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Influences of Propeller Advance Ratio on Delta-Winged UAV Model Vortex Properties *

Santhoshinii Ramalingam **, Shabudin Mat, Khushairi Amri Kasim, Mazuriah Said, Mohd Nazri Mohd Nasir, Nik Ahmad Ridhwan Nik Mohd, Shuhaimi Mansor, Nor Haizan Mohamed Radzi, and Kannan Perumal

Faculty of Engineering, Universiti Teknologi Malaysia, Malaysia

ABSTRACT

The flow above the upper surface of delta wing is dominated by a very complicated and unresolved vortex structure. This study investigates the effects of the propeller advance ratio on the vortex properties and vortex breakdown above a generic 55° sharp-edged non-slender delta wing UAV model. The experiments were conducted in a closed circuit UTM-LST wind tunnel at the wind speeds of 15 m/s, 20 m/s and 25 m/s respectively at various angles of attack ranging from 0° to 18°. In this project, the propeller is installed in front of the UAV model. Two measurement techniques were employed on the model; steady balance measurement and surface pressure measurement. The experimental data highlight the effects of propeller advance ratio on lift, drag, pitching moment and vortex characteristics of the UAV model. The results from the steady balance data showed that the propeller advance ratio has increased the lift and drag coefficients respectively. The results from the surface pressure measurement have showed that the propeller advance ratio influences the development of the primary vortex above the delta-winged model. The main observation from this study was the vortex breakdown developed in the trailing edge has been much influenced by the propeller advance ratio.

Keywords: Delta-winged UAV, Advance ratio, Primary vortex, Vortex Breakdown

I. INTRODUCTION

Delta wing is the best planform for the UAV design because at a certain angle of attack, the primary vortex is formed on the upper surface of the wing. However, delta wing has some disadvantages because the vortex breakdown occurs at high angle of attack. The flow above the sharp-edge is very complicated and disorganized. Primary vortex is developed on the upper surface at certain angle of attack. Underneath the primary vortex, the adverse pressure gradient has initiated separation and another vortex termed as secondary vortex developed underneath the primary vortex at certain flow condition. The formation of the primary and secondary vortex has influenced the lift and other aerodynamic parameters of the wing [2]. When the angle of attack is further increased another phenomenon called as vortex breakdown is developed in the trailing edge [1]. Vortex breakdown occurs when the adverse pressure gradient along the vortex axis increases at a certain flow condition and angle of attack. Within the breakdown, the flow will no longer attach to the suction side surface of the wing and suffers the loss of its coherence.

There are several advantages and disadvantages when the vortex forms on the wing at high angle of attack. On the positive side, the vortex will increase the lift and improve the stall characteristics. However, once the vortex breakdown occurs, it will influence the handling quality for pilots during maneuvers. Since there are advantages from vortex formation on the wing, several studies have been conducted to control its characteristics. There are two flow techniques to control the vortex; namely active and

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** To whom correspondence should be addressed, E-mail: santhoshiniiramalingam@hotmail.com

passive. One of the techniques used in passive flow control is using blowing method [3].

There are many techniques used to control the vortex breakdown of the delta wing, one of the techniques used is propeller. Normally the propeller is installed in front or in the rear position of the wing. In 2016, a comprehensive study has been performed on a generic delta wing model with the propeller placed at locations. In that experiment, the propeller has been placed at three locations namely; front, middle and rear position. From the study, the result suggested that the suction effect from the propeller has improved the vortex properties compared to other flow control mechanisms [4]. In order to observe the effects of the propeller advance ratio on the vortex and vortex breakdown properties on the same model, another experiment has been conducted by using a bigger propeller. The propeller is installed in front of the model to create the blowing effect for the vortical flow. The propeller advance ratio formula is given in Equation 1 below where V_a = freestream velocity; n = propeller rotating speed and D = propeller diameter.

