Aerodynamic Pressure Mapping Technique from CFD to FEM Model of N219 Winglet

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ARTICLE INFO	ABSTRACT
	Due to relatively complex geometry of N219 winglets, CFD simulations have to be conducted to predict the aerodynamic load by the structure in some critical flight conditions. Since the aerodynamic CFD model is not the same as the finite element model of the structure, there is a need to accurately transform the load data between the two models. This paper discusses a simple alternative technique to map pressure distribution from the mesh or face zone of a CFD simulation to an FEM model using a Matlab based in-house code program. The technique focuses on how an FEM shell element has same pressure value with its nearest CFD element. Although the cumulative forces sometimes give different result, the pressure distribution is highly accurate, moreover when the FEM model has smoother elements. Validation has been conducted by comparing with other pressure mapping technique of a commercial software Patran. The results show a good agreement where the present technique provide a more accurate result especially for the critical biggest load among the cumulative forces in the three-dimensional direction. The proposed technique is currently suitable to evaluate loading characteristics of semi monocoque structures. A further treatment of the technique for other types of structure is currently under development.

1. Introduction

N219 "Nurtanio" is a new 19 passenger aircraft developed by PT Dirgantara Indonesia to answer a new niche market in global aircraft industry. With configuration of high-wing, mid-tail, and fixed landing gear, N219 is intended to serve many remote areas. To improve its performance, the use of winglet is proposed. Winglet is a wingtip device designed to improve wing efficiency by reducing drag due to wingtip vortex. Adding winglet to the existing wing will require wingtip fitting and other structures modification. FE analysis has to be conducted to analyze this structure modification.

Due to relatively complex shape of the winglet, the aerodynamic pressure load will be performed using CFD on various flight conditions, such as angle of attack, Mach number, side slip angle (β), etc.

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From that CFD simulations, the output is coefficient of pressure (cp) distribution that has to be transferred to FEM model which has totally different mesh or element [1-7].

There are many tools and study to map pressure data to FEM model [8-11,18]. Many studies also point out how to model fluid-solid interaction [12-15]. MSc Patran provide tools to map continuous load, pressure in this context, to another model with different element mesh [16]. This paper proposes a robust technique using Matlab based code program to transfer the pressure distribution from the CFD Ansys Fluent model to the FEM model. To validate this technique, pressure mapping using MSc Patran will be compared.

2. Methodology
2.1 Pressure Mapping Method

Pressure is the force applied perpendicular to the surface of an object. As illustrated in Figure 1, pressure will always in normal vector to the surface, resulting in force in three directions if the surface located in 3D space.
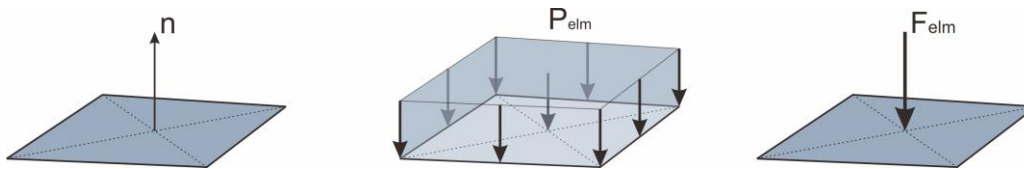

Fig. 1. Pressure on Surface

The objective of this transfer program is for transferring the CFD pressure onto FEA model that meshed differently. A Matlab program was built to accommodate this task. It will read the output of the CFD coefficient of pressure (cp) distribution, the CFD model, and the FEA model as inputs. The result is pressure distribution on the FEA model.

As shown in Figure 2, the first step of this transferring program is to read the CFD and FEM models. The program will generate some matrices such as grid, element, and cp matrices to accommodate all of the information in these inputs. A grid matrix will be generated to save the node number and coordinate for each model. This matrix consists of four columns, the first column is for the node number and the rest are for the X, Y, and Z coordinate of the node respectively. An element matrix will be generated to accommodate the number of element and the number of grids that form that specific element. The last matrix is the cp matrix, it contains the value coefficient of pressure for each element.
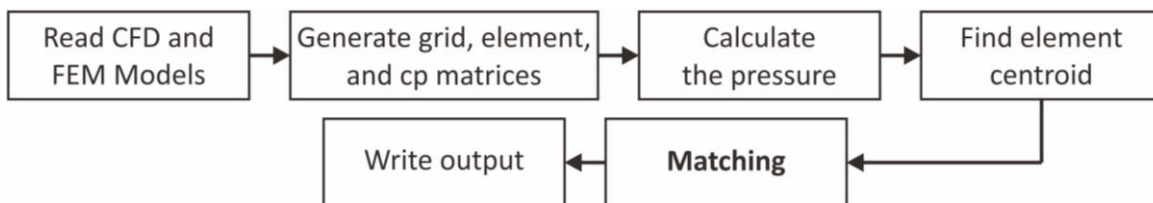

