined during this test had two different issues, but both relating to the temperatures inside of the machine. The first problem that arose was that Generator A (it will be called to protect information) had an Amp power requirement but because of temperature limitations it was not able to reach that. In Generator B, bearing failure is occurring and the suspect is grease life limitations. Both of these issues are attempting to be solved by the incorporation of a new fan.

The following sections will show the design, manufacturing and testing of these new and old fans.

Design

Base Design

The base mixed-flow fan design was designed using in-house created and validated with testing tools by the design team. This fan was made up of many curved blades, a solid center, and a built-in cover to help direct the air, shown in Figure 3. As stated before, this fan will create a more direct path for the air to travel through the generator. Mixed-flow fans are also typically chosen because it creates a high flow rate while also increasing the fan outlet pressure. This will cool the machine more effectively throughout the different load and RPM ranges.

Figure 3: mixed-flow fan design

After the base design was created, the base design was modified to fit the two generators depending on their size and interfaces with different parts in SolidWorks and the interfaces were altered to create fans to fit in the problematic generators for testing. These designs had to be verified within a stack-up analysis and a finite element analysis to ensure when moving on to testing that it will not face stress failures or interference failures.

Stack-up Analysis

The following paragraphs will justify the design sizing for the replacement of the current fan. It will describe in detail the results from the stack-up analysis on the fan assembled on the generator rotor. The design needed to clear the air inlet and the end bell assembly of both generators A & B. There will be three stack-up calculations for the three critical areas of interest shown in Figure 4, and the stack-up calculations represent generator A, but was also similarly done for generator B but with slightly different dimensions.

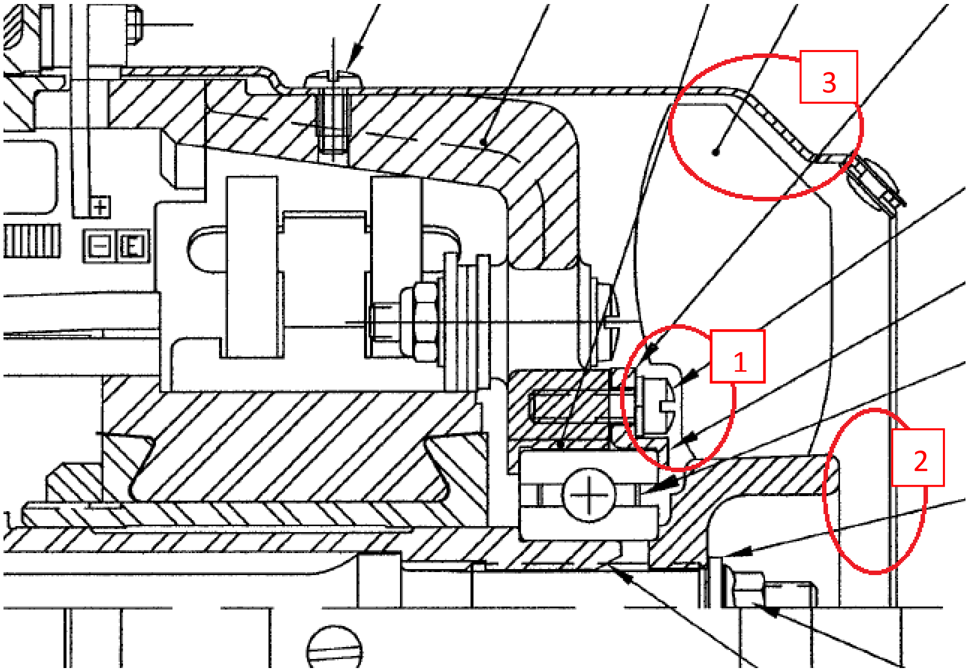


Figure 4: Generator A Section View

Stack-Up 1: Bolt Head Clearance

Stack-up				
End bell bolt axial clearance				
Item	Description	Dimension	Tolerance	Notes
1	End bell depth	2.05	0.003	
2	end bell depth 2	-2.03		

3	rib thickness	0.3761	0.0025	
4	retainer thickness	0.10	0.01	
5	lock washer thickness	0.053	0.005	
6	bold head height	0.1262	0.0075	
		0.674	0.028	height from end bell mount to top of retainer bolt
7	End bell depth	-2.05	0.003	
8	end bell depth 2	2.03		
9	bearing height	-0.5822	0.0025	
		0.0748	0.0305	clearance from top of bearing to top of retainer bolt

Table 1: Bolt Head Axial Stack-Up Clearance

The stack-up above calculates the gap labeled as 1 in Figure 4. It is the distance between the bolt head and the bearing interface that the fan must have to clear the bolt. It is calculated by starting at the end bell mounting hole on the housing and adding the nominal values axially of the end bell, washer, and bolt and subtracting the bearing height. With the symmetrical tolerance, the clearance will always be positive. Comparing the needed clearance to the fan, the large diameter and uppercut on the bottom of the fan, it will easily clear the needed gap.

Stack-Up 2: Air Inlet Screen Clearance

Stack-up				
axial top of air inlet and fan clearance				
Item	Description	Dimension	Tolerance	Notes
1	inlet height from bolt hole	2.34	0.01	
2	End bell depth	-2.05	0.003	
3	from bolt hole	1.27	0.01	
4	bearing height	-0.5822	0.0025	
5	fan height from bearing interface	-0.952	0.005	
		0.021	0.0305	clearance from top of fan to top of inlet

Table 2: Top of Fan to Top of Inlet Axial Stack-Up

The stack-up above calculates the gap labeled as 2 in Figure 1. It will be the clearance between the top of the fan and the top of the air inlet with the mixed-flow fan in place. Using similar parts as before but subtracting from the air inlet height and using the full fan height, it shows to have a very minimal clearance. With the large tolerance, at maximum condition interference is very possible. The model was not adjusted before the prototype was created, in hopes that nominally it would be fine. In an unfortunate situation of the dimension interfering, Safran has in house machining in order to alter the fan slightly for it to fit during the development test.

Stack-Up 3: Fan Tip Clearance

Stack-up				
Item	Description	Dimension	Tolerance	Notes
1	air inlet hole to top	1.67	0.01	(height of taper found from trig)
1	End bell depth	-2.05	0.003	
2	from bolt hole	1.27	0.01	
3	bearing height	-0.5822	0.0025	
		0.3017	0.0255	clearance from fan interface to air inlet taper (lower)
4		0.127		at 4.082 fan dia, height into taper
		0.428		clearance at fan diameter
6	fan height from bearing interface to major dia	-0.384	0.005	
		0.0442	0.0305	clearance from fan major dia to inlet taper

Table 3: Fan Major Diameter to Air Inlet Radial Stack-Up

The stack-up above calculates the axial gap labeled as 3 in Figure 1.

1. First, the vertical distance from the mounting hole to the top of the taper had to be found. Using the diameters on the air inlet drawing, the small vertical distance was found to take the 1.878 height to 1.951, giving the height of the top of the taper to the mount hole.
2. The height of the taper was calculated with by using the 4.335 and 3.76 diameters to find 0.285 height of the taper. This was subtracted from the 1.951 height to find the distance from the mount hole to the lower end of the taper.
3. The end bell depth and height from mount hole were used to find the distance from the mount hole to the bottom of the bearing liner.

4. Subtracting the bearing height give the clearance the fan can have from the bearing interface to the lower end of the taper, 0.302
5. Using trigonometry, the location at which the major diameter of the fan was found to be .158 into the taper, which creates a max axial clearance of 0.127.

