Optimization of Bump Fairing in DLR-F6 Aircraft Related to Coefficient of Drag Using Simulation and Design of Experiment Method

Gabriel Jeremy Gotama[1], Fandi Dwiputra Suprianto[2], Sutrisno Teng[3]
Department of Mechanical Engineering, Petra Christian University [1,2,3]
Jl. Siwalankerto 121-131, Surabaya 60236. Indonesia [1,2,3]
Phone: 0062-31-8439040, Fax: 0062-31-8417658[1,2,3]
E-mail : gabrieljeremy25@gmail.com[1], fandi@petra.ac.id[2], tengsutrisno@petra.ac.id[3]

ABSTRACT

Fairing is an aircraft component which is responsible in reducing drag force. By reducing the coefficient of drag, drag force will be reduced and aircraft fuel consumption will be leaner. A bump fairing FX2 was designed by Vassberg for DLR-F6 aircraft. The design process doesn't involve coefficient of drag effect. This research focuses in optimizing bump fairing FX2 by reducing the coefficient of drag produced for DLR-F6 aircraft. Optimization was done by changing the dimension value of chord, span and thickness. Optimization method used in this research was 2^k factorial Design of Experiment (DoE) with Computational Fluid Dynamic (CFD) for acquiring data.

The result of the research shows that bump fairing FX2 can be optimized, although not by utilizing the 2^k factorial design of experiment. This is caused by the assumption of linear function in 2^k factorial. In this research, it was discovered that the function of chord, span and thickness related to coefficient of drag is non-linear. Even though 2^k factorial was unable to be used to optimize bump fairing FX2, the results are able to show correlation between variables and which variable are important. The highest reduction of coefficient of drag value was achieved by 8.75 drag count.

Keywords: Coefficient of Drag, Design of Experiment, Design Optimization, Aerodynamic, Fairing, Computational Fluid Dynamic

1. Introduction

In this day, the need of energy increases in an alarming rate. This condition is made worse by the fact that human still depends their energy resources from fossil fuel which is non-renewable. Human dependency to fossil fuel can be indicated from vehicles use on a daily basis still operate by burning fossil fuel. This condition will lead to scarcity of fossil fuel in the near future.

In order to reduce the consumption of fossil fuel, many methods have been conducted. One example of such method is to reduce the fuel usage. Reduction of fossil fuel usage can be achieved by increasing the efficiency of the vehicles. In an aircraft, increasing efficiency can be done by adding fairing component which reduces the drag force in an aircraft. Fairing works by reducing the pressure and induced drag in an aircraft. In the study of such case, a non-dimensional variable *coefficient of drag* is used. Coefficient of drag is a non-dimensional variable which represent the magnitude of drag force in an object.

A bump fairing FX2B was designed by Vassberg to eliminate side-of-body vortex in DLR-F6 aircraft. Bump fairing FX2B is a two combination of fairings (FX1 and FX2). Image of bump fairing FX2B presented in Figure 1 and its location in DLR-F6 aircraft in Figure 2. The design of bump fairing FX2B does not involve the reduction of coefficient of drag [1]. In such case, bump fairing FX2B still has room for optimization regarding to coefficient of drag.

In this study, optimization of bump fairing FX2B was done by using Design of Experiment (DoE) method. Design of Experiment method capable to investigate effect of variable and interaction between variables. Among various Design of Experiment model, 2^k full factorial design was chosen. The 2^k full factorial DoE was chosen due to its main advantages of being simple and economical and as a screening designs to determine which variables are important [2].

Dimension variables that were chosen for factorials are chord, span and thickness. These variables are presented in Figure 3, Figure 5, and Figure 6. Chord is the length of bump fairing FX2B, similar to that of airfoil chord. Span is the width of bump fairing FX2B frontal area, similar to that of airfoil span. Thickness is the vertical length of bump fairing FX2B which is tangent to FX1 fairing.