$$J = \frac{V_a}{nD} \tag{1}$$

II. METHODOLOGY

The experiment has been conducted in UTM Low Speed Wind Tunnel (LST) facility with the maximum speed of 80 m/s. The delta wing UAV model was mounted on two-strut support system as shown in Figure 1 and Figure 2. The model is attached to the steady external balance equipment (Figure 3) located underneath the test section to measure C_L, C_D, and C_M of the model. The experiment was conducted at two configurations namely clean wing configuration (without propeller) and propeller configuration (with propeller installed in front of the model). For the clean wing configuration (Figure 1) the experiment was conducted at 20 m/s and 25 m/s. The experiment with propeller configuration was carried out (Figure 2) at 15 m/s and 20 m/s for the safety reason. Both configurations were tested at the angles of attack ranging from 0° to 18°, with increment by 3 degrees. For each configuration, two measurement techniques were employed on the wing; the first one was the steady balance measurement, followed by surface pressure measurement. The surface pressure measurement method was used to analyze the flow behavior above the delta wing. The surface pressure on the upper surface were measured using a digital pressure scanner (Figure 4). The surface pressure was then converted into the coefficient of pressure in order to observe the pressure distribution above the wing. For the propeller configuration experiment, a brushless DC motor powered by a LiPo battery was used. During the experiment, the propeller speed was controlled using a remote control. The speed of the propeller was maintained at 4000 RPM for all cases. Table 1 shows the Reynolds number of the experiment corresponding to the respective free stream velocities.