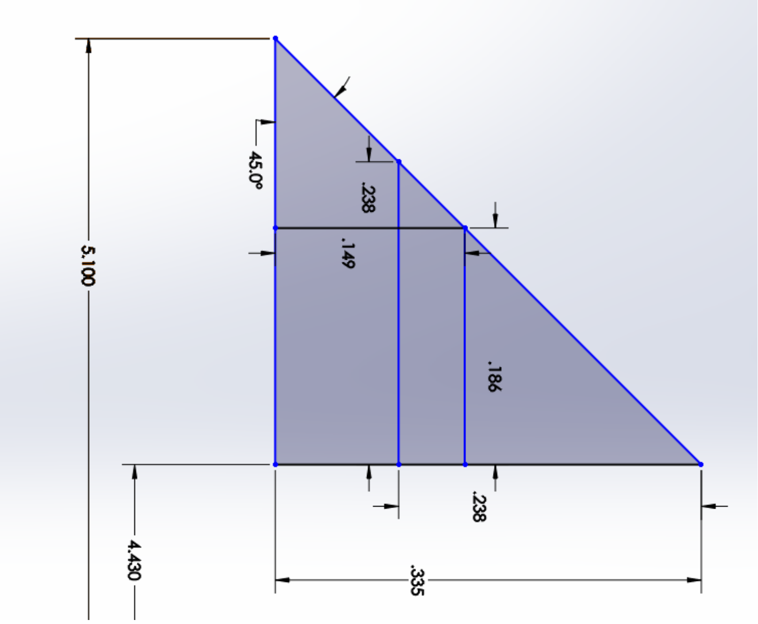


Figure 5: Geometric Representation of Air Inlet Angle

6. The clearance at the fan diameter was found by adding 0.127 to the 0.302 clearance.
7. From this, the axial fan distance from the bearing face to the major diameter, 0.384 is subtracted to find the nominal axial clearance between the fan and the air inlet.

The last stack-up that is important is the radial clearance between the fan and the air inlet. It can be simply analyzed because the taper has a 45-degree angle, the clearance is the same both radially and axially at 0.0442. Radially, the stack-up tolerance is smaller and will not cause any interference.

The stack-up analysis can be difficult to follow without the exact drawings to look at and if it is not repeated while reviewing it, but this stack-up was reviewed by multiple engineers to verify that it is a correct procedure and proper dimensions were chosen. The design of the fan was verified when upon prototyping the fan and assembling it into the generator, it fit well and did not have any interferences.

FEA Analysis

Finite Element Analysis is used to determine the strength and robustness of a component or assembly. In this simulation, both the legacy fan and the new mixed-flow fan are evaluated when put under similar loads with similar material properties. The test will be used to compare the fan to what it will undergo in a real-life test. FEA simulations help designers prevent failure and save a lot of time and money. They can be beneficial because if a component is manufactured and fails much sooner than predicted, the money spent on the component is gone and so is the time spent waiting for it and testing it. It can also show if a component is over designed. In this case, material could be reduced, or details removed that were once thought to be necessary. This alteration can save weight and cost on a component. The FEA simulations for the legacy fan and mixed-flow fan will be discussed in detail in the following pages.

Legacy Fan:

This analysis provides a baseline for the structural performance of the legacy fan. It then is used as a comparison to the newly designed mixed-flow fan. They are both subjected to an acceleration located at the center of the fan, a rotational velocity that will spin radially around the z-axis, and a fixed support is applied to the inner spline interface to simulate operation. The analysis was performed on the fan alone with no shaft or mounting features for simplicity of the model. Boundary conditions will simulate these pieces. A static structural analysis was performed to simulate the mounted fan taking on the load of the rotational force. It is applied to the center of the fan to rotate around the center axis of which the drive shaft would rotate. It is rotated at 100% of its normal operating speed as that is the acceptance test procedure design requirement. The fan is supported by a fixed support around the internal diameter on the spline interface. The fan is tested using the Aluminum Alloy which is used when the fan is sand casted. The material properties are outlined in Table 4 below.

Material	Aluminum, Alloy
Form	Sand Casting
Density *(lb/in³)*	0.097
Tensile Ultimate Strength *(ksi)*	45
Tensile Yield Strength *(ksi)*	40
Young's Modulus *(ksi)*	9860
Shear Modulus *(ksi)*	3630
Poisson's Ratio	.36

Table 4: Aluminum 356-T6 Material Properties

The boundary conditions that illustrate the analysis are outlined in Figure 7 below. All elements are as follows: The fixed support is labelled "C" and located on the internal splines of the fan, the rotational velocity is labelled "B" and rotates around the center axis of the fan at 100% of its normal operating speed, and the acceleration force is based off the force the rotational speed generates. It is represented by arrow on the fan with the direction shown from the center. The element is parameterized, and it is broken down to 905.51 in/s^2 in each direction. The arrow displays one direction as an example.

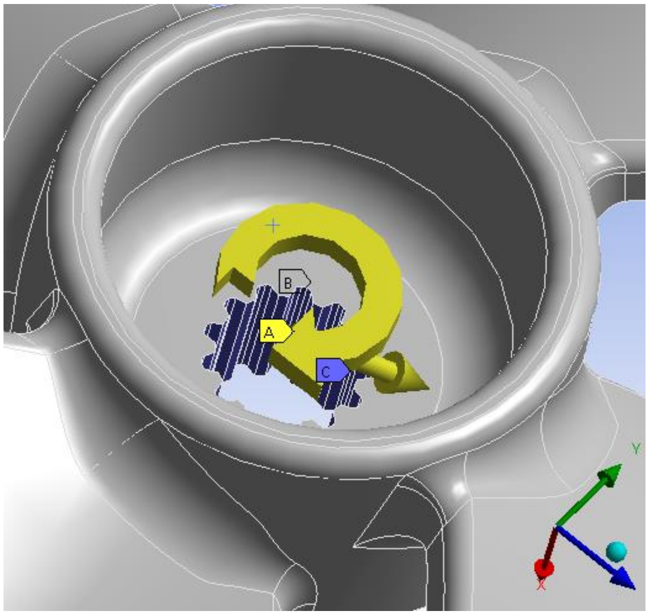


Figure 6: Legacy Fan Boundary Conditions

Once all conditions have been applied, the analysis is initiated. The outputs that were evaluated were the stress and deformation. The critical results are outlined in Table 5. The contour plots for stress and deformation are also shown below.

Design Point	X-Accel *(in/s²)*	Y-Accel *(in/s²)*	Z-Accel *(in/s²)*	Min Stress *(psi)*	Max Stress *(psi)*	Margin of Safety	Max Total Deformation *(in)*
0	905.51	905.51	905.51	2.0616	7923.2	0.578	4.89 e-3

Table 5: Legacy Fan FEA results

To take into account the temperature variation and the quality of the testing value sampling, a factor of safety of 1.2 will be applied on the maximum stress 7923.2 psi. Therefore, the yield limit of the material becomes 9507.8 psi.

$$Margin\ of\ Safety = \frac{Strength}{1.2 * Stress\ Max} - 1 = \frac{15000}{9507.8} - 1 = 1.578 - 1 = 0.578$$