Fig. 2. Pressure mapping program flowchart

$$[grid] = \begin{bmatrix} n & X_n & Y_n & Z_n \\ m & X_m & Y_m & Z_m \\ ... & X_{...} & Y_{...} & Z_{...} \end{bmatrix} \tag{1}$$

$$[element] = \begin{bmatrix} a & grid_{a1} & grid_{a2} & grid_{a3} & grid_{a4} \\ b & grid_{b1} & grid_{b2} & grid_{b3} & grid_{b4} \\ ... & ... & ... & ... & ... \end{bmatrix} \tag{2}$$

$$[cp] = \begin{bmatrix} cp_a \\ cp_b \\ ... \end{bmatrix} \tag{3}$$

The next step is to calculate the pressure for each element based on the cp and some parameters predefined in the program as defined in Eq. (4). These pressures will be listed in the new matrix called pressure matrix.

$$P_{elm} = 0.5 \cdot \rho \cdot v^2 \cdot cp_{elm} \tag{4}$$

The next step is to find the element's centroid for both CFD and FE model elements with simply averaging the X, Y, and Z coordinates of each element.

Once the centroid of each element of both models is found, the next step is to match the target element (FEM model) to the source element (CFD model). The overall concept is to transfer the pressure on the source element to the target element which are overlapped. But, in the actual condition, there will be no element that perfectly overlapped. So, to overcome this problem, the FEM model shall have at least the same element size or finer compared to the CFD model.

This matching procedure can be done by finding the closest element using Eq. (5) from a certain target element to the source element by calculating the linear distance

$$l = \sqrt{(X_s - X_t)^2 + (Y_s - Y_t)^2 + (Z_s - Z_t)^2} \tag{5}$$

between centroids of those elements. Where l is the linear distance between two centroids and subscripts s and t on X, Y, and Z are source and target respectively. Once it is found, the pressure of the source element will be defined as the target element pressure and listed in new matrix. Figure 3 shows the illustration on how to choose shortest distance from aero model to FEM model.
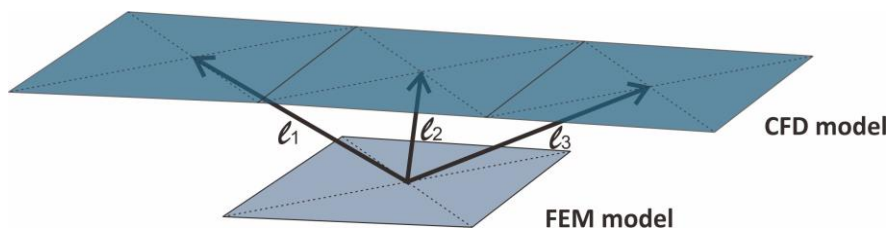

Fig. 3. Shortest Distance Illustration

For validation purpose, force resultant will be calculated and compared between CFD model and FEM model. To calculate force on element, the area of that element and its normal vector must be calculated. To calculate the area and its vector of an element, there are several steps
I.   Define vector of the element from each node to another
II.   For triangle element, the area is half of the absolute product of its 2 vectors like in Eq. (6) and Figure 4
III. For quad element, doing step 2 for two times and sum it can result in the area of its element. To eliminate the overlap area, calculate three possible area and sum it like example in Table 1 and Figure 5.