The three dimension variables chosen will have two different levels of size. Level 0 indicates the original size of bump fairing FX2B. Level 1 indicates a 30% increased size of bump fairing FX2B. 30% increase was chosen due to the rule of Design of Experiment to avoid extreme value which is 40%. Maximum size increase is limited to 40% due to the tangent limitation to FX1 fairing.

Combination of these three variables result in eight different combinations. Eight different combinations were obtained by 2^k factorial formula. The ^{k} nomenclature indicates number of variables. Therefore, 2^3 factorials will result in eight combinations of variable. To indicate those combinations, a three digits' number is used. The first digit indicates level of chord length size. The second digit indicates level of span size. The third digit indicates level of thickness size. For example, a 1 0 1 number shows a 30% increase size of chord, original size of span, and 30% increase size of thickness.

All of these combinations of dimension size were simulated using Computational Fluid Dynamic (CFD) software. Coefficient of drag data was obtained from this simulation. Those data were processed using statistical software using Design of Experiment method. The Design of Experiment process resulted in statistic significant test and information about correlation between variables.

For ease purpose, in this paper, coefficient of drag data will be represented in drag count unit. Drag count unit is equal to 10^{-4} coefficient of drag.

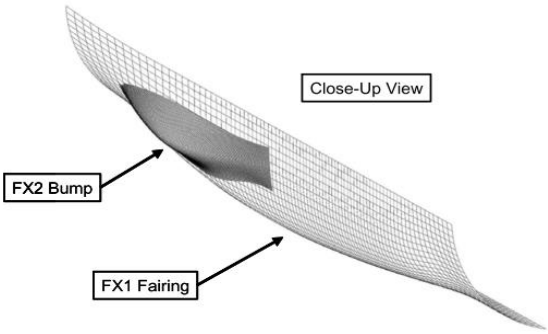

Figure 1. Physical appearance of bump fairing FX2B [1]

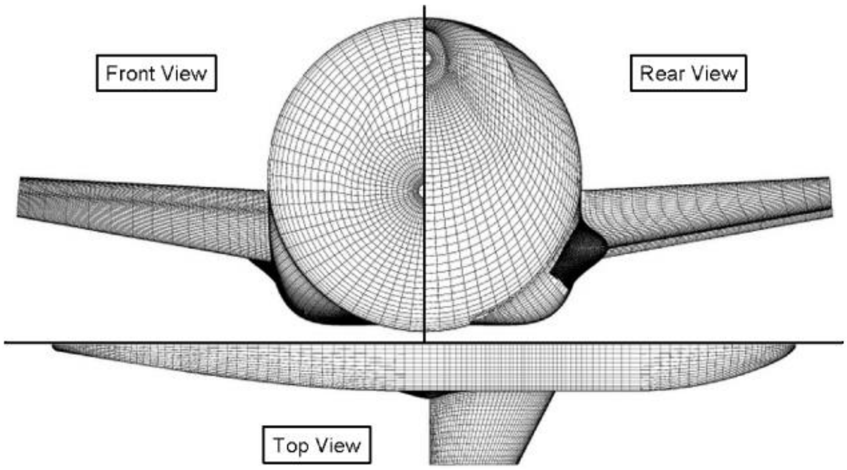

Figure 2. Position of bump fairing FX2B in DLR-F6 Aircraft. FX2 Bump is indicated in this picture with dark color [1]

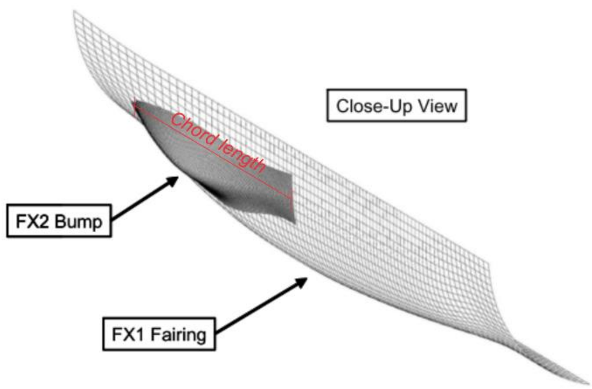

Figure 3. Indicator of Chord variable dimension for fairing FX2 bump

2. Research Method

The method applied in this research is presented in Figure 4.