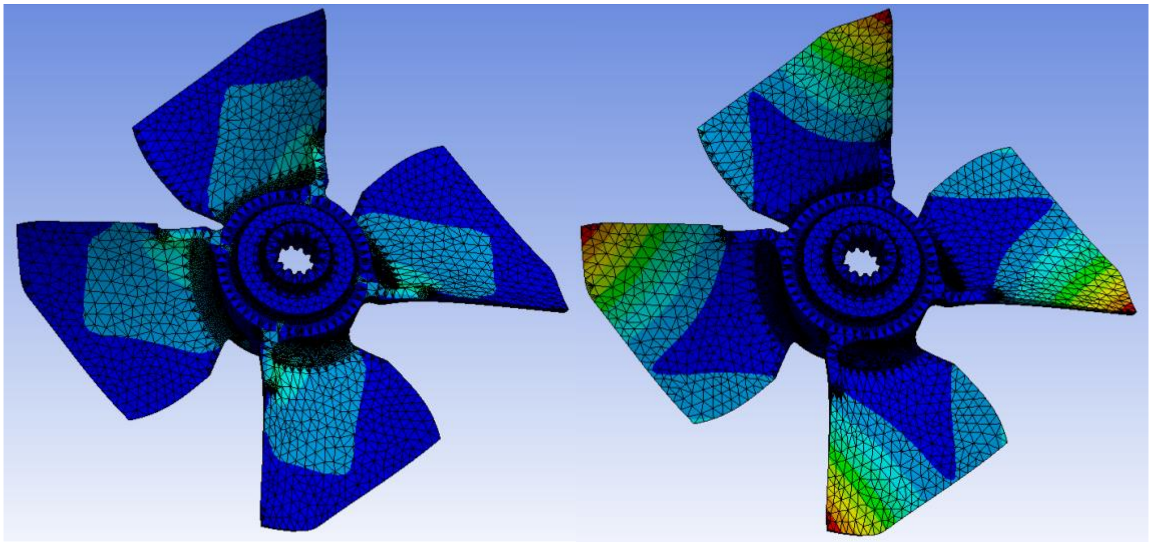


Figure 7: Von-Mises Stress (left), Total Deformation (right)

New Fan:

The fan chosen for the FEA analysis was the fan designed for Generator A, but it will be very similar to Generator B as it is the same design but just a slightly different interface. Again, the analysis was performed on the fan alone with no shaft or mounting features for simplicity of the model. Boundary conditions will simulate these pieces. A static structural analysis was performed to simulate the mounted fan taking on the load of the rotational force. It is applied to the center of the fan to rotate around the center axis of which the drive shaft would rotate. It is rotated at 100% of its normal operating speed as that is the acceptance test procedure design requirement. The fan is supported by a fixed support around the internal diameter on the spline interface. The material properties remained the same and can be reviewed in Table 4. The boundary conditions that illustrate the analysis are outlined in Figure 9 below. They are identical to the legacy fan set up. All elements are as follows: The fixed support is labelled “C” and located on the internal splines of the fan, the rotational velocity is labelled “B” and rotates around the center axis of the fan, and the acceleration force is based off the force the rotational speed generates. It is represented by arrow on the fan with the direction shown from the center. The element is parameterized, and it is broken down to 905.51 in/s^2 in each direction. The arrow displays one direction as an example.

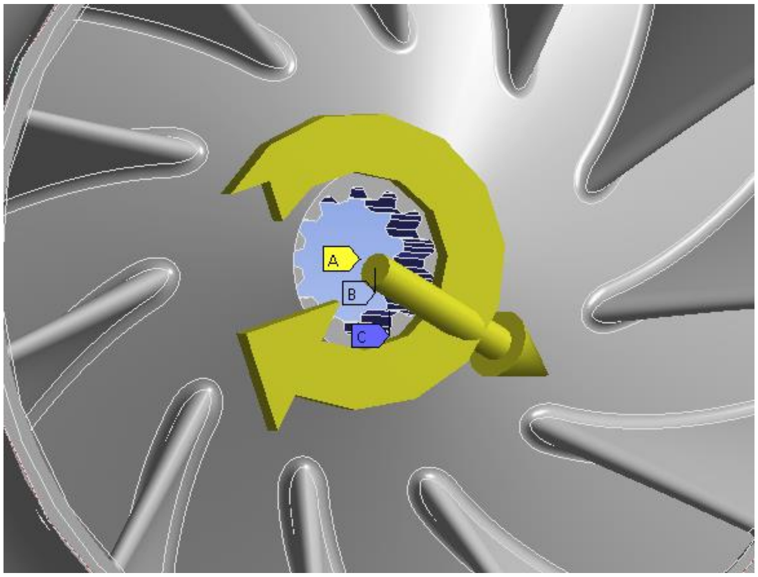


Figure 8: Mixed-Flow Fan Boundary Conditions

Similarly, as to the legacy fan design, the results can be outlined in the table below. The most important values are for maximum stress and deformation. These will determine whether the component is designed well enough to be manufactured and tested. The contour plots are shown in Figure 10.

Design Point	X-Accel *(in/s²)*	Y-Accel *(in/s²)*	Z-Accel *(in/s²)*	Min Stress *(psi)*	Max Stress *(psi)*	Margin of Safety	Max Total Deformation *(in)*
0	905.51	905.51	905.51	0.1683	6325.2	0.9762	1.157 e-3

Table 6: Mixed-Flow Fan FEA Results

To take into account the temperature variation and the quality of the testing value sampling, a factor of safety of 1.2 will be applied on the maximum stress 6325.2 psi. Therefore, the yield limit of the material becomes 7590.2 psi.

$$Margin\ of\ Safety = \frac{Strength}{1.2 * Stress\ Max} - 1 = \frac{15000}{7590.2} - 1 = 1.9762 - 1 = 0.9762$$

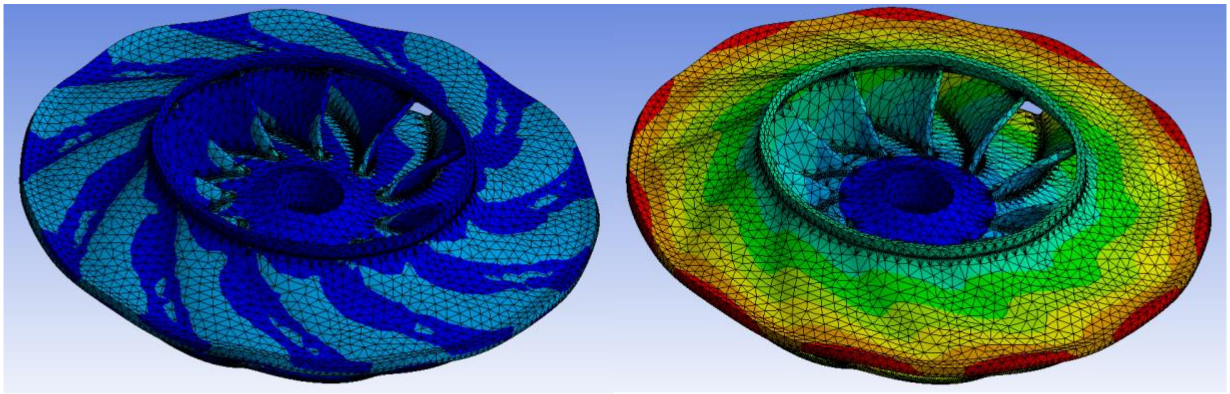


Figure 9: Mixed-flow fan Von-Mises stress (left), total deformation (right)

Test Procedure

This section summarizes the fan performance test procedure for Generator B. This procedure and its data are shown instead of Generator A because the procedure and data was more formally collected and documented than the test with Generator A. It is meant to verify the design of a prototype fan and show improvements from the legacy fan design. The main area of concern is the bearing of this generator. It has failed in multiple generators and decreasing the temperature in the bearing could improve its life. Lower temperatures can extend grease life in the bearing. A prototype mixed flow fan and the legacy fan are used in six different tests and the results will be analyzed and discussed. The test set-up, mounting, cooling and equipment is created based on the acceptance test procedure outlined for this generator and its performance requirements.

Test Set Up

Unless otherwise specified, all tests were performed under the following environmental conditions:

Parameter	Requirement
Temperature	77° ± 27°F (25° ± 15°C)
Pressure	Ambient Atmospheric at sea level up to 6000 ft

Unless otherwise specified, the following conditions were maintained during testing:

- The test was performed with fan cover.
- Thermal stabilization was reached when the following condition was met.

The frame temperature measured on the side opposite of the terminal block does not rise more than 2°F (1.1°C) in 5 minutes. The temperatures cannot exceed the limits shown in table 7.

