Lift and Drag Comparison of Flat Airfoil vs. Whale Inspired Airfoil for Wind Turbine Applications

[1]

***Abstract*– Nature inspired engineering application is the focus of the present study. The lift and drag coefficient of a whale inspired airfoil is numerically evaluated and compared with an asymmetric airfoil. A three dimensional numerical simulation of an airfoil inspired by whales' fins was developed to better understand the aerodynamic effect it creates on the lift and drag respectively. The asymmetric airfoil selected was the NACA 63(4)-421. To simplify the complex geometry of the whale fin, and to have an easier way to model, it was placed spheres as form of tubercles along the leading-edge side. The airfoils were built on the dimensions of 3.8 meters of chord and 10 meters of spam, commercial computational solver was use for the numerical simulation. The airfoils performance was analyzed at different angle of attacks, ranging from 0 degrees to 20 degrees with a constant Reynolds Number of 3.8×10^6. Different sphere diameters were used in this study to see the effect of these tubercles on the aerodynamic of the airfoil. According to the numerical results it was found a slightly improvement of the lift coefficient by augmenting the sphere size; however a bigger sphere size cause an earlier stall. The drag coefficient is slightly reduced too. The lift-drag ratio had increased up to a 2% which could cause a high impact for different applications.**

***Keywords*-- tubercle, humpback whale, lift coefficient, drag coefficient, lift-drag ratio**

NOMENCLATURE

C: chord length. m
C_D: drag coefficient
C_L: lift coefficient
l: length, m
L: lift force, N
N_x: stress x, N/m^2
N_y: stress y, N/m^2
R_e: Reynolds number
S: Platform area, m^2
V_∞: Velocity, m/s
q_∞: Dynamic pressure , N/m^2
α: Angle of Attack, degree
ρ_∞: air density, kg/m^3
V: Dynamic viscosity, m^2/s
ν: Kinematic viscosity, m^2/s

I. INTRODUCTION

Airfoils are involved in many areas of engineering applications; it may be related to the form of wing or turbine blades in turbines. In the growth of bio-inspired engineering, investigations around animals' physics have been augmenting and the discovery on the Humpback whale flippers has drawn special attention [1]. This application concerns the utilization of leading-edge tubercles that are found in the flippers of the Humpback whales, Fig., and how it is applied to standard airfoils [2]. Computational simulations are gaining importance in the field research for large scale wind turbines. Since modeling the airfoils required more time and cost to develop, numerical simulation are been use for the study of wind turbine and airfoil performance [3].

Fig. 1 Tubercles on the leading-edge of the flippers of the Humpback whale [4]

Airfoils subjected to fluids in motion produces an aerodynamic force [5]. The component of this force perpendicular to the direction of motion is called lift and the component parallel to the direction of motion is called drag. Investigations on different airfoil profiles have been investigated through the years in order to increase the lift and reduce the drag forces. Numerical simulations related to whale airfoils have been conducted to study its particular effects on lift and drag [6]. In a two dimensional study [7], the tubercle caused vortices that increased the momentum exchange within the boundary layer, thus maintaining a higher momentum downstream of the trailing edge which increased the lift on the airfoil. Another Abdel's numerical study [8], found that the presence of tubercles delays the stall of a corresponding operating condition (angle of attack and Reynolds number). He found a penalty of increasing the drag coefficient while using tubercles. Also experimental studies show that the humpback whale-inspired commercial fans move pump air and use less power than conventional fans. The result is that wind turbines with tubercles may operate more effectively at moderate wind speeds problems. The stalling at the tip is virtually eliminated, and the wind turbines are better able to handle higher wind speeds. Canter [9], mentioned that "The tubercles allow the operating angle to increase from 11 degrees to 17 degrees, prior to stalling". This represents a lift/drag improvement of nearly 40%. Turbines fitted with tubercles on the leading edges of each blade are able to produce more power at low fluid speeds, are quieter, and perform much better in turbulent fluid streams. From Hansen's study on performance, the tubercles did not cause and advantageous use for low angles of attack, instead the benefit is more directed to augmenting the angle of attack avoiding an earlier stall condition [10].