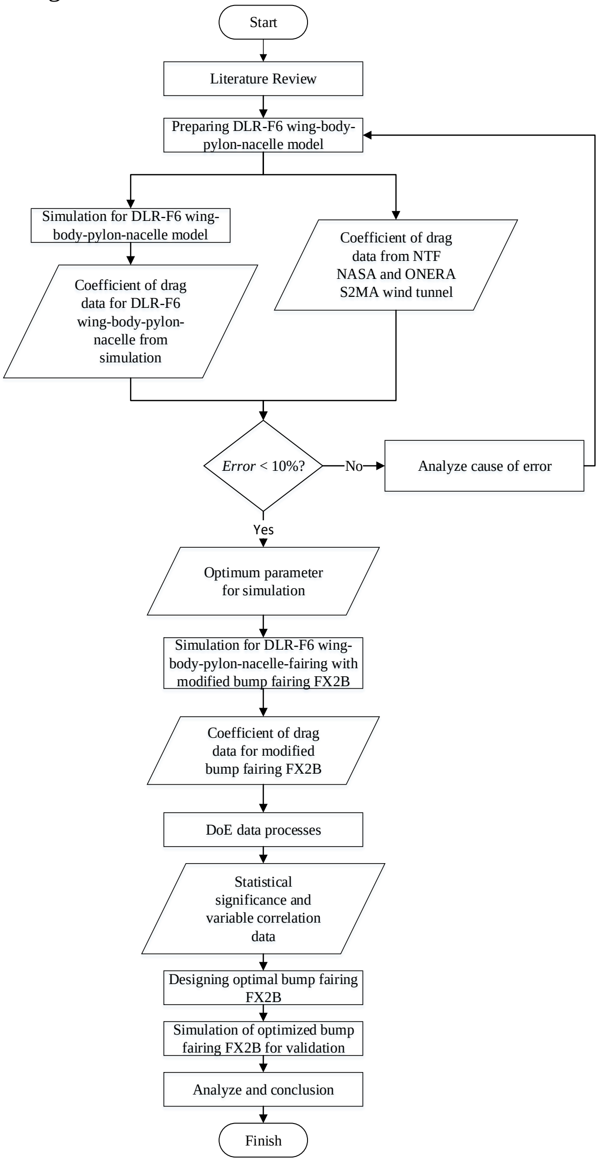

Figure 4. Flowchart of research method

DLR-F6 aircraft CAD file can be downloaded from Drag Prediction Workshop III website. DLR-F6 data obtained from this website consists of DLR-F6 wing-body-pylon-nacelle configuration (without fairing) and bump fairing FX2B. Both models are in separate file. A CAD software is needed to combine both model into a DLR-F6 wing-body-pylon-nacelle-fairing configuration.

In order to obtain optimum simulation parameter, a DLR-F6 wing-body-pylon-nacelle (without fairing) was simulated with 10^{-3} convergence criteria and compared with wind tunnel test result from NTF NASA and ONERA S2MA. 10^{-3} convergence criteria was chosen as an estimator for optimum parameter. NTF (National Transonic Facility) NASA wind tunnel test for DLR-F6 wing-body-pylon-nacelle configuration was conducted by Gatlin [3]. As for ONERA S2MA wind tunnel test, it was conducted by Rudnik [4]. The optimum parameter achieved in condition of 10% difference between simulation data and wind tunnel test result. 10% difference was used based on Zhang method which classified error under 10% as good [5].