Sensing Location	**Max Continuous Operating Temperature [°F]**	**Max Transient Operating Temperature [°F]**
Positive Diode	247	289
Negative Diode	247	289
Main Stator	365	445
Exciter	365	445
DE Bearing Liner	263	297
ADE Bearing liner	263	297

Table 7: Thermocouple Limits

Mounting

The generator axis shall be horizontal. The generator shall be mounted to a drive stand via an adapter and V-band clamp. The adapter & clamp shall be the standard parts for aircraft application as supplied by the client, or equivalent.

Cooling

The generator will be self-cooled for configurations 1 and 3 and will have a heated air-in temperature for configurations 2 and 4.

Equipment

The generator tests shall be conducted using a variable speed test stand that is capable of driving the generator at speeds from 0 to 110% of its normal operating condition at full load. Use of a blast air nozzle will be attached to the air inlet. Set up thermocouples referencing the thermocouple setup drawing in addition to an air-out location.

S/No.	Sensor or Signal Type	Quantity
1	Accelerometer 3- axis	1
2	Thermocouple, k-type	7
3	Mass Flow Meter	1
4	Pressure Tap, static and total	2
5	Signal Conditioner	1
6	Dewetron	1
7	Voltage Module	1
8	Temperature Module	1
9	Decibel Reader	1

Table 8: Instrumentation list

Parameter	Measurement Accuracy
Speed	±5 RP<
DC Voltage	±0.05 VDC
DC Voltage (PMG Output)	±0.10 VDC
DC Load Current	±2.5 A
DC Field Current	±0.1 A
Temperature	±1.0°F (±0.55°C)
Pressure	± 0.3 in-H2O
Mass Flow	± 2% of reading

Table 9: Equipment Accuracy

Fan Curve test: Legacy Fan

Both fan curve tests are used to create a mass flow vs static pressure curve. This can be used to compare different fans side by side to make the best selection.

Fan Curve – Legacy Fan							
RPM	RPM Measured	Mass Flow [lb/min]	Mass Flow Measured [lb/min]	Static Pressure at Inlet [in-H2O]	Total Pressure at Inlet [in-H2O]	Air Temp in [°C]	Air Temp Out [°C]
7600		23					
7600		19					
7600		15					
7600		11					
7600		7					
7600		1					
11000		23					
11000		19					
11000		15					
11000		11					
11000		7					
11000		1					
14500		23					
14500		19					
14500		15					
14500		11					
14500		7					
14500		1					

Configuration 1: Generator Base unit

a. Set up similar with acceptance test procedure directions, add blast air attachment and use the thermocouple configuration. Test setup will remain consistent through all configurations except for different fan configurations
b. Increase speed to first data point.
c. Set Total Pressure to 0 in-H2O
d. Set Load to 0 A.
e. Maintain speed until temperature stabilization, record data in table
f. Repeat steps b-e for the variables of speed and load in table
g. Remove load and power down

Configuration - I										
RPM	Static Pressure [in-H2O]	Input Load [A]	RPM Measured	Static Pressure [in-H2O]	Voltage [V]	Current [A]	Efficiency (%)	Total Pressure [in-H2O]	Mass Flow [lb/min]	Power Input [W]

7300	0	150								
7300	0	300								
12800	0	350								
12800	0	450								
14500	0	350								
14500	0	450								

Configuration - I										
RPM	Voltage [A]	Air-in Temp [°C]	Air-Out Temp [°C]	Bearing liner Temp [°C]	Stator Temp [°C]	Exciter Temp [°C]	Pos Diode Temp [°C]	Neg Diode Temp [°C]	Vibe [g's] Y axis	Vibe [g's] Z axis
7300	150									
7300	300									
12800	350									
12800	450									
14500	350									
14500	450									

Configuration 2: Generator Base Unit hot air intake

a) Increase air-in temperature to hot air
b) Increase speed
c) Set pressure
d) Set load
e) Maintain speed until temperature stabilization, record data in table
f) Repeat steps b-e for the variables of speed and load in table

Configuration - II										
RPM	Static Pressure [in-H2O]	Input Load [A]	RPM Measured	Static Pressure [in-H2O]	Voltage [V]	Current [A]	Efficiency (%)	Total Pressure [in-H2O]	Mass Flow [lb/min]	Power Input [W]
7300	6	150								
7300	6	300								
12800	6	350								
12800	6	450								
14500	6	350								
14500	6	450								

Configuration - II

RPM	Voltage [A]	Air-in Temp [°C]	Air-Out Temp [°C]	Bearing liner Temp [°C]	Stator Temp [°C]	Excitor Temp [°C]	Pos Diode Temp [°C]	Neg Diode Temp [°C]	Vibe [g's] Y axis	Vibe [g's] Z axis
7300	150									
7300	300									
12800	350									
12800	450									
14500	350									
14500	450									

Fan Curve test: Mixed flow fan

Fan Curve – Mixed Flow Fan							
RPM	RPM Measured	Mass Flow [lb/min]	Mass Flow Measured [lb/min]	Static Pressure at Inlet [in-H2O]	Total Pressure at Inlet [in-H2O]	Air Temp in [°C]	Air Temp Out [°C]
7600		23					
7600		19					
7600		15					
7600		11					
7600		7					
7600		1					
11000		23					
11000		19					
11000		15					
11000		11					
11000		7					
11000		1					
14500		23					
14500		19					
14500		15					
14500		11					
14500		7					
14500		1					

Configuration 3: New Fan

a) Switch base fan with new prototype fan
b) Increase speed
c) Set Pressure to 0 in-H2O
d) Set Load to 0 A.

e) Maintain speed until temperature stabilization, record data in table

f) Repeat steps b-e for the variables of speed and load in table

g) Remove load and power down

Configuration - III										
RPM	Static Pressure [in-H2O]	Input Load [A]	RPM Measured	Static Pressure [in-H2O]	Voltage [V]	Current [A]	Efficiency (%)	Total Pressure [in-H2O]	Mass Flow [lb/min]	Power Input [W]
7300	0	150								
7300	0	300								
12800	0	350								
12800	0	450								
14500	0	350								
14500	0	450								

Configuration - III										
RPM	Voltage [A]	Air-in Temp [°C]	Air-Out Temp [°C]	Bearing liner Temp [°C]	Stator Temp [°C]	Excitor Temp [°C]	Pos Diode Temp [°C]	Neg Diode Temp [°C]	Vibe [g's] Y axis	Vibe [g's] Z axis
7300	150									
7300	300									
12800	350									
12800	450									
14500	350									
14500	450									

Configuration 4: Generator with New Fan hot air

a. Keep prototype fan assembly
b. Increase air-in temperature to hot air
c. Increase speed
d. Set pressure
e. Set load to 0 A
f. Maintain speed until temperature stabilization, record data in table
g. Repeat steps b-e for the variables of speed and load in table

Configuration - IV

RPM	Static Pressure [in-H2O]	Input Load [A]	RPM Measured	Static Pressure [in-H2O]	Voltage [V]	Current [A]	Efficiency (%)	Total Pressure [in-H2O]	Mass Flow [lb/min]	Power Input [W]
7300	6	150								
7300	6	300								
12800	6	350								
12800	6	450								
14500	6	350								
14500	6	450								

Configuration - IV

RPM	Voltage [A]	Air-in Temp [°C]	Air-Out Temp [°C]	Bearing liner Temp [°C]	Stator Temp [°C]	Excitor Temp [°C]	Pos Diode Temp [°C]	Neg Diode Temp [°C]	Vibe [g's] Y axis	Vibe [g's] Z axis
7300	150									
7300	300									
12800	350									
12800	450									
14500	350									
14500	450									

Results

Using the above test procedure, the test was conducted on site at the Safran test center. The test was run following the test procedure. Each fan configuration went through three tests. The generator began in the legacy fan configuration. The first test ran through baseline parameters for RPM, mass flow, static & total pressure, and air temperatures in order to build a Fan Curve graph. The second test the generator was run with an added load. Additionally, temperatures were measured at locations outlined in the setup. Finally, during flight, the generator may be induced to draw in hot air at temperatures up to 64 °C. The previous test was run, but at increased temperatures to evaluate the difference. All results were recorded on a data acquisition system, and stabilized results were recorded in the test procedure tables. The summary of results is shown in the following table.

