Aerodynamic optimization of the body of a bus

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Abstract: The research is aimed at the aerodynamic study of the bus bodywork with computational dynamic fluids (CFD) software and through a wind tunnel in order to validate the results obtained in the virtual software, different geometries of the bodywork were evaluated by printing 3D prototypes on a scale of 1:200, which has resulted in a body formed by two spoilers, another one with a front deflector and a finally one with the original body, presenting the second option a higher lift coefficient with the reduction of turbulence zones and an optimum drag coefficient according to the INEN 1323-2009 standards. For the data acquisition process it was necessary to use sensors to measure the wind pressure generated in the tested area and in the process and visualization of the generated signals in the wind tunnel as well, for this reason it was necessary to make a conditioning of the signal obtained by the sensor circuit designed in the Proteus software. Finally, to develop the interface for signal data processing and monitoring it was necessary a data acquisition card programmed in LabView.

1. INTRODUCTION

Aerodynamics is a science that deals with movement and the actions exerted by air on solid bodies immersed in it [1]. Any object that moves will do so against the resistance of the air. In each instant, its movement must displace the air from its position, and this in turn, moves preferably towards the space that has been left free [2]. This study is based on increasingly sophisticated physicist-mathematical theories and is controlled by powerful and sophisticated CFD software and then validated by means of tests carried out in experimental installations (wind tunnels) [3].

Wind tunnels are devices that provide a stream of air flowing under controlled conditions so that different items can be tested. High-speed tunnels, in this case, are those whose usual operating speeds require the inclusion of compressible flow effects [4]. For the data acquisition process, it is necessary to use sensors that measure the wind pressure generated in the test area [5]. For this reason, it is intended to analyse the aerodynamic behaviour, so that engineering criteria can be issued to seek improvements in the design and construction process of GR model bus structures [6,7,8,9,10].

2. AERODYNAMIC TESTS

2.1. Design Parameters

Aerodynamic analysis aims to determine the aerodynamic characteristics of the Gr model bus by evaluating the following parameters:

- Calculate drag and lift coefficients, and visualize the areas where most turbulence is generated.

- Evaluate the efficiency to propose improvements in the design of two new aerodynamic...
profiles according to the aerodynamic characteristics of the original model of the bodywork, where the width (a) is 2455 mm, the length (l) is 10540 mm and the height (h) is 2100 mm, see figure below.

- Estimate the power needed by the bus to overcome drag resistance.

Several study parameters have been taken with which the CFD software will calculate different aerodynamic values of the body in its original model and in the two modified geometries, the variables of interest are shown in table 1, these variables were established with average values of the city of Latacunga - Ecuador (0.9316° S, 78.6058° W), the maximum speed allowed for buses by the National Transit Agency (ANT)[11] was also considered and the bus cross-sectional area was calculated with the measurements shown in figure 1. Three body proposals were analyzed, the first with the original bus, the second with the modified bus with two spoilers and finally the bus with a front deflector.

Table 1. Parameters for the design.

| Variable                        | Value   |
|---------------------------------|---------|
| Ambient air temperature [°C]    | 15      |
| Atmospheric pressure [Pa]       | 101325  |
| Air Density [kg/m³]             | 1.225   |
| Air Viscosity [Pa.s]            | 1.3x10⁻⁵|
| Average Bus Speed [m/s]         | 25      |
| Transversal bus area [m²]       | 8,743   |

2.1. Software Testing

*Original Bus.* The turbulence is caused by variations in pressure and speed that are generated in the contour of the surfaces with greater irregularity causing the flow of air to be chaotic in the part of the air conditioning.

Figure 2. Dynamic pressure in the original bus model, a) side view; b) top view
On the other hand, the turbulence generated in the lower part of the bus is due to the mechanical parts found in this place such as the wheel axles, transmission and differential, as shown in figure 2. As can be seen in figure 3, the front surface of the bus is the zone in which most pressure is exerted, since it tends to be perpendicular to the air trajectory, which generates an increase in the resistance to advance, so more power is needed to overcome this resistance.

Figure 3. Turbulence intensity in the original bus model, a) side view; b) top view

*Bus proposal with two spoilers.* Two spoilers were designed to direct the air circulation, the first is mounted in front of the air conditioning system for the air to pass over the system and thus prevent it from colliding directly with it. The second wing goes in the back of the bus, as this place generates the greatest amount of turbulence. With the implementation of the front wing, the pressure in the upper part of the bus has been increased, which is why the negative lift force is increased, as shown in figure 4. The increased negative lift helps the bus to have greater stability.