IV.   For its normal vector, just calculated the unit cross vector of the 2 sides vector of each element like in Eq. (7)
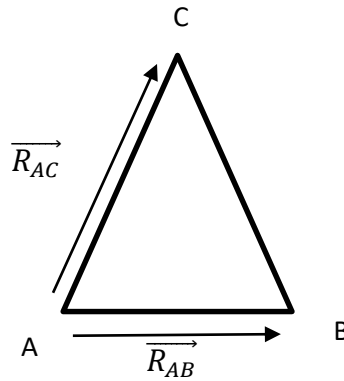

Fig. 4. Triangular Element

$$A_{elm} = \frac{1}{2} \times \left\| \overrightarrow{R_{AB}} \times \overrightarrow{R_{AC}} \right\| \tag{6}$$
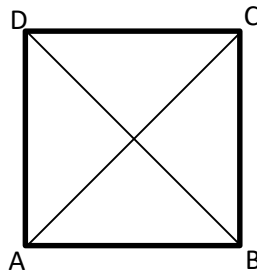

Fig. 5. Quadrilateral Element

Table 1
Three different combination areas of two triangle; the combination with maximum total area will represent quad area

Quad Area	First Triangle	Second Triangle
Combination 1	ABC	ABD
Combination 2	ACB	ACD
Combination 3	ADB	ADC

$$Unit\ Normal\ Vector = \ \overrightarrow{R_N} \ = \frac{\overrightarrow{R_{AB}} \times \overrightarrow{R_{AC}}}{\left\| \overrightarrow{R_{AB}} \times \overrightarrow{R_{AC}} \right\|} \tag{7}$$

After the area and normal vector of each element are calculated. The force component can be calculated using Eq. (8)

$$F = P_{elm} \ \times A_{elm} \ \times \overrightarrow{R_N} \tag{8}$$

At this point, it should be noted that the total element area of the FEM model can be not the same as that of the CFD model especially for a shell type surfaces due to the difference of the grid generation. Therefore, to take into account this difference, a correction factor can be introduced to take into account the differences in the mapping area. In this paper, the result of the mapping with and without correction factors will be presented.

The final step of this Matlab pressure mapping program is to write the outputs. There are three outputs that written by this program, the first is the CFD model and its pressure distribution but using Nastran input format, the second is the pressure distribution on the FEM model, and the third will be for comparing load resultant. The first output is written in purpose of comparing the source and target pressure distributions visually.

2.2 Validation by Comparison with MSc Patran Approach

For this study, pressure mapping using MSc Patran will be compared to the code that has been written with Matlab. Patran will require pressure distribution that has been written in Nastran format, and that pressure must be in the same unit that FEM model use. This will reduce flexibility because CFD analysis must output pressure for the exact condition as the flight condition that is being analyzed. The technique in this paper has the edge because it only required coefficient of pressure input and this data can be extrapolated if the Mach number of flight condition being analyzed still has small difference as the coefficient of pressure. These are the step,

Step 1: Import FEM model and CFD model and its pressure to different group as shown in Figure 6
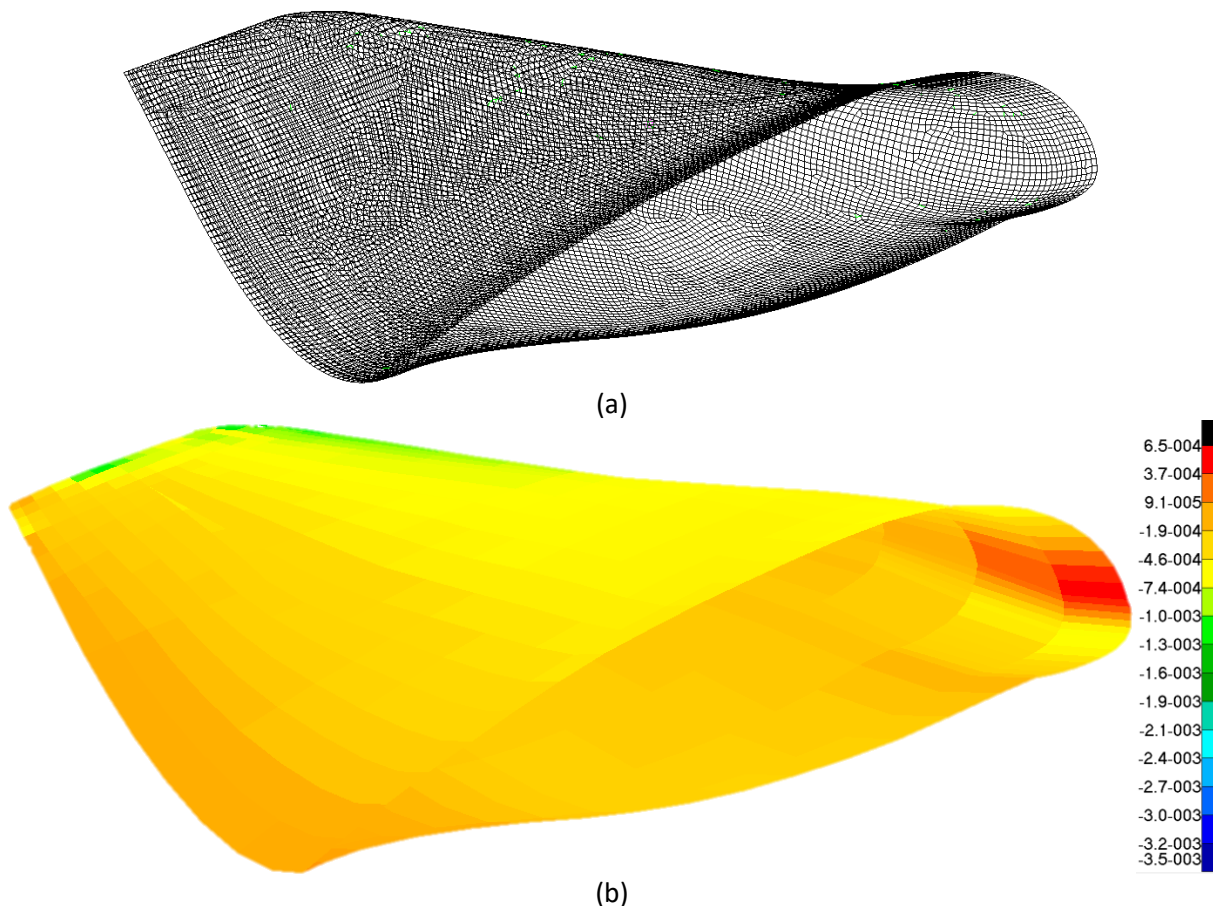