No.	Test	Success Criteria	Pass/Fail
1	Fan Curve Test: Legacy Fan	Able to run through RPM and mass flow conditions and stabilizing with enough points to create a fan curve chart	PASS
2	Config. 1: Generator base unit	Generator runs as designed and gain a base level comparison for its performance	PASS
3	Config. 2: Generator Base unit hot air	Generator runs as designed and gain a base level comparison for its performance	PASS
4	Fan Curve Test: Mixed Flow Fan	Able to run through RPM and mass flow conditions and stabilizing with enough points to create a fan curve chart	PASS
5	Configuration 3: Generator with new fan	Lower temperatures throughout the generator as compared to Config 1	PASS
6	Configuration 4: Generator with new fan hot air	Lower temperatures throughout the generator as compared to Config 2	PASS

Table 10: Summary of Results

Test Objectives

- Generate fan performance curves for the design configuration
- Compare the performance of the new fan design for Generator B with respect to the existing fan design
- Validate the cooling system design process by comparing the results from CFD and the test
- Increase bearing grease life by reducing internal temperatures

Test Setup

The test setup was as described in the procedure, with the addition of the terminal block boot. A noticeable amount of air escapes without the boot, and it was added to maintain stable airflow. Thought, similar points were run with and without the boot and there was minimal difference. The configuration with the boot created slightly cooler temperatures.

Figure 10:Test Setup, Without Blast Air Attachment

Deviations

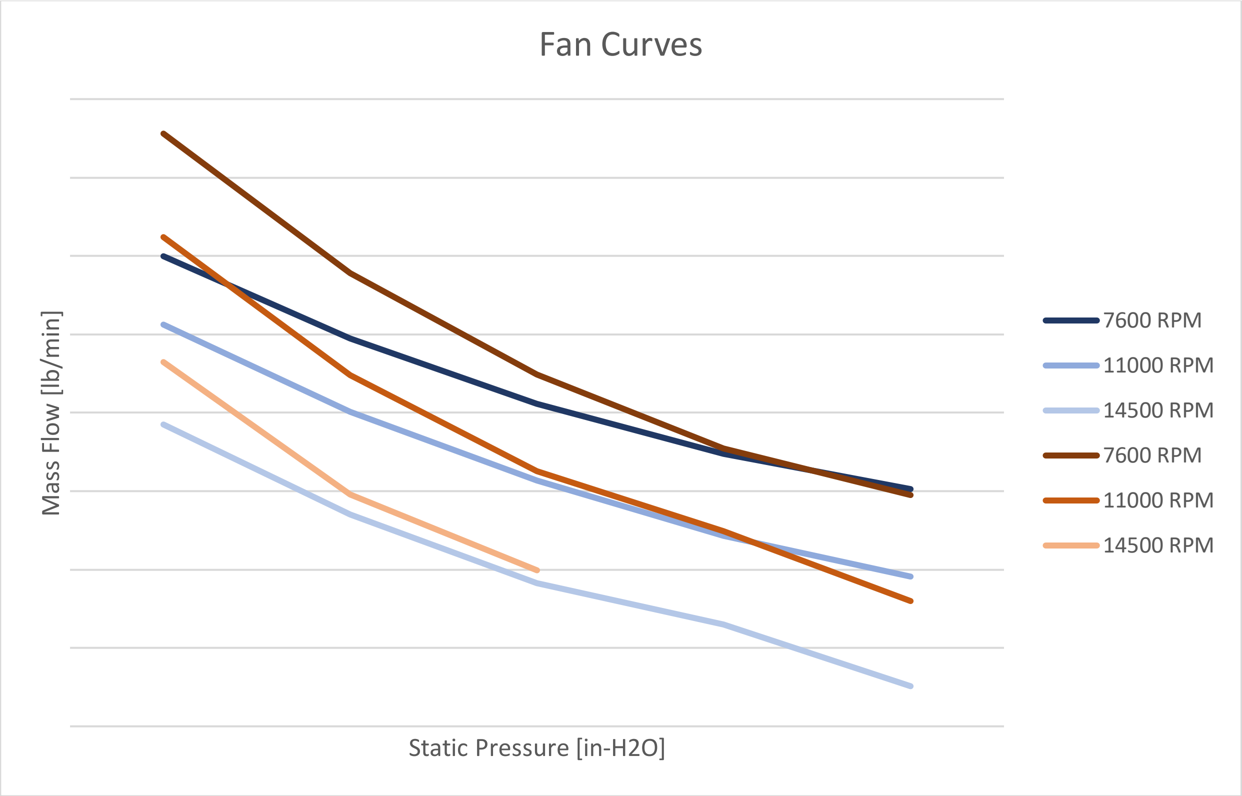
The test did encounter a few deviations which are outlined.

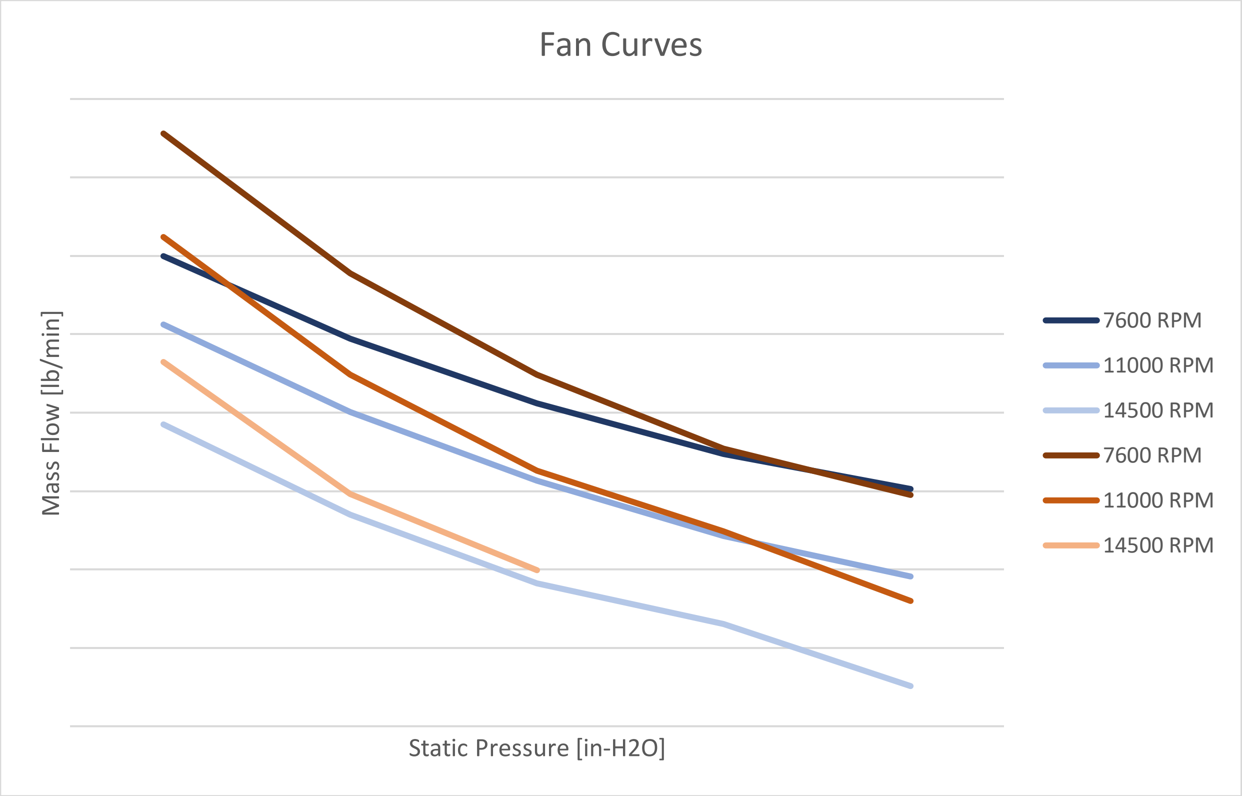
Deviation	Procedure	Description
1	All configurations	Added terminal block boot to simulate real flight conditions
2	Fan Curve configurations	The test procedure required a higher mass flow test point. The blast air system is not able to provide air flow at this requirement, so the maximum was reduced within the setups capabilities
3	Configuration 4	For conditions at 110% nominal RPM the required static pressure input was not able to be met at the high speeds in this configuration. Data was accepted at lower pressures.