After optimum parameter obtained, DLR-F6 wing-body-pylon-nacelle was combined with modified bump fairing FX2B model. This result in DLR-F6 wing-body-pylon-nacelle with modified fairing. All eight different combinations of DLR-F6 wing-body-pylon-nacelle-fairing were simulated to obtain coefficient of drag data. Simulation was done with 10^{-4} convergence criteria and only one sample of data for each model. This was due to the fact that multiplication of similar simulation will result in exact same result.

After acquiring the desired data, statistical software was used to conduct Design of Experiment method. The result of DoE method will be a statistical significance variable combinations effect on coefficient of drag. With this information, an optimum design of bump fairing FX2B is able to be acquired.

In order to validate whether the optimized bump fairing FX2B is truly optimum, a simulation needs to be conducted. The result of simulation will be able to inform whether the model is able to reduce the coefficient of drag value or not.

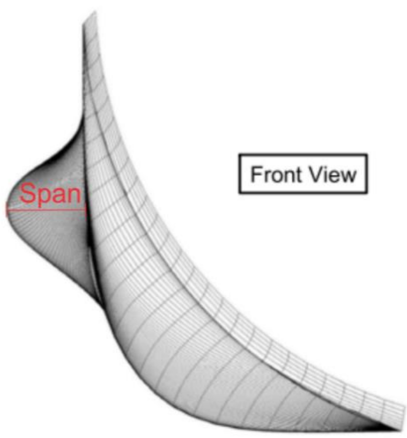

Figure 5. Indicator of Span variable dimension for fairing FX2 bump

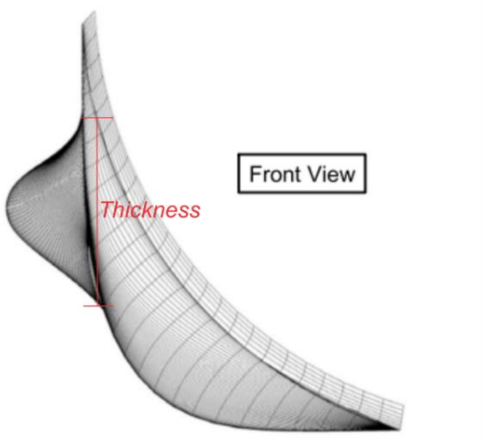

Figure 6. Indicator of Thickness variable dimension for fairing FX2 bump

3. Result and Discussion

Optimum simulation parameter was obtained from simulation DLR-F6 wing-body-pylon-nacelle. Lift of parameter is presented in Table 2. This optimum parameter is verified with an error less than 10%. Information regarding comparison between simulation and wind tunnel data available in Table 1. The data used for comparison was from NTF NASA due to the similar non-dimensional number used in simulation (Reynolds number $3x10^6$, Mach number 0.75).

After verified optimum parameter was acquired, a DLR-F6 with modified bump fairing FX2 were simulated using similar parameter. The results of this simulation are presented in Figure 7. The result shows a significant difference between one another which prove the possibility of bump fairing FX2B to be optimized.

Compared to the effect of fairing from ONERA S2MA wind tunnel test, the effect of fairing acquired from this simulation shows significant difference value. Comparison between these two sources of data is presented in Table 3. Although two sources of data tested two different model, the information are able to present the different effect of fairing. This phenomenon most likely be caused by the condition of simulation. In this simulation, y+ value averages in 574.8086. This high value of y+ resulted from the limitation of resources to mesh the model.

Table 1. Comparison between simulation result and NTF NASA wind tunnel test for DLR-F6 wing-body-pylon-nacelle model

Cd simulation	Cd NTF NASA wind tunnel [3]	Percentage of difference
360.654	329	9.62%

After acquiring eight coefficient of drag data, the data were processed using statistical software for DoE method. The results of DoE processes are presented with Pareto chart, normal plot chart, and half normal plot chart. All of these charts are presented respectively in Figure 8, Figure 9, and Figure 10.