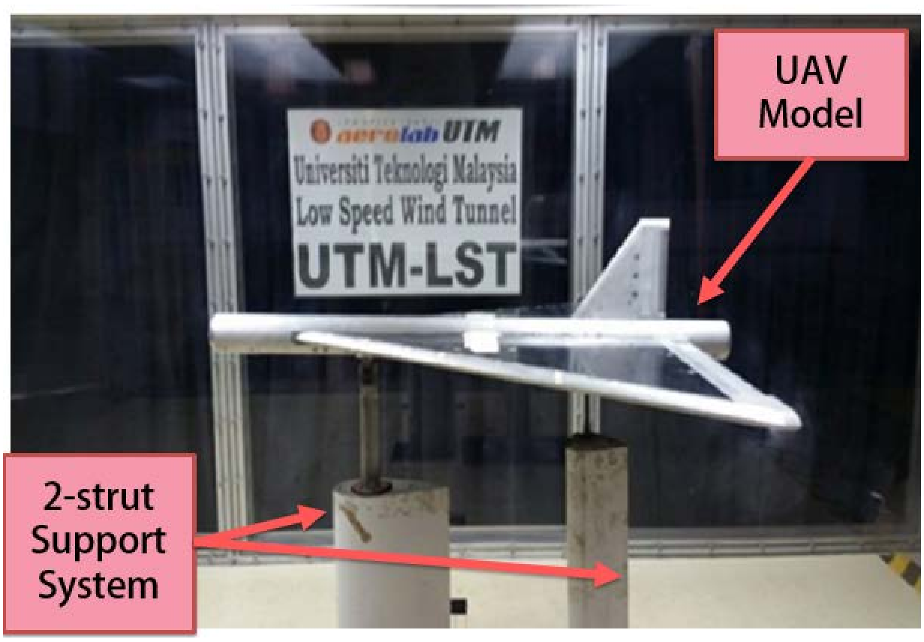

Figure 1 Clean wing configuration

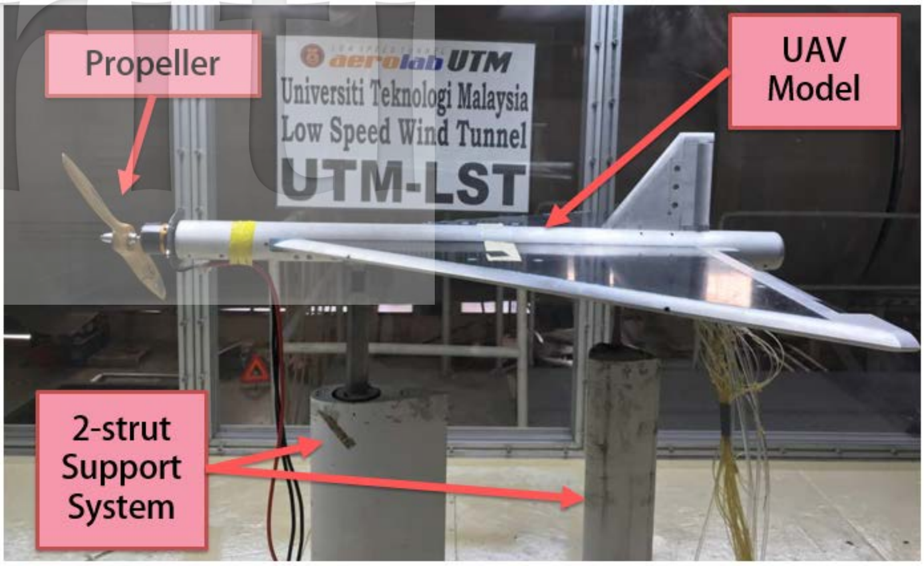

Figure 2 Propeller configuration

Figure 3 UTM-LST External Steady Balance

Figure 4 Electronic Pressure Scanner 30 DP

Table 1 Reynolds numbers and wind speeds

Reynolds Number, Re	0.46×10^6	0.62×10^6	0.77×10^6
Wind speed, V	15 m/s	20 m/s	25 m/s

III. RESULTS AND DISCUSSIONS

3.1 Steady Data

A. Effects of Reynolds Number on Clean Wing Configuration

The effects of Reynolds number on C_L, C_D, C_M and L/D are shown in Figure 5 to Figure 8 respectively. The discussion begins with the C_L-α plot in Figure 5. From this figure, it can be observed that the lift coefficient increases as the Reynolds number increases. From the graph, it can be observed that the lift coefficient increased at higher Reynolds number. For the drag coefficient, in Figure 6, the effect of Reynolds number is insignificant. The results obtained here is consistent with the previous finding by Verhaagen in 2010, which stated that the Reynolds number does not affect the drag as much as it does for the lift [5]. The characteristic of the pitching moment with increasing angle of attack is shown in Figure 7. From the figure, it can be noticed that when the Reynolds number is increased, the pitching moment coefficient also increases slightly. The results suggested that the magnitude of the primary vortex increases when Reynolds number is increased. The results also indicate that the progression of the vortex breakdown is slowed gradually when the Reynolds number is increased [6]. Hence, the magnitude of the primary vortex remains higher even at the leeward surfaces of the delta wing. Another observation is that the increase in lift has only caused a very small change in drag coefficient. The results also showed that the L/D ratio is higher at higher Reynolds number. This plot is consistent with the C_L-α plot and C_D-α plot for clean wing configuration.