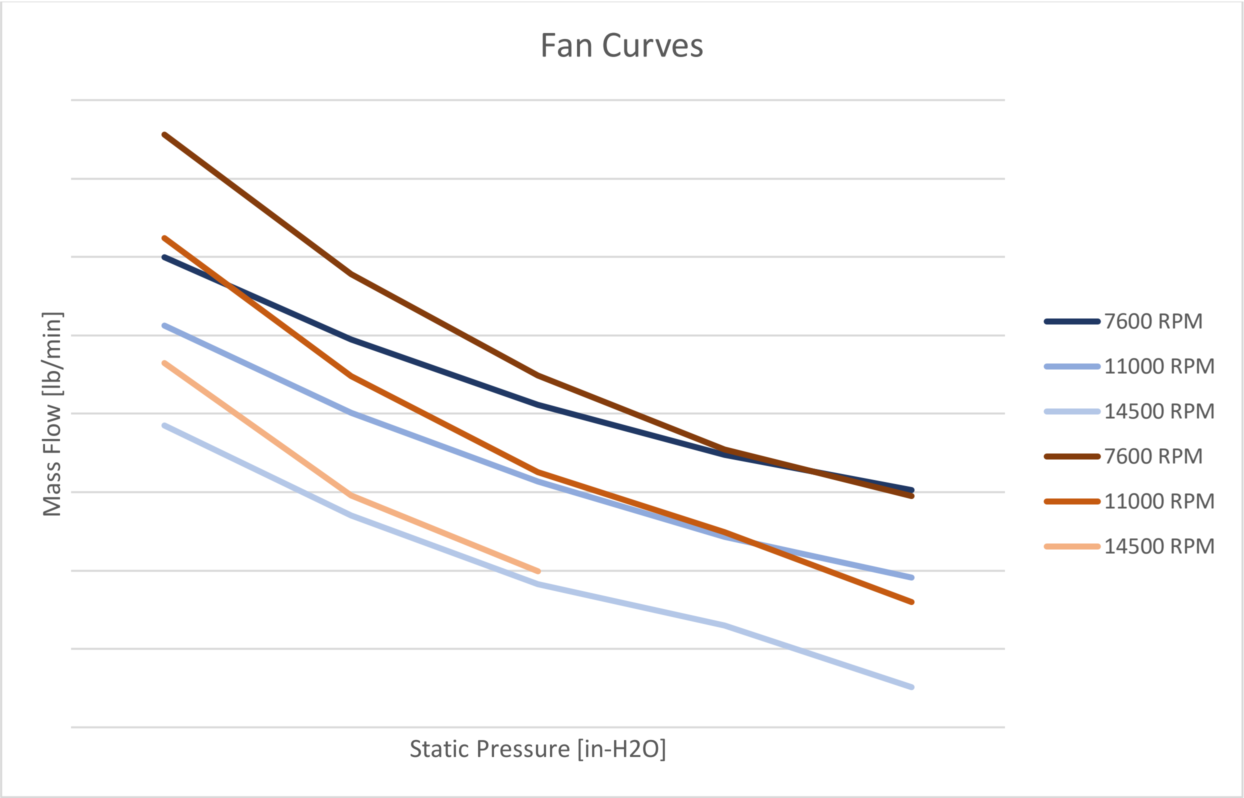
Table 11: Deviations

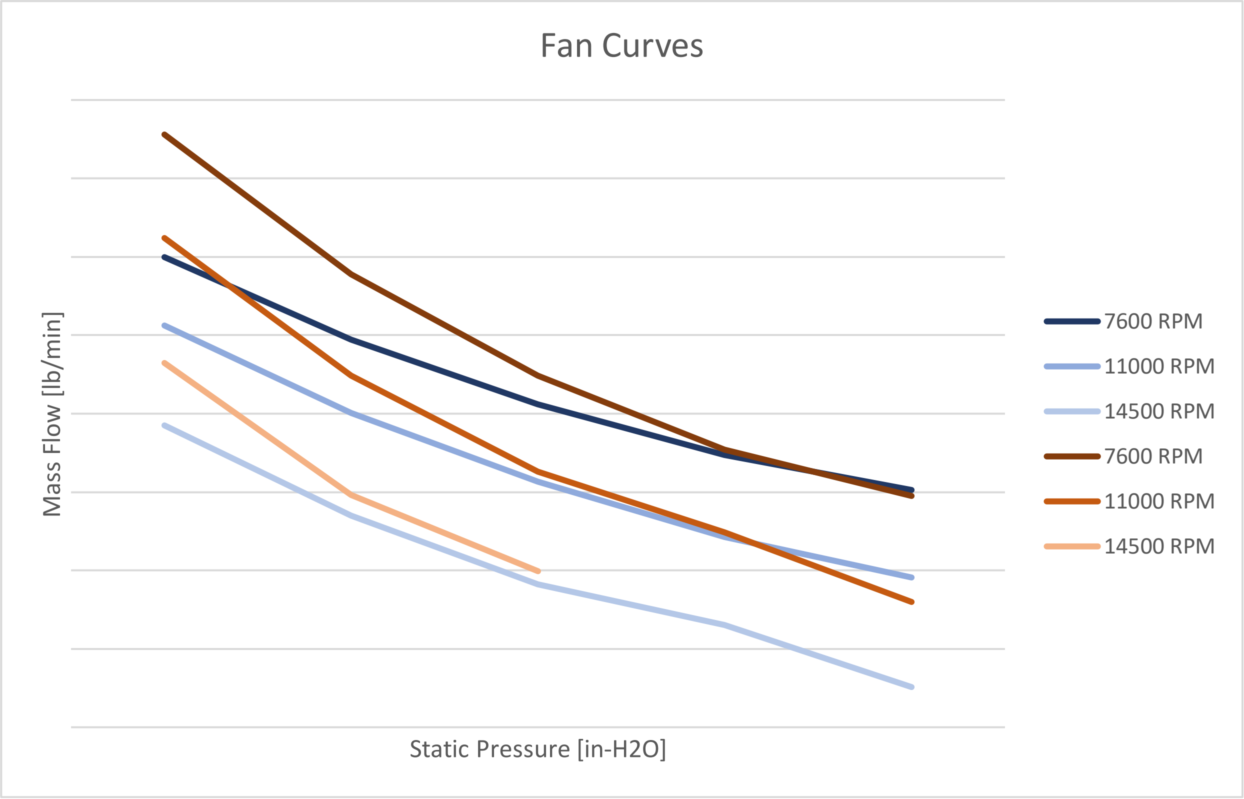
Results

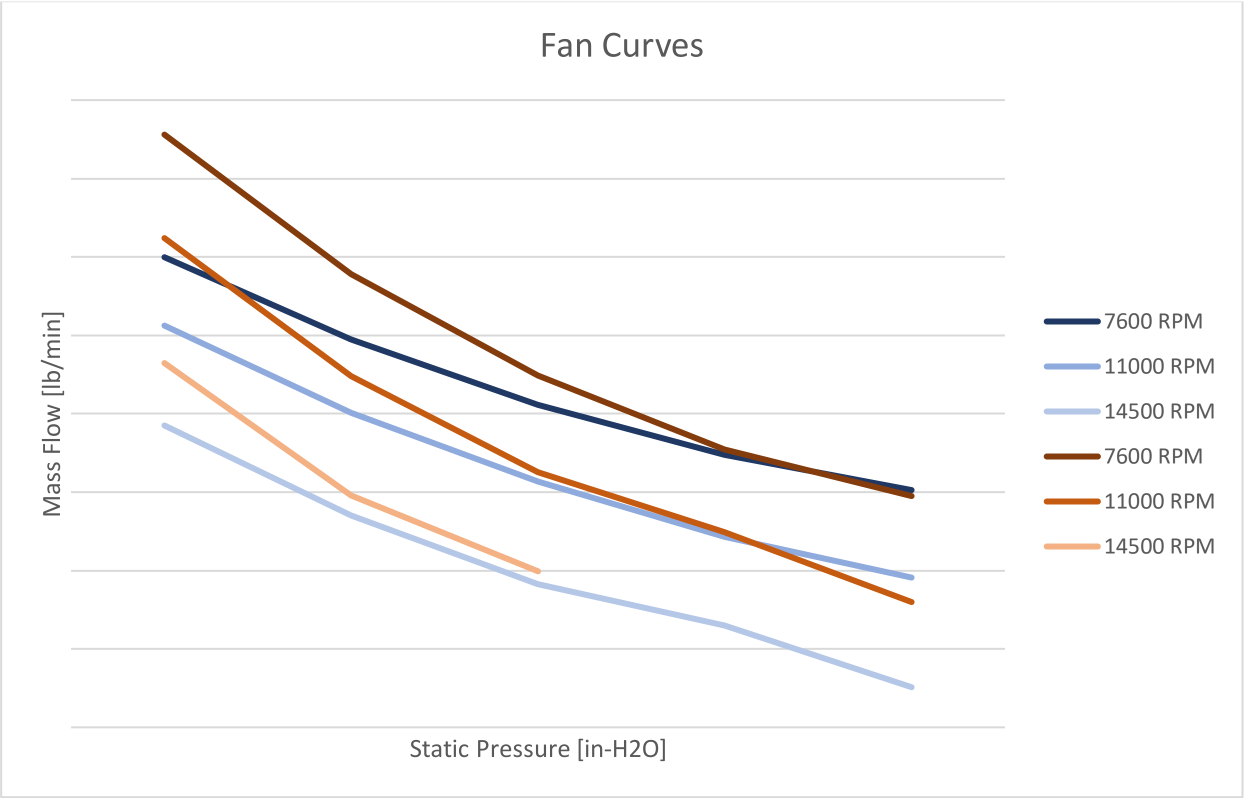
The results were gathered with a data acquisition system and was viewed during post processing, but also values were recorded during the test in the tables from the test procedure. To not disclose data from a Safran product, the actual result numbers will not be shown. The graphs below show the comparison between the legacy fan and the new mixed flow fan designs.


Fan Curves
Mass Flow [lb/min]
Static Pressure [in-H2O]
7600 RPM
11000 RPM
14500 RPM
7600 RPM
11000 RPM
14500 RPM


Fan Curves
Mass Flow [lb/min]
Static Pressure [in-H2O]
7600 RPM
11000 RPM
14500 RPM
7600 RPM
11000 RPM
14500 RPM


Fan Curves
Mass Flow [lb/min]
Static Pressure [in-H2O]