Statistical significance was tested using Lenth's PSE method due to the condition of no replication in data [6]. The result of DoE statistical analysis shows no variables that was observed to be statistically significant. In Pareto chart, this was indicated by the position of bar chart variables in which none pass through Lenth's PSE line. This condition possibly caused by non-linearity function between variables and coefficient of drag.

Although no variables were statistically significant, the data was able to show correlation between variables and its magnitude of effect on coefficient of drag. This was shown by both normal and half normal plot. It can be inferred from the result that the most important variable is the chord variable. Chord variable are the closest to Lenth's PSE line and has the highest effect to coefficient of drag. For the combination variables, an increase in size for all three variables has the highest significance value and effect.

In order to provide evidence whether the function of all three variables are non-linear to coefficient of drag, another simulation was conducted. In this simulation, a two different models were tested. The first model has a 40% increased size for chord. The second model has a 40% increased size for all three variables. A number 2 digit used to indicate these level of size and thus both models can be represented with 2 0 0 and 2 2 2 digits respectively. These two models were chosen based on the result of DoE processes in which both have the highest statistical significance.

The result of level 2 simulation indicates a non-linear function between variables and coefficient of drag. For 2 0 0 model, an increase from 30% size to 40% does not cause any much change in coefficient of drag value. In contrast with level 2 2 2, an increase from 30% to 40% size for all variables causes the coefficient of drag value to increase. The increase of this value were major and thus proving the non-linearity function of variables and coefficient of drag. The result of this simulation of 2 0 0 and 2 2 2 models are presented in Figure 11 and Figure 12, respectively.

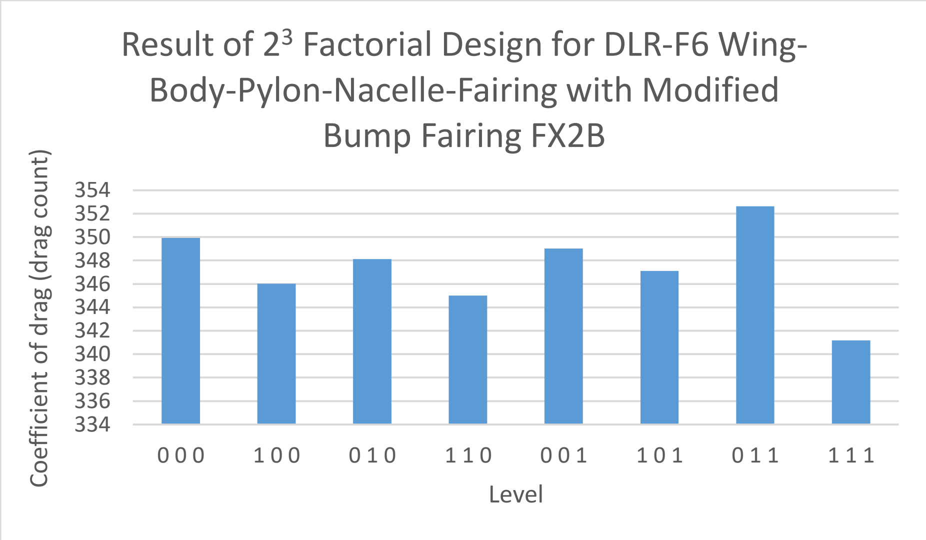

Figure 7. Bar chart of simulation result for 2^3 factorial design data

Table 2. Optimal parameter used for 2^3 factorial design simulation

Parameter	Setting
Mesh type	Hybrid (Polyhedral, Quad)
Numbers of tetrahedral elements converted into polyhedral	7750226
Solver	Type: Density-based
	Time: Steady
	Velocity formulation: Absolute
Energy Model	On
Turbulence model	RNG K-ε
Fluid	Ideal gas with sutherland viscosity
Boundary Condition	Pressure far-field
	Symmetry
	Wall
Mach number	0.75
Gauge pressure (Pa)	128596.9
Operating pressure (Pa)	0
Absolute pressure (Pa)	128596.9
Reference area (m^2)	0.0727
Solution method	Formulation: Implicit
	Flux type: AUSM
	Gradient: Least Squares Cell Based
	Flow: Second order upwind
	Turbulent kinetic energy: Second order upwind
	Turbulent dissipation rate: Second order upwind
Convergence criteria	0.0001 (10^{-4})
Initialization	Hybrid
Flow type	Transonic
Courant number	Initial: 1
	Max: Depends on the model