(a)

(b)

Fig. 6. (a) FEM model and (b) CFD model with pressure distribution in daN/mm^2

Step 2: Create New Field with continuous definition of CFD pressure distribution like in Figure 7
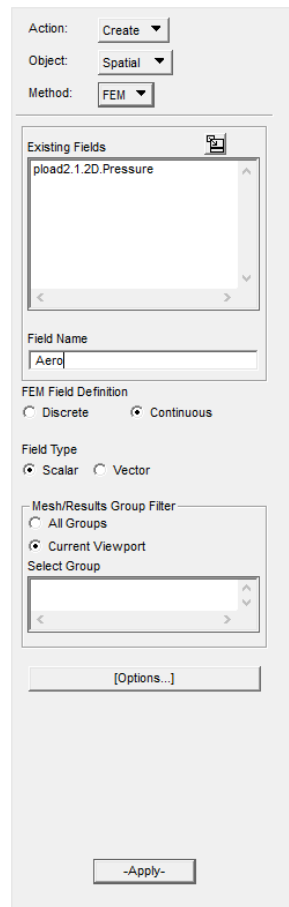

Fig. 7. Creating new field

Step 3: Create new pressure on Loads/BCs from the field created in step 2 to FEM structure as shown in Figure 8
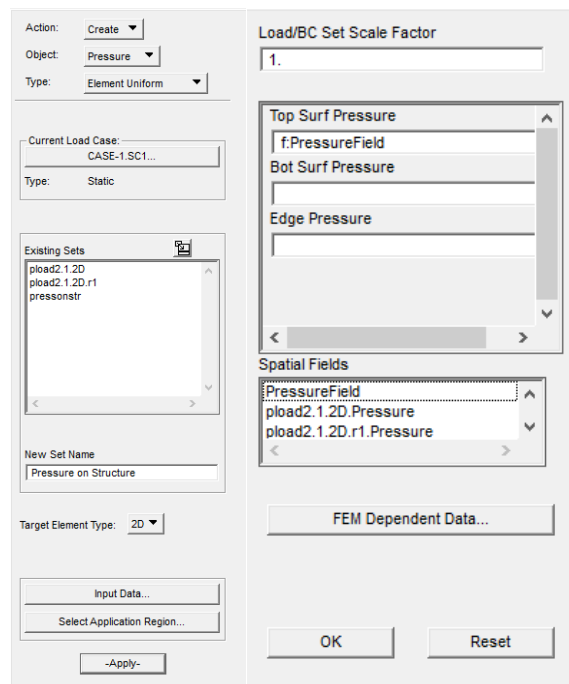

Fig. 8. Creating pressure

3. Results and Discussion

The features of the present method are demonstrated on aircraft load analysis of winglet component of N219 aircraft and validated by comparison with the result of Patran on the same CFD input.