II. The Governing Equations

Different equations were used to model the aerodynamic of the airfoils. The Reynolds number was used to evaluate if the flow was laminar or turbulent. It was assumed the conditions of a flat plate for laminar and turbulent flow.

$$\mathrm{Re} = (\mathrm{VD})/\nu = \rho VD/\mu \tag{1}$$

The numerical study was conducted with a commercial computational fluid dynamic software (Comsol Multiphysics 5.2). The Reynolds Average Navier Stokes equation (RANS) was applied for modelling the turbulent flow in this calculation. Specifically, it was used the k-ω model for the momentum equation. It was assumed an incompressible flow and steady state conditions. The Navier-Stokes equations and the continuity equation, can be written in dimensionless form as follows:

$$\partial \mathrm{u}/\partial t + u \bullet \nabla u = -\nabla p + \nabla^2 u/\mathrm{Re} \tag{2}$$

$$\nabla \bullet u = 0 \tag{3}$$

The expressions for the lift and drag forces equations to find the lift and drag coefficient in the airfoils are listed as follows:

$$L = q_\infty S C_L \tag{4}$$

$$D = q_\infty S C_D \tag{5}$$

$$C_L = L/(q_\infty S) \tag{6}$$

$$C_D = D/(q_\infty S) \tag{7}$$

Where, q_∞ and S (surface) can be calculated by:

$$q_\infty = (\rho_\infty V_\infty^2)/2 \tag{8}$$

$$S = c \bullet \ell \tag{9}$$

III. NUMERICAL SIMULATION

The numerical simulation was developed to compare the typical airfoil versus the whale inspired airfoil. The purpose of this simulation is to use the available data from the NACA 63(4)-421 and compare with the whale's airfoil [11]. The NACA 63(4)-421 is a common airfoil applied to wind turbine blades. At first to validate the data gathered and validate the results of the simulation a three dimensional model of a simple airfoil, as shown in Fig. 2A, was built and simulated on different angles of attack to compare to the Airfoil Investigation Database, this airfoil it's called the flat airfoil due to lack of tubercles. After validating the data acquired a new model for the whale inspired airfoil has to be build, and compare to the normal airfoil. Our propose design use the NACA 63(4)-421 as base line, adding the tubercles along the leading edge. For an easier computational study the whale model (Fig. 2C) was simplify to the position of spheres (Fig. 2B). Also the spheres are easier to manufacture if they are to be implemented.

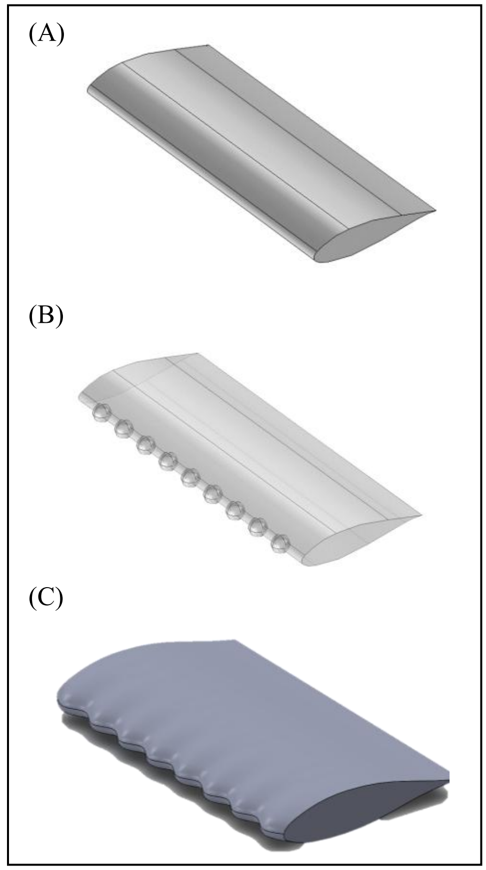

Fig. 2 Three-dimensional models simulated, (A) NACA 63(4)-421 flat airfoil, (B) Whale inspired airfoil, NACA 63(4)-421 with sphere as tubercles in CAD (C) Whale inspired airfoil and NACA 63(4)-421 with sphere as tubercles in CFD.

The chord length selected was 3.8 m to have a higher reaction of the effect of the tubercles and the length selected was 10 m. The spheres were built at different diameters to study the effect of the tubercles, a diameter of 0.5 m, or 0.13 the chord length, also it was studied a diameter length of 0.7, 0.9 and 1.1 meters, as seen on Table 1. The model with spheres can be seen on figure 2B. The separation of each sphere was separated by one sphere length.