Table 3. Comparison of fairing effect between data acquired from self-conducted simulation and ONERA S2MA wind tunnel test

Aircraft configuration model	Coefficient of drag (drag count)	Difference of value between base model and fairing model	Source of data	Reynolds number
DLR-F6 *wing-body-pylon-nacelle*	360.7	9.7	Self-conducted simulation	$3x10^6$
DLR-F6 *wing-body-pylon-nacelle-fairing*	351			
DLR-F6 *wing-body*	290	2	ONERA S2MA Facility [4]	
DLR-F6 *wing-body-fairing*	288			

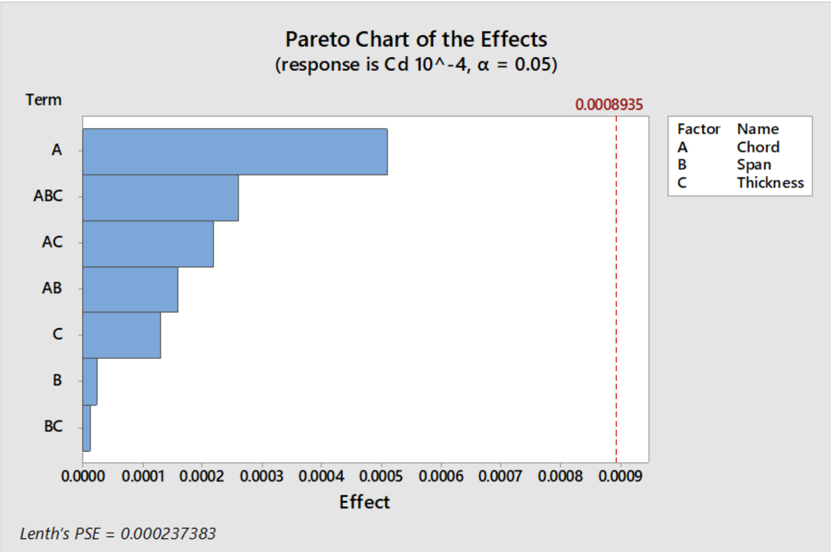

Figure 8. Pareto chart of effects for 2^3 factorial design result.