Figure 4. Dynamic pressure in the bus with two spoilers, a) side view; b) top view

In addition, with the implementation of the front wing the turbulence in the upper part of the bus was significantly reduced, as well as in the rear part it was possible to improve the direction of the air in comparison with the original model see figure 5.
Figure 5. Turbulence intensity in the bus with two spoilers, a) side view; b) top view

Bus proposal with front deflector. For the second proposal, an air deflector was designed that goes over the bus in the front part and whose objective is to direct the air flow so that it passes over the air conditioning system preventing pressure gradients from being generated around said system. As it can be seen in figure 6, the air no longer has as much incidence in the surroundings of the air conditioning system, making the flow homogeneous in the upper part of the bus.

Figure 6. Dynamic pressure in the bus with front deflector, a) side view; b) top view

In figure 7 it can be observed that there is a minimum region in the part of the deflector where turbulence is generated due to the geometry of the deflector, but it is evident that the deflector helps the air to have a laminar flow on the surface of the bus, whereas in the posterior part the behavior of the air becomes turbulent again like the original model.
2.2. Aerodynamic tests in the wind tunnel

By means of the BoxPlot diagram, the values obtained in the wind tunnel tests will be analysed, determining the real values and the outliers for their respective analysis, by means of the following process:

- Determining the lower and upper limit at which the data of each of the sensors should vary.
- Determining the three quartiles of the data, Q1 (quartile 1) is the median of the first half of the data, Q2 (quartile 2) is the median of all the data and Q3 (quartile 3) is the median of the second half of the data, and constructing the diagram from the values obtained and thus separates the outliers from the actual data to be analysed [12].

**Original Model Bus.** Figure 8 shows 5 sensors installed in the profile of the original bus, which will allow pressure and time values to be obtained to make a comparison through the values obtained with the CFD software. Table 2 shows the actual pressure and time values in the wind tunnel analysis where pressure variation is common from 0 to 63.7 Pascal, indicating that it is within the range.
Table 2. Actual values sensor 1 original bus.

| Time [s] | Pressure [Pa] |
|----------|---------------|
| 2        | 0             |
| 18       | 0             |
| 59       | 0             |
| 5        | 3.92          |
| 4        | 29.4          |
| 38       | 36.26         |
| 71       | 52.92         |
| 28       | 63.7          |

Table 3. Actual values sensor 1 bus with two spoilers.

| Time [s] | Pressure [Pa] |
|----------|---------------|
| 4        | 0             |
| 16       | 0             |
| 34       | 7.84          |
| 62       | 2.94          |
| 64       | 0             |
| 79       | 4.9           |
| 97       | 14.74         |
| 98       | 36.26         |

Table 4. Actual values sensor 1 bus with deflector.

| Time [s] | Pressure [Pa] |
|----------|---------------|
| 15       | 0             |
| 53       | 0             |
| 73       | 0             |
| 100      | 0.98          |
| 38       | 2.45          |
| 80       | 7.84          |
| 63       | 24.01         |
| 90       | 32.34         |

Bus with two spoilers. In figure 9 you can see the location of 5 sensors installed which will allow to obtain pressure and time values to make a comparison with the values obtained from the CFD software analysis where it is observed that the variation of pressure and time are within the range. In Table 3 it is observed the real values obtained in the analysis of the wind tunnel. The variation of the pressure is of a common of 0 to 36, 26 Pa, which indicates that it is within the range.

Bus with front deflector. Figure 10 shows the location of 5 sensors placed on the front deflector profile that will allow time and pressure values to be obtained, and analyze and compare the ranges with those obtained from CFD software analysis. Table 4 shows the actual values obtained in the wind tunnel analysis, the pressure variation is a common from 0 to 32.34 Pa, which indicates that it is within the established parameters.

3. AERODYNAMIC TEST RESULTS

3.1. Software Results

Original Bus. Table 5 shows the results of the software for the designing of the original bodywork, which allows us to establish a criterion of the current aerodynamics of the bodywork from which was obtained an average value of drag coefficient and lift coefficient of 0.62133 and 0.26451 respectively.

| Variable                     | Value   | Average |
|------------------------------|---------|---------|
| Drag force (Fx) [N]          | 2043.6  | 2006.4  |
| Lifting force (Fy) [N]       | 866.1   | 869.8   |
| Reynolds Number (Re)         | 6402946.8 | 6403115.4 |
| Drag coefficient             | 0.62133 | 0.61013 |
| Lift coefficient             | 0.263354 | 0.26451 |
| Power (Pot) [W]              | 51081.5 | 50161.1 |

Bus with two spoilers. Table 6 shows the results obtained by the Solid Works Flow software for the design with two spoilers, whose objective will be to direct the air flow over the air conditioning system avoiding the generation of pressure gradients around this system by obtaining an average value of drag coefficient and lift coefficient of 0.63961 and 0.30256 respectively.

| Variable                     | Value   | Average |
|------------------------------|---------|---------|
| Drag force (Fx) [N]          | 2103.3  | 2103.5  |
| Lifting force (Fy) [N]       | 994.8   | 991.5   |
| Reynolds Number (Re)         | 6402195.9 | 6400665.2 |
| Drag coefficient             | 0.63961 | 0.63965 |
| Lift coefficient             | 0.30256 | 0.30153 |
| Power (Pot) [W]              | 52584.9 | 52587.6 |