TABLE I
SPHERE DIAMETERS

Sphere Size	Diameter length (m)
1	0.5
2	0.7
3	0.9
4	1.1

For the computational simulation the airfoil models were placed on a similar to infinite open case. Using symmetry on the sides and top and bottom boundaries and given enough space not to the flow normalized again before exiting the case. The case was built rectangular with a circular entry for the air as can be seen on figure 3A. The mesh is a free tetrahedral mesh, very fine next to the solid boundary (airfoil) and the size of the elements increases towards the far field away from the airfoil. The computational unstructured mesh is based on tetrahedral-shaped elements.

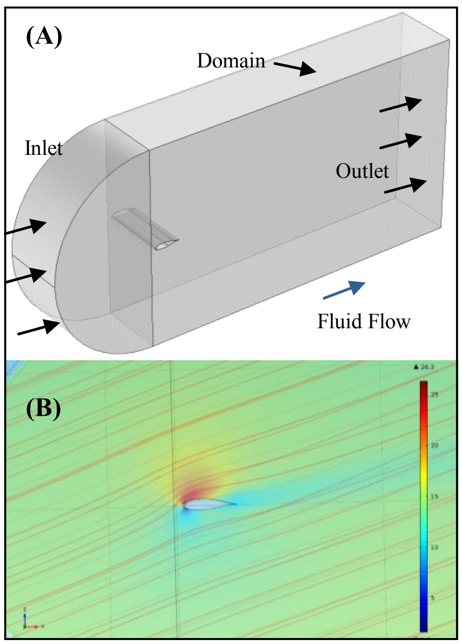

Fig. 3 (A) Testing Case for the airfoils and (B) Streamline plot of the Flat airfoil test

The tests were run ranging the angle of attack from 0 degrees to 20 degrees to found the maximum lift coefficient and to compare the results between the flat airfoil and the sphere airfoil. To give the angle to the airfoil it was changed the direction of the wind instead of the airfoil's angle (Fig. 3B), a brief explication of how this is analyzed can be found on Figure 4. Solving equation 4, for D = N_x, and equation 5, for L = N_y. Also, to see if the tubercles have a mayor effect on the changing speed it was evaluated the airfoil ranging from 5 m/s to 25 m/s, or a Reynolds number of $1.3x10^6$ to $6.3x10^6$, to have a better understanding of the work developed it was built a schematic flow chart on figure 5.