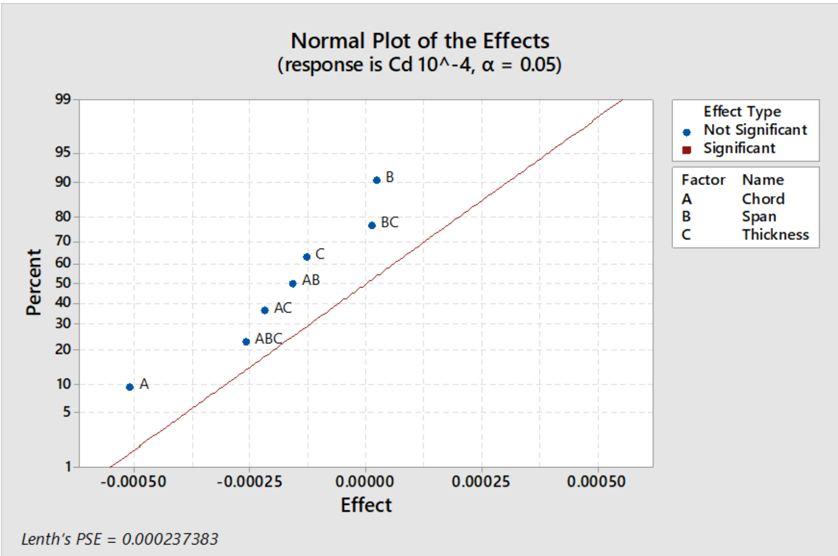

Figure 9. Normal plot of the effects for 2^3 factorial design result

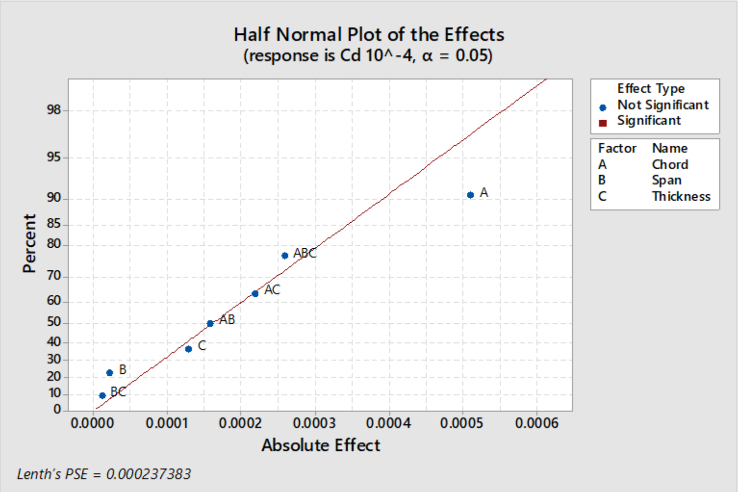

Figure 10. Half normal plot of the effects for 2^3 factorial design result

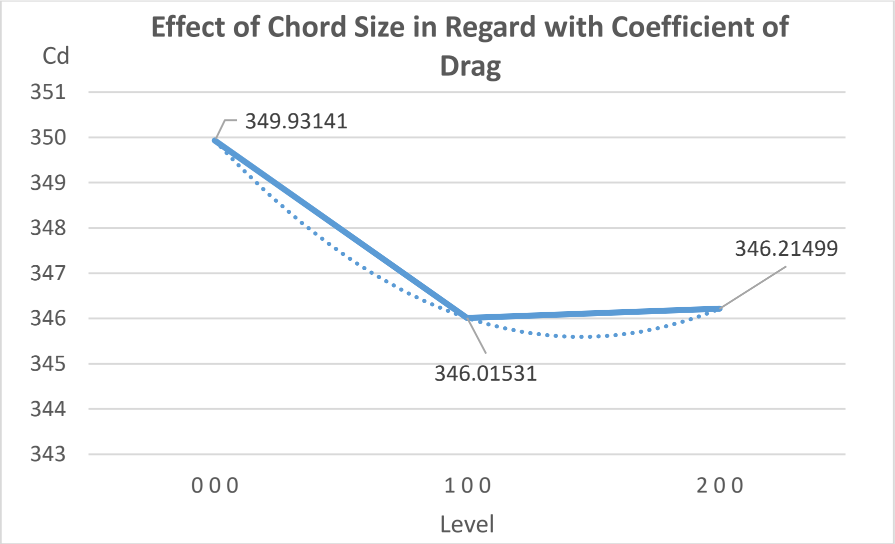

Figure 11. Function of chord variable size increase in regard with coefficient of drag value presented in drag count. The straight line indicates real value of data acquired. The dotted line indicates a polynomial regression to provide a possible curve relation between chord size and coefficient of drag