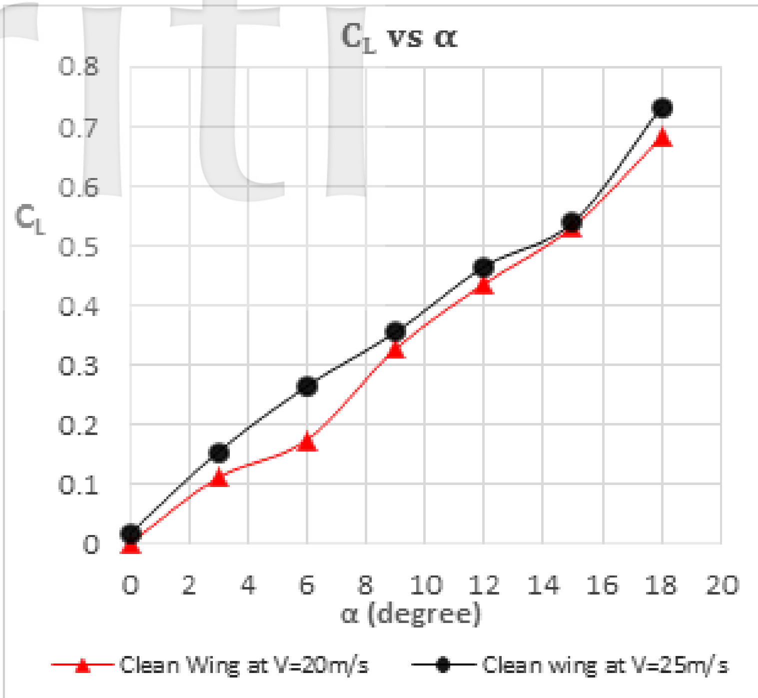

Figure 5 C_L-α for clean wing

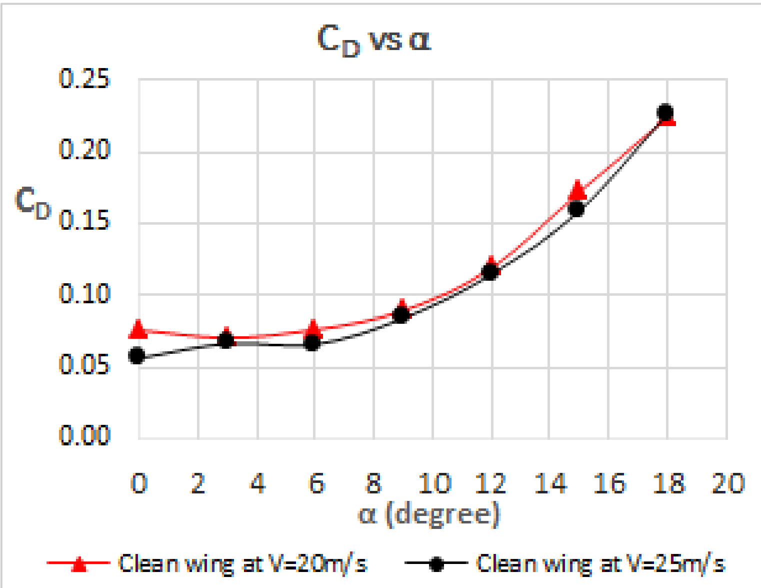

Figure 6 CD-α for clean wing

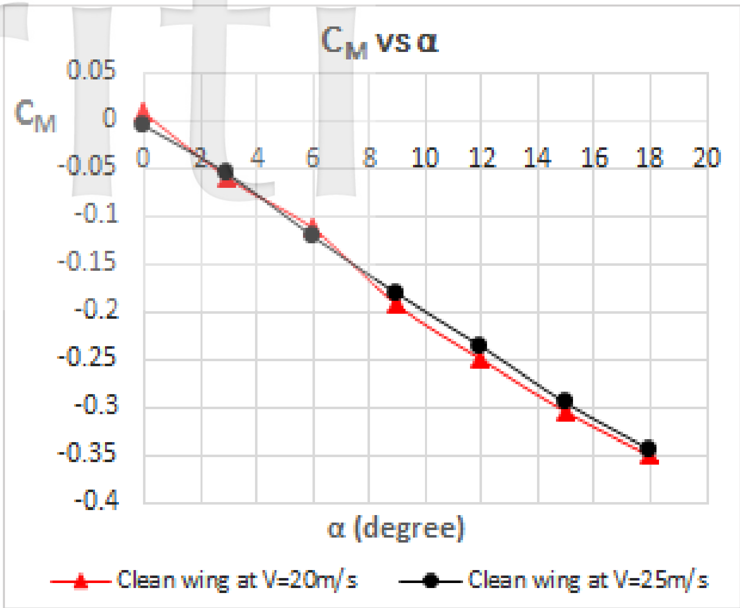

Figure 7 CM-α for clean wing

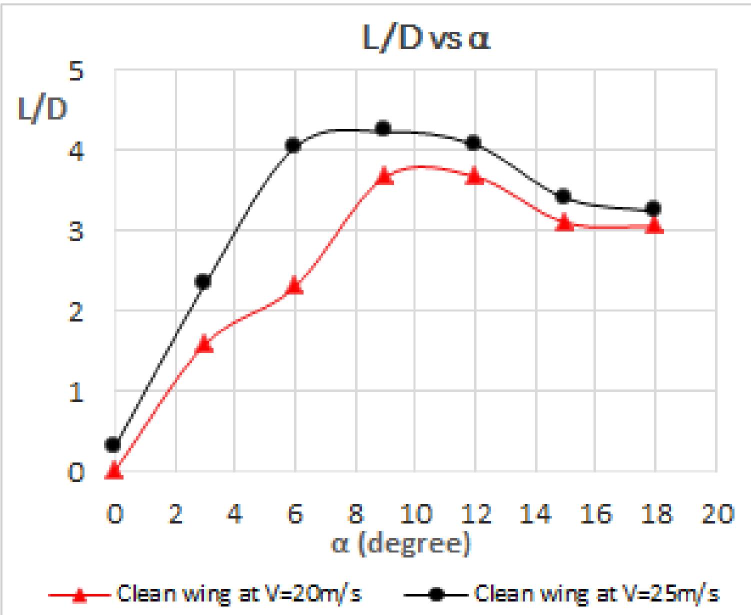

Figure 8 L/D-α for clean wing

B. The Effects of Propeller Advance Ratio for Propeller Configuration

The effects of propeller advance ratio on steady data are illustrated in Figure 9 to Figure 12. The main observation from these graphs is that the installation of propeller has a significant effect on the aerodynamic characteristics. Propeller advance ratio means propeller performance compared to the free stream velocity. If the propeller advance ratio is low, this means that the propeller effect is higher than the free stream speed effect and if the advance ratio of the propeller is high, this means that the free