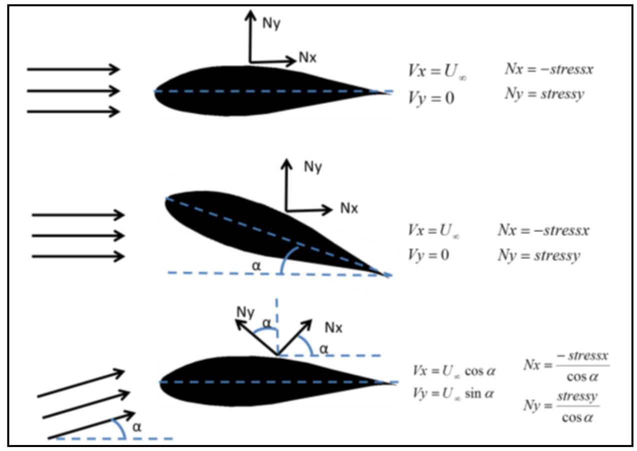

Fig. 4 Air upstream with angle of attack and analysis

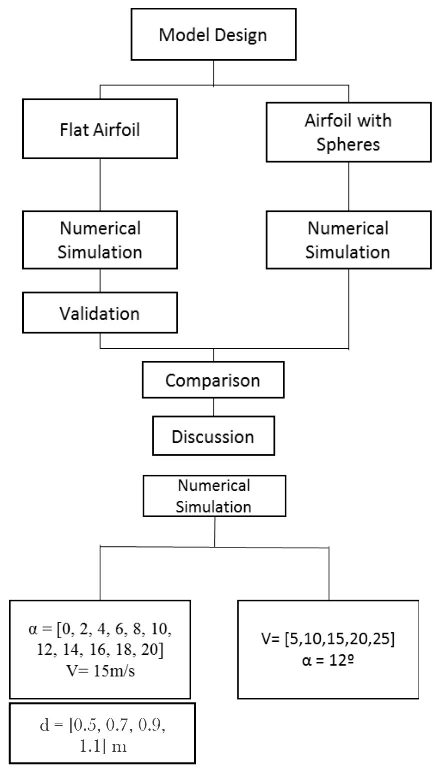

Fig. 5 Flow chart of the numerical simulation procedure

IV. RESULTS AND DISCUSSION

The Figure 6 shows a cross sectional view of the velocity field for both different types of surfaces. Both cases were run at same conditions, under an air velocity of 15 m/s, resulting in a Reynolds of $3.8x10^6$, and an angle of attack of 12 degrees. In both cases can be observed that the higher concentration of velocity is shown above the surfaces as expected, but a little difference can be seen on the section of the tubercle. A higher velocity is shown on the tubercle airfoil reaching up to 27.6 m/s (Re=7.4x10^{6}), against the maximum velocity of 25.7 m/s (Re=6.8x10^{6}). The velocity fields keep more attached to the tubercle airfoil, having higher zones of higher velocity, giving a higher difference effect between the models by augmenting the angle of attack (Fig. 7A). At certain points the tubercles helps to distribute the pressure points around the upper surface as show in (Fig. 6A).

A mesh independence analysis was elaborated to determine the mesh size for obtaining valid results. A mesh independence analysis was performed to the present simulation. Figure 7 shows the lift and drag coefficients versus the number of tetrahedral elements. After developing several simulations it was found that small differences were occurring between simulations when augmenting the number of elements used. Based on the result it was selected an extra fine mesh for the simulations with an approximate of 6 million of tetrahedral elements.

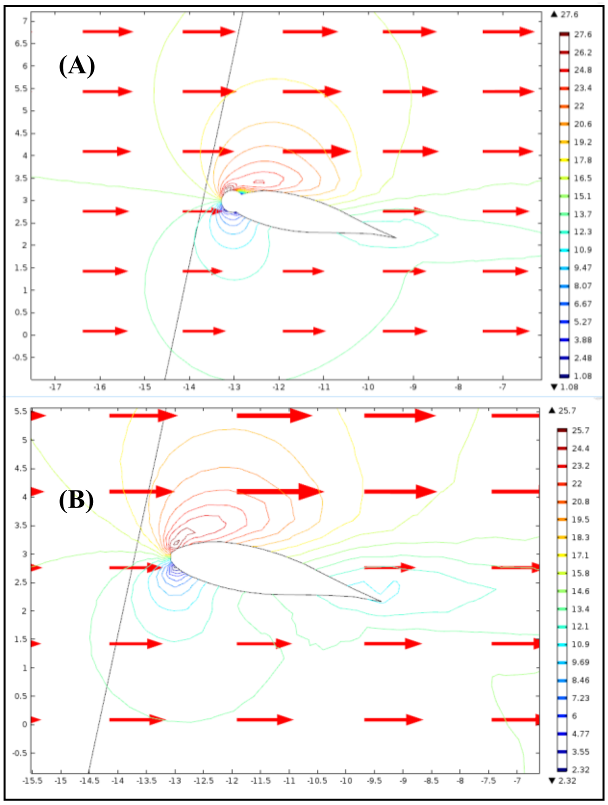

Fig. 6 Vector Plot of the Velocity field on (A) Airfoil w/ sphere and (B) Flat Airfoil

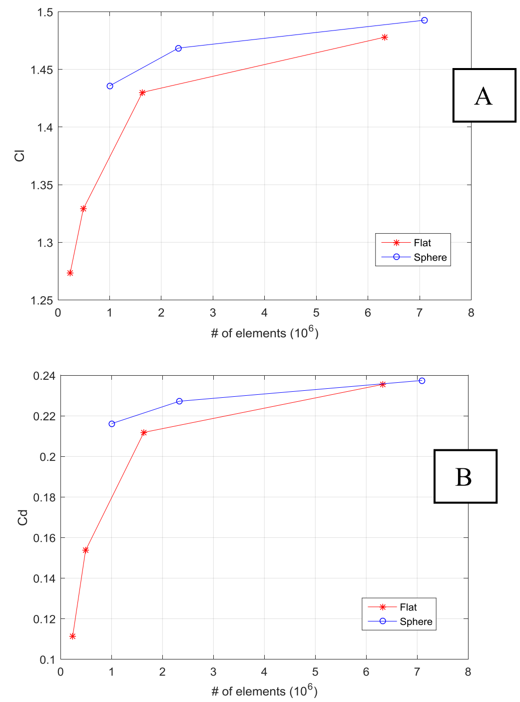

Fig. 7 Mesh independence analysis, (A) Lift Coefficient vs. Number of tetrahedral elements and (B) Drag Coefficient vs. Number of tetrahedral elements