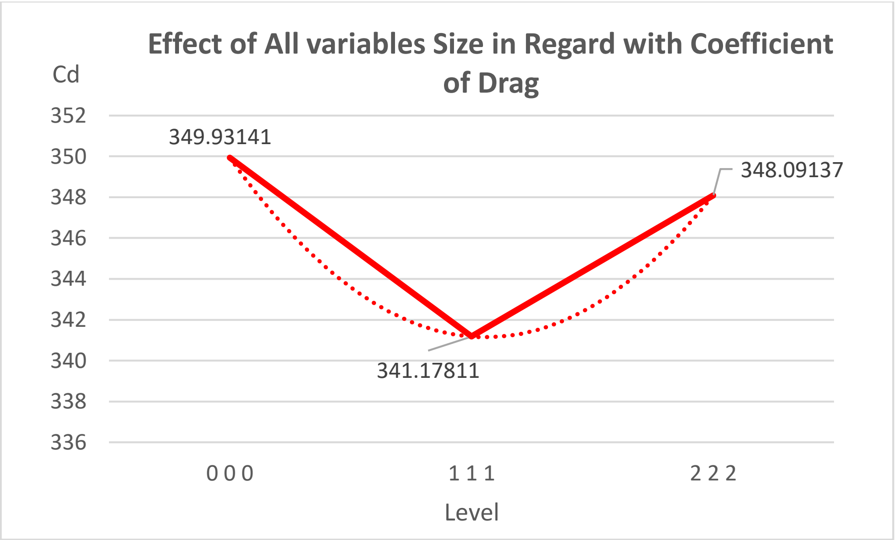

Figure 12. Function of all variables size increase in regard with coefficient of drag value presented in drag count. The straight line indicates real value of data acquired. The dotted line indicates a polynomial regression to provide a possible curve relation between all variables size and coefficient of drag

4. Conclusion and Further Study

Based on the research conducted, a few points can be raised as follow:

a. Bump fairing FX2B is optimizable.
b. 2^k factorial design DoE is unable to be utilized to optimize bump fairing FX2B due to the non-linearity function between variables and coefficient of drag.
c. Although no combination of variables is statistically significant, correlation between variables and important variables are found in this research. Important variable found in this research is the chord variable. The combination variable found to be important is the all three variables increase.
d. The lowest value of coefficient of drag in this research is found in level 1 1 1 model with 8.75 drag count reduction from original bump fairing FX2B.
e. Optimal parameter for DLR-F6 aircraft simulation has been discovered.

In further study, a 3^k factorial can be utilized to overcome the non-linearity function between variables and coefficient of drag. With 3^k factorial design, a 27 combinations of models will be tested. In regard with time and economical condition, 27 combinations might not be favorable. In that case, 2^k factorials with center points can be utilized to reduce the number of data required to obtain. Although simplified, center points method is able to give a good estimate of 3^k factorial result [7].

5. Bibliography

1. Vassberg, J.C., Sclafani, A. J., DeHaan, M.A. (2005). *A wing-body fairing design for the DLR-F6 model: a DPW-III case study.* AIAA 24th Applied Aerodynamics Coneference, 1 – 17.
2. NIST/SEMATECH. (2013). *NIST/SEMATECH e-Handbook of Statistical Methods*. NIST. Retrieved from http://www.itl.nist.gov/div898/handbook/eda/section3/normprpl.htm
3. Gatlin, G. M., River, M.B., Goodliff, S.L. (2008). *Experimental investigation of the DLR-F6 transport configuration in the National Trasonic Facility.* AIAA Journal, (August), 1 – 22.
4. Rudnik, R., Sitzmann, M., Godard, J. (2009). *Experimental Investigation of the Wing-Body Juncture Flow on the DLR-F6 Configuration in the ONERA S2MA Facility*. AIAA Journal, (June), 1 – 26.
5. Zhang, Z., Zhang, W., Zhai, Z., Chen, Q. (2007) *Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part-2: Comparison with Experimental Data from Literature*. HVAC&R Research, 13(6).
6. Lenth, R. V. (2006). Lenth's Method for the Analysis of Unreplicated Experiments. Wiley.
7. Montgomery, D. C. (2009). *Introduction to Statistical Quality Control* (Sixth Edition). Hoboken: John Wiley & Sons, Inc.