Bus with front deflector. Table 7 shows the results for the designing with a deflector, for the trajectory of the air that is distributed around the bus as the air approaches the windshield making the current lines have a discontinuous flow of this system, obtaining an average value of drag and lift coefficient
of 0.69668 and 0.30366 respectively.

| Variable                | Value  | Average    |
|------------------------|--------|------------|
| Drag force (Fx) [N]    | 2258.8 | 2256.8     |
| Lifting force (Fy) [N] | 998.6  | 997.6      |
| Reynolds Number (Re)   | 6388272.8 | 6387933.9 |
| Drag coefficient       | 0.69668 | 0.68629    |
| Lift coefficient       | 0.30366 | 0.30336    |
| Power (Pot) [W]        | 56470.4 | 56422.2    |

Figure 11 shows the comparison of the results of drag force, lift force and power in the three study profiles, obtaining that the front deflector designing is the best option, because Fx was 2256.8 N and Fy of 997.6 N being proportional to the increasing of the power necessary to overcome the resistance of the air.

3.2. Wind Tunnel Results

*Original Bus.* Figure 3 shows the values obtained in the analysis by means of the design software where it is observed that the pressure variation is from 202 to 315 Pa, while in figure 12 and table 8 it is observed that the real values obtained in the wind tunnel analyzing the pressure variation is from a common of 254,016 to 300,762 Pa, which indicates that it is within the range.
**Table 8.** Overview of sensor values on the original bus

| Sensor  | Pressure [Pa] | Speed [m/s] |
|---------|---------------|-------------|
| Sensor 1 | 0             | 0           |
| Sensor 2 | 651,651       | 32,62       |
| Sensor 3 | 375,952       | 24,77       |
| Sensor 4 | 150,381       | 15,67       |
| Sensor 5 | 300,762       | 22,16       |

**Table 9.** Overview of values of bus sensors with a deflector

| Sensor  | Pressure [Pa] | Speed [m/s] |
|---------|---------------|-------------|
| Sensor 1 | 0             | 0           |
| Sensor 2 | 701,778       | 33,85       |
| Sensor 3 | 401,016       | 25,59       |
| Sensor 4 | 230,584       | 19,40       |
| Sensor 5 | 531,346       | 29,45       |

Bus with two deflectors. Figure 4 shows the values obtained in the analysis by means of the designing software where it is observed that the pressure variation is from 500 to 550 Pa, while figure 13 and table 9 show that the real values obtained in the wind tunnel analyzing the pressure variation is from a common 501.74 to 531.346 Pascal, which indicates that it is within the range from 501.74 to 531.346 Pascal.

![BoxPlot sensor 5 diagram with two deflectors](image1)

**Figure 13.** BoxPlot sensor 5 diagram with two deflectors

Bus with front deflector. Figure 6 shows the values obtained in the analysis through the designing software where it is observed that the pressure variation is from 350 to 400 Pa, while figure 14 and table 10 show that the real values obtained in the wind tunnel analyzing the pressure variation is from a common 351,624 to 401,016 Pascal, which indicates that it is within the range.

![BoxPlot sensor 5 diagram with front deflector](image2)

**Figure 14.** BoxPlot sensor 5 diagram with front deflector
Table 10. Overview of sensor values on the bus with a deflector

| Sensor  | Pressure [Pa] | Speed [m/s] |
|---------|---------------|-------------|
| 1       | 0             | 0           |
| 2       | 601,524       | 31,34       |
| 3       | 576,46        | 30,68       |
| 4       | 300,762       | 22,16       |
| 5       | 401,016       | 25,59       |

4. CONCLUSIONS

The wind tunnel control circuit was designed by a signal conditioning based on the amplification of the integrated LM324 so that the sensors will work correctly amplifying the signal obtained in the tests, generating a gain of 112 times, the voltage generates a signal from 0 to 330 mV and thanks to the amplification, and the voltage obtained is from 0 to 5V. The aerodynamic analysis in the wind tunnel of the bus model and its two prototypes, results in a prototype with the deflector which is the best because it complies with the drag coefficient established by NTEINEN 1323:2009.

The three designs obtained through the analysis in the wind tunnel were very similar to the values generated in the computational analysis by means of the designing software, which let us to determine that this wind tunnel can be used for analysis of prototypes to scale. The number of values obtained in the wind tunnel tests was reduced with the help of the BoxPlot diagram, due to the fact that not all the values are real, which would cause a bad analysis of this one, after separating the atypical values from the real ones we proceeded to the analysis of them. The increasing of the necessary power to overcome the air resistance is 75,39 Kw (227 Hp) regarding to the original model. However, it was possible to increase the sustentation coefficient making the bus more stable.

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