The numerical simulation shows a slightly increase in the lift coefficient by augmenting the size of the spheres, as seen on figure 8A. Also it can be noted that at the biggest size, of 1.1 m of diameter of the sphere the stall condition occurred at lower angle of attack. As for the drag coefficient, shown on figure 8B, it decreases by augmenting the size of the sphere. In figure 8C can be seen better the improvement of the lift coefficient by augmenting the sphere diameter size.

To calculate the aerodynamic efficiency of the airfoils the lift to drag ratio enters to consideration. Calculated the C_L/C_D ratio and by plotting versus the different angles of attack a slightly difference can be found between models (Fig. 9A), only angles after 6 degrees were analysed because is where the tubercles have a higher differentiate effect. A higher efficiency can be found for the whale inspired airfoils at every angle of attack; therefore the tubercles increase the efficiency of the airfoil and limit the areas where they can be implemented. For a better understanding it was graphed a percentage of improvement of the C_L/C_D ratio (Fig. 9B), were it can be seen up to a 2% improvement for the sphere of 0.9 m of diameter size.

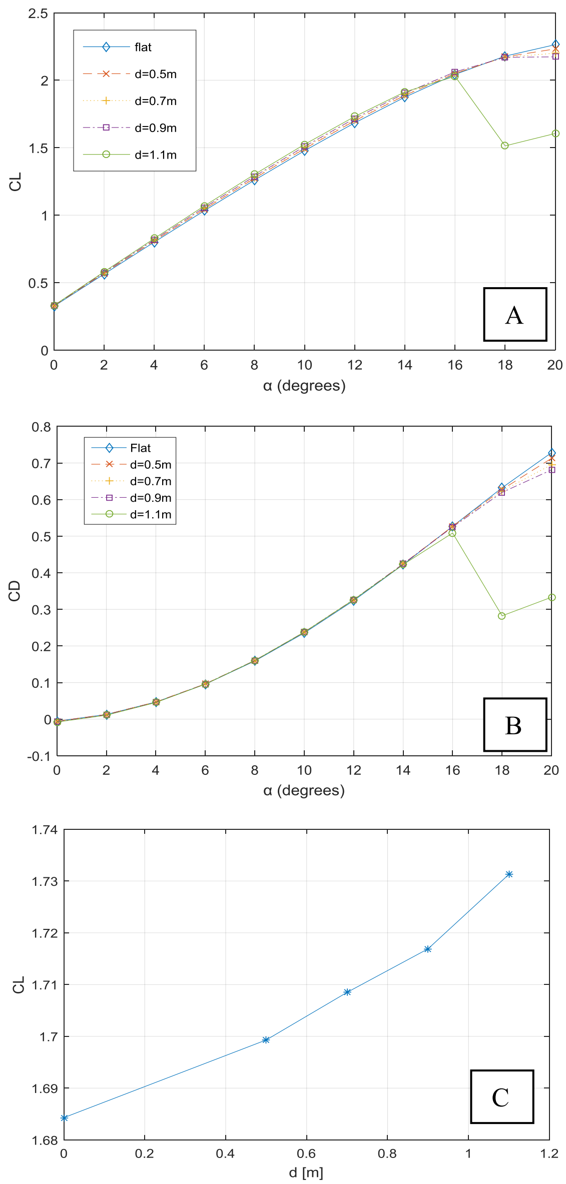

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Fig. 8 (A) Lift Coefficient vs. Angle of Attack , (B) Drag Coefficient vs. Angle of Attack and (C) Whale Inspired Airfoil with different sphere sizes, Lift Coefficient vs. Sphere Diameter (at α = 12º)