7600 RPM
11000 RPM
14500 RPM
7600 RPM
11000 RPM
14500 RPM


Fan Curves
Mass Flow [lb/min]
Static Pressure [in-H2O]
7600 RPM
11000 RPM
14500 RPM
7600 RPM
11000 RPM
14500 RPM


Fan Curves
Mass Flow [lb/min]
Static Pressure [in-H2O]
7600 RPM
11000 RPM
14500 RPM
7600 RPM
11000 RPM
14500 RPM

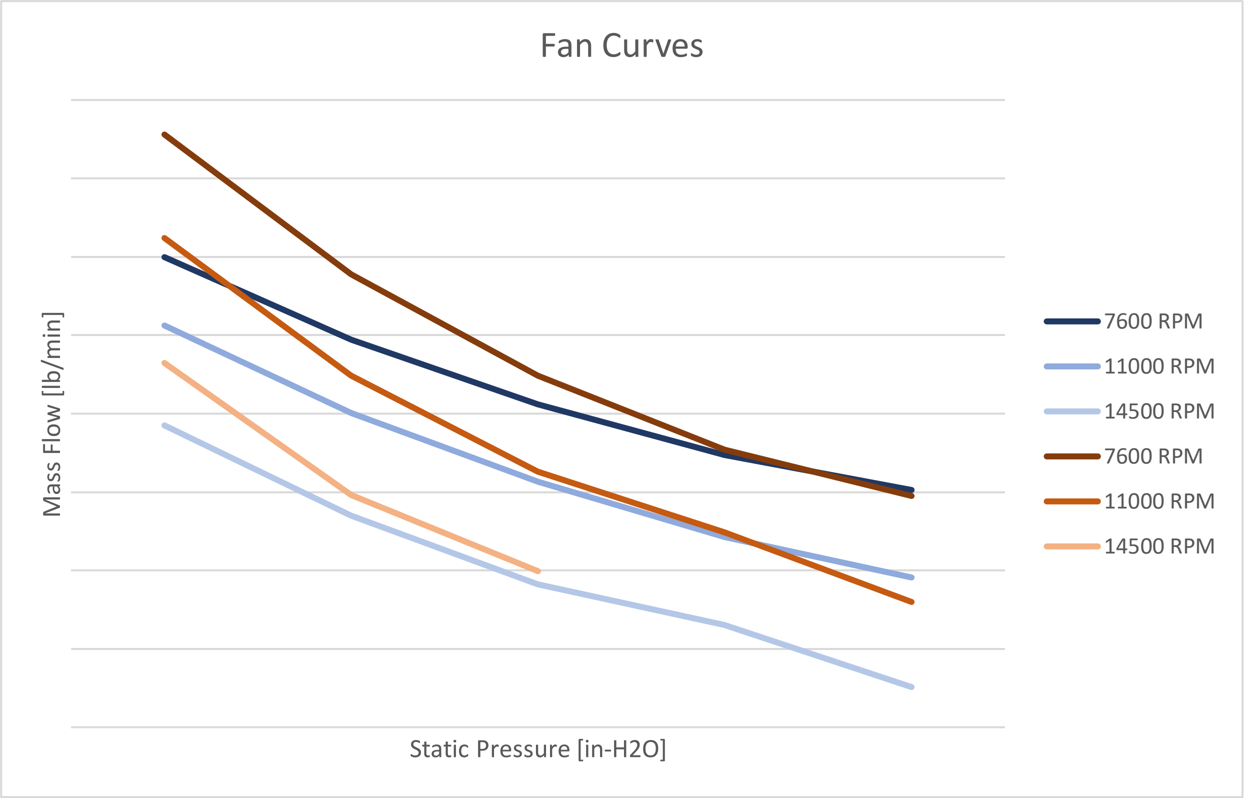

Fan Curves
Mass Flow [lb/min]
Static Pressure [in-H2O]
7600 RPM
11000 RPM
14500 RPM
7600 RPM
11000 RPM
14500 RPM

Figure 11: Fan Curve Graph

The three blue lines represent the legacy fan design and the three red lines represent the mixed-flow fan. It shows that the mixed-flow fan can produce a higher mass flow rate than the legacy fan at similar pressures, until they equal out. There is missing data that was not able to be recorded at the 14500 RPM for the mixed-flow fan.