stream speed effect is higher than the propeller effect. The result here suggests that the propeller slipstream is very unsteady; it may cause a very high pressure drag which contributes to parasitic drag. The pitching moment characteristics show a significant drop of the gradient at higher advance ratio in as shown in Figure 11. This may be related to the vortex burst that takes place at the leeward surfaces above the wing. The L/D ratio versus angle of attack plot is shown in Figure 12. It shows that the lower propeller advance ratio is having the least favorable L/D ratio. This might be due to the higher drag generated from unsteady propeller slipstream which can be seen in C_D-α plot (Figure 10).

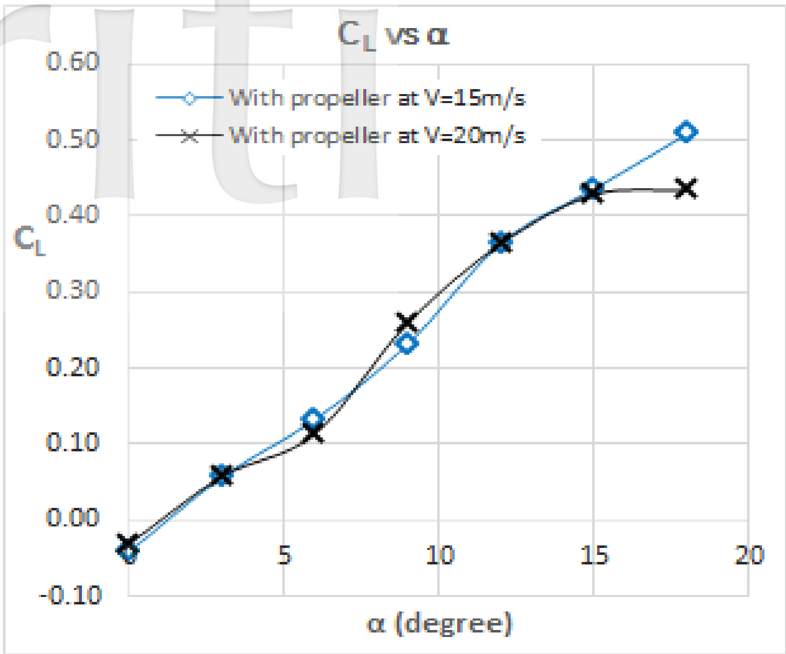

Figure 9 C_L-α for propeller configuration

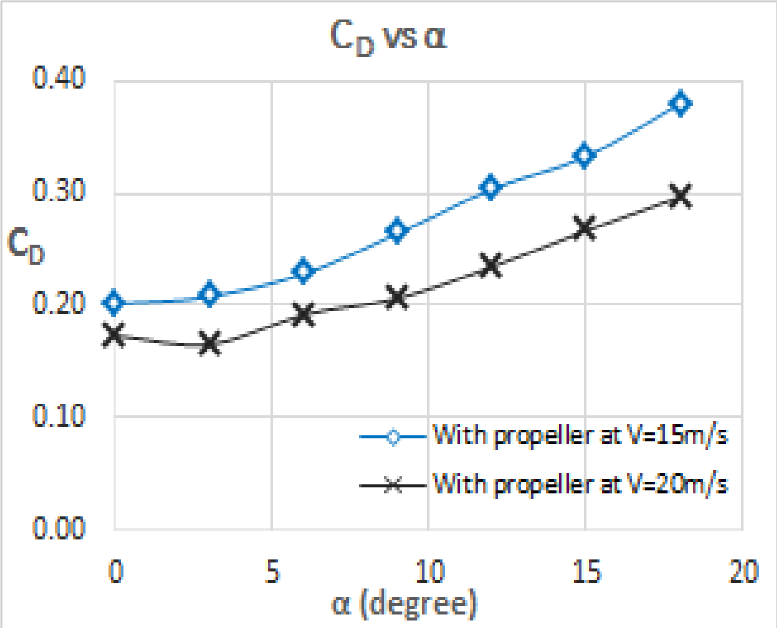

Figure 10 C_D-α for propeller configuration