3.1 Winglet of N219

N219 is a 19-passenger aircraft with configuration of high-wing, mid-tail, and fixed landing gear. Table 2 presents the N219 geometry data. The aircraft is designed and manufactured by PT Dirgantara Indonesia (Indonesian Aerospace Industry). The aircraft main features including the capability to have a short take-off and landing distance in rough runway which is important as mean of air transportation in remote areas. Currently the aircraft is in an improvement process in order to have a better aircraft performance. The first design of N219 does not have any winglet component. The winglet is considered in the later design of N219 to improve the aircraft aerodynamic performance. This additional winglet component needs to be deliberated on its effect on structural strength, fatigue and aeroelastic stability. For this reason, a detailed aircraft load analysis is performed which includes the present aerodynamic pressure mapping technique from CFD to FEM model in order to accurately estimate the load received by structural components of the winglet. It should be noted that the limited data and output described in the present paper is only to demonstrate the features of the present technique. The real calculation which involves a more detailed data and result are classified and are not presented to protect the proprietary of the aircraft design.

Table 2
N219 Geometry Data

Geometry	Wing	Horizontal Tail	Vertical Tail
Area (sq.m)	41.500	10.880	8.340
Span (m)	19.50	7.50	3.700
Aspect Ratio	9.16	5.17	1.64
Taper Ratio	0.52	0.53	0.50
Sweep at c/4 (deg)	-0.79	3.43	30.95
Incidence (deg)	2.0	0.0	-
Dihedral (deg)	3.0	0.0	-
Root Chord (m)	2.800	1.900	3.000
Tip Chord (m)	1.456	1.000	1.510

For this paper, the winglet has a dihedral angle of 70° with height of 500 mm (Figure 9). Based on extensive CFD simulations, this winglet configuration reduces induced drag, improves aerodynamic performance of the aircraft, and has little impact on wing bending moment. Based on the flight envelope of N219, the most critical case that affected winglet is a lateral gust case with the aircraft speed of V = 200 KEAS and aircraft side slip angle $\beta = 7^o$ [17]. Considering this critical case, the aerodynamic pressure distribution investigated in this paper is based on Mach number $M = 0.2$ and aircraft side slip angle $\beta = 7^o$.
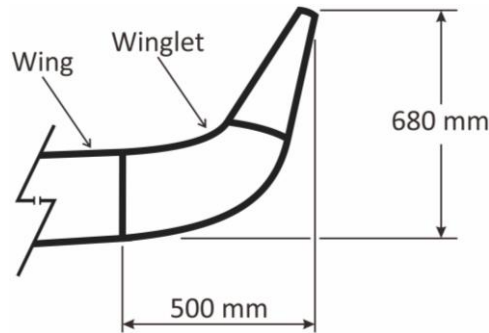
Fig. 9. Winglet of N219

3.2 Pressure Distribution Map using Matlab Program

The result of pressure distribution mapping from CFD meshed model onto FEM model can be seen in Figure 10. Visually, the result of Matlab mapping program matched closely.
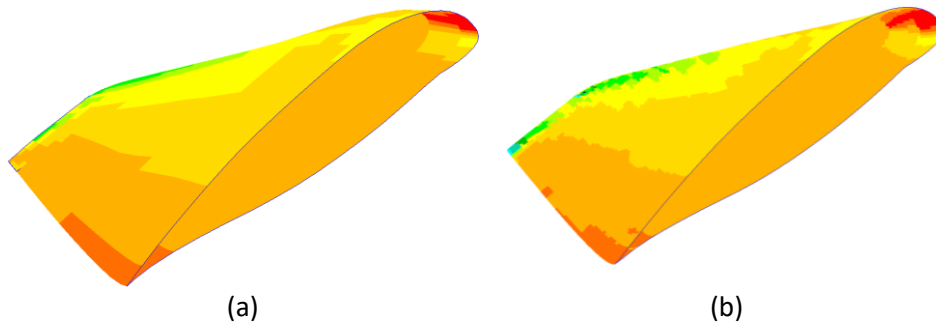

(a)   (b)

Fig. 10. Visual comparison of the pressure distribution (a) CFD model (b) FEM model (without correction)

Table 3
Load resultant comparison for present technique (without the area correction)

Force (daN)	FX	FY	FZ
CFD (Source)	-4.58	64.47	116.24
FEM (Target)	2.66	70.41	136.76