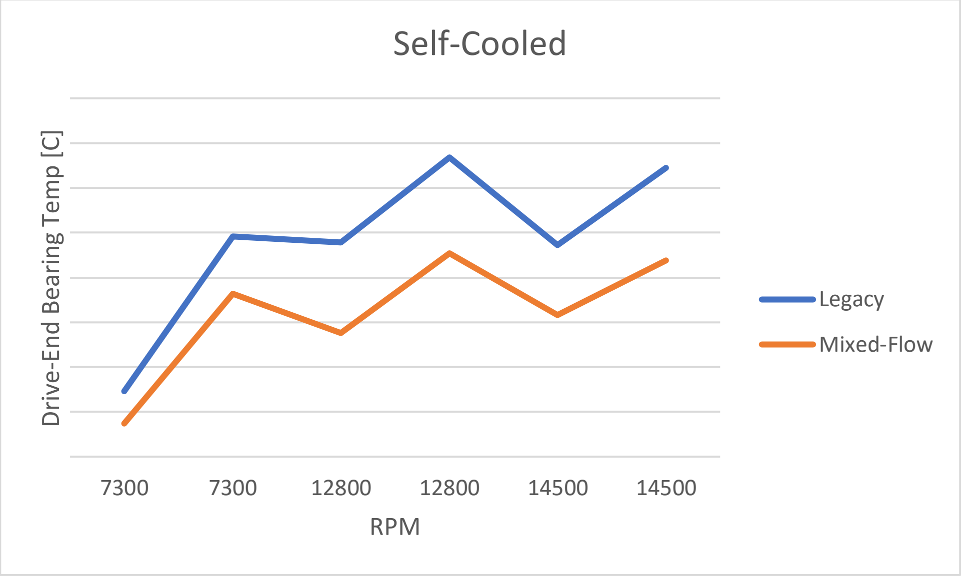


Figure 12: Self-Cooled Configurations Results

This graph represents configurations 1 & 3 in which the generator intake is room temperature. It shows the improvement that the mixed-flow fan has on temperature. The thermocouple observed here is the one attached to the drive end bearing liner. This was the location that was most critical to the test because this is the bearing that fails the most often due to the high temperatures. The high temperatures accelerate the deterioration in the bearing grease. If the temperature can be reduced internally, it could extend the life of the bearing. So in the case of reducing the temperatures, it was a success.

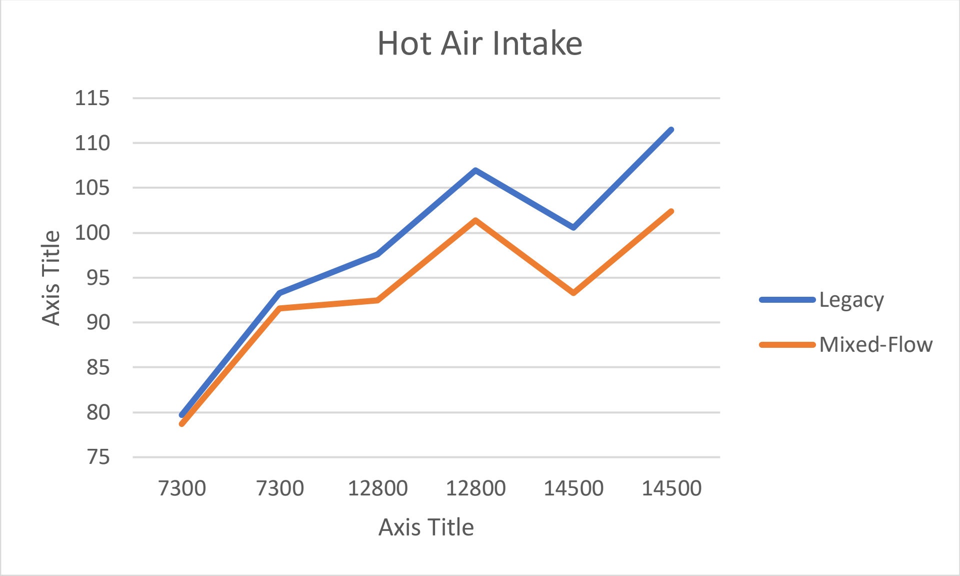


Figure 13: Hot Air Configurations Results

This graph represents configurations 2 & 4 in which the generator was given an inlet temperature initially higher than room temperature. This is a common environment the generator experiences during normal operations, so it had to have been evaluated. The results show that the higher the RPM, the better the mixed flow fan performs and the larger the temperature gap becomes. Again, since the main goal was to reduce the bearing liner temperature, this test was also a success.

Conclusion

Both fans successfully completed all configurations without failure. The structural stability was monitored by keeping vibration at less than ±0.15 g's. The generator was able to hold RPM and all loads applied. The only configuration that was not able to hold the inputs was Configuration 4. It is outlined in the deviations. Overall, the new mixed-flow fan performed better than the legacy fan. During the self-cooled configurations 1 and 3, the new fan was able to decrease the DE bearing liner temperature by a max of 14.3% or 10.3°C. For the hot air conditions, configurations 2 & 4, the new fan was able to decrease the DE bearing liner temperature by a max of 6.5% or 9.1°C. Mass flow was also improved with the new fan. In configurations 2 & 4, it was able to increase a maximum of 2.3 lb/min. In configurations 1 & 3, it was able to increase a maximum of 2.48 lb/min. These numbers are very significant for a generator air flow efficiency. A few degrees go a long way in the performance and life of the machines. In order to further improve the fan, the mixed-flow fan shape would have to be optimized to a shape that fits in between the contours of the heatsink and air inlet of Generator B. Some other recommendations could be that the built-in air inlet. It seems as though it is just an additional air inlet on top of the fan. Having the blades shaped around the air inlet will create almost the same effect. Removing this would also decrease the weight and cost of the mixed-flow fan.

Though the results for both Generator A & B were positive improvements, there are some things that the mixed-flow fan is having difficulty competing with the legacy fan design. They legacy design has not only been around so long because it works, but because of how easily manufactured, economical and light weight its design is. The mixed-flow fan is opposite of all of these things. It is more expensive, heavier, and creates a much more difficult manufacturing process. Because of these things, the fan was not chosen for either generator for the future. The requirements were instead altered to overcome the issues being seen. Not always do positive result tests come with the finalization of a new design. The benefits of the mixed-flow fan just did not outweigh those of the legacy fan.

References

Bianchi, N & Bolognani, Silverio & Luise, Fabio. (2003). Analysis and design of a brushless motor for high speed operation. 44 - 51 vol.1. https://www.researchgate.net/figure/Simplified-motor-lateral-section-and-cooling-air-paths-A-Stator-core-B-Water-jacket_fig1_4022770

Rs-online.com. (2019). *Fan Types - Why Choose an Mixed Flow / Diagonal Fan*. [online] Available at: https://www.rs-online.com/designspark/fan-types-why-choose-an-mixed-flow-diagonal-fan [Accessed 13 May 2019].

Dieselserviceandsupply.com. (2019). *How Does A Generator Create Electricity? Article on How Generators Work*. [online] Available at: https://www.dieselserviceandsupply.com/How_Generators_Work.aspx [Accessed 13 May 2019].

Rigb.org. (2019). *Michael Faraday's generator*. [online] Available at: https://www.rigb.org/our-history/iconic-objects/iconic-objects-list/faraday-generator [Accessed 13 May 2019].