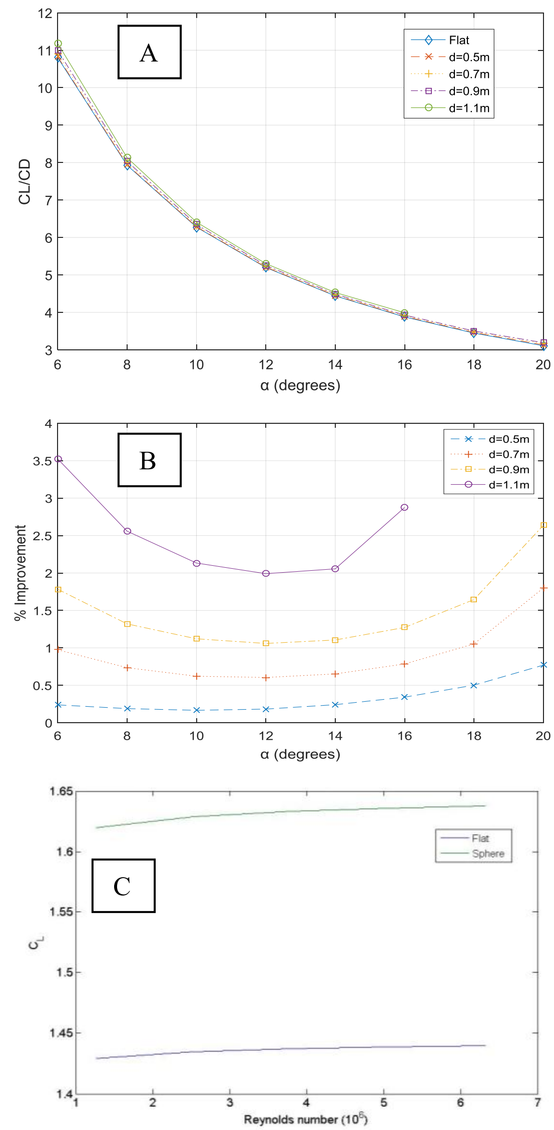

Fig. 9 (A) Lift coefficient and drag coefficient ratio vs. Angle of Attack, (B) Lift coefficient and drag coefficient ratio percentage improvement vs. Reynolds Number and (C) Lift Coefficient vs. Reynolds Number

Finally to determine if the tubercles have a noticeable effect by varying the velocity, a simulation was placed with different wind velocity. Ranging from 5 m/s to 25 m/s, or a Reynolds number of $1.3x10^6$ to $6.3x10^6$, at an angle of attack of 12 degrees (Fig. 9C). The results indicate a little increase of the coefficient at a higher Reynolds Number, but both behave similarly. So it can be deduced that the tubercles do not have a notable effect under velocity variations for this range.

V. Conclusion

The numerical results show a slightly increase in the lift and a decrease in the drag coefficients of the whale inspired airfoil compared to the NACA 63(4)-421. It was found that the lift coefficient increased by 2.25 percent by augmenting the size of the sphere to 0.9 m, until it reaches the maximum angle of attack-stall condition. For the biggest sphere, of size of 1.1 m of diameter, it was discovered and earlier angle of attack of 16 degrees for stall condition. Also that a 1 meter sphere would be too big and difficult to applied in wind turbines. The drag coefficient was decreased by 2 percent for the 0.9 m diameter sphere. The lift to drag coefficient ratio of the whale inspired airfoil is increased by 2 percent compared to the flat airfoil. The results suggest that the tubercle model could be a good asset to fans and possible for wind turbines, since they look for a higher lift to drag ratio. The results suggest that the whale inspired airfoil lift to drag ratio was not affected for lower angles, ranging from 0 degrees to 6 degrees. . A study was made varing the Reynolds number at a constant angle of attack but no a significant difference was found on the analysis. Accordingly to this result, the sphere tubercles do not have a notable effect under velocity variations the range studied. There is more opportunity to develop more models to study and have a better understanding of variations at the leading edge. As for the whale inspired model, find a model in which the augmentation in lift would not have side effects in the drag and have a higher efficiency model. The model of sphere tubercles has a potential area of research and development in wind turbines. Other researchers and manufactures claim that whale inspired airfoils are practical for their product and there are more areas to improve in this concept. Having a different profile at the leading edge for the airfoils could cause a higher cost because of its manufacture complications, so the model should have a high impact so it cost-effective application.

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