Furthermore, Table 3 shows the comparison of the load resultant for both models with its own pressure distribution. It is obvious that the load resultant of the target model is greater than the source. It is because the surface area of the target model is also larger than the source model. To compensate this, the program will be introduced with correction factor for all elements of FEM model. With correction factor of 0.85 the load resultant will be closely matched and can be seen in Figure 11 and Table 4.
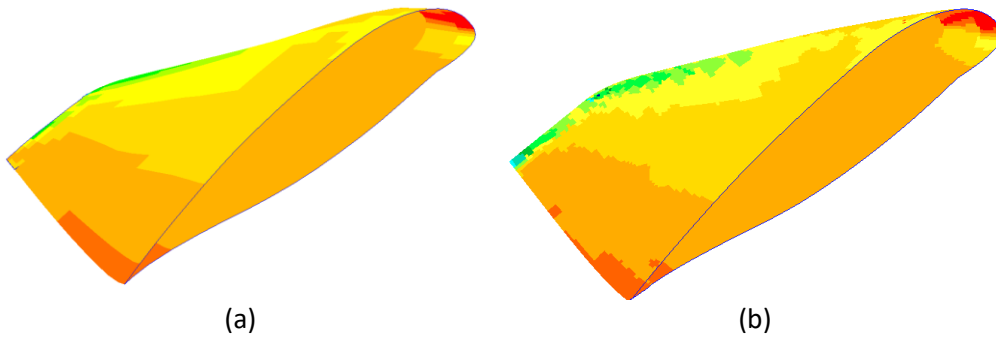
(a)   (b)

Fig. 11. Visual comparison of the pressure distribution (a) CFD model (b) FEM model after area correction

Table 4
Load resultant comparison for new technique after area correction factor

Force (daN)	FX	FY	FZ
CFD (Source)	-4.58	64.47	116.24
FEM (Target)	2.26	59.85	116.24

The time it takes to run this program in Matlab platform is 8.9 seconds for the number of finite element model of 16988.

3.3 Pressure Distribution Map from Patran

Figure 12 shows the difference between pressure distribution on CFD model and FEM model of Patran. Table 5 shows the comparison of the load resultant between the two models. It can be seen that Patran cannot accurately interpolate the data on some elements and the pressure distribution is different between the two in some locations of the surface. Although the load resultant shown in Table 5 is closer to CFD data, the difference on local pressure distribution shown in Figure 12 is apparent. The time it takes to finish mapping CFD data to FEM is 17.4 seconds.
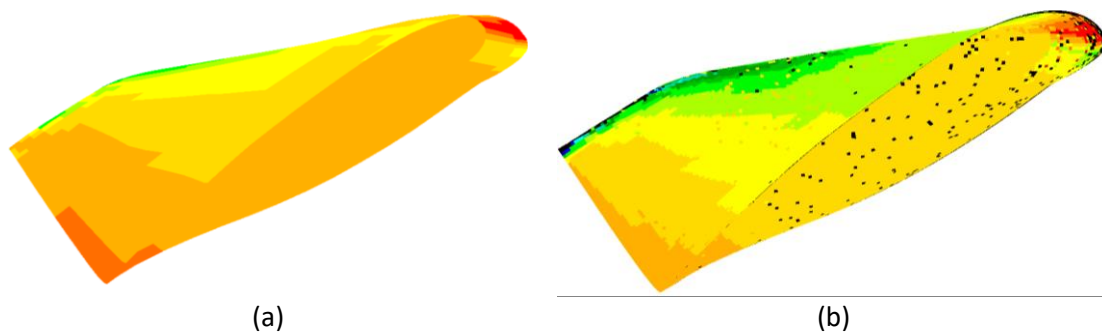

(a)   (b)
Fig. 12. Distribution pressure on(a) CFD model (b) FEM model (Patran)

Table 5
Load resultant comparison for Patran method

Force (daN)	FX	FY	FZ
CFD (Source)	-4.58	64.47	116.24
FEM (Target)	-0.47	66.54	114.48

4. Conclusions

The result shows that pressure mapping can be done using Matlab, or any other programming language, with enough understanding on how to determine the shortest distance. It can be concluded that this simple technique is proven to transfer CFD result pressure distribution to FEM model with different mesh. This technique can improve calculation speed to design winglet fitting because the input can be in coefficient of pressure, rather than pressure unit, and this input can be used or interpolate on its own if the Mach number is similar. Computing time also shows that it is faster than mapping using Patran by ±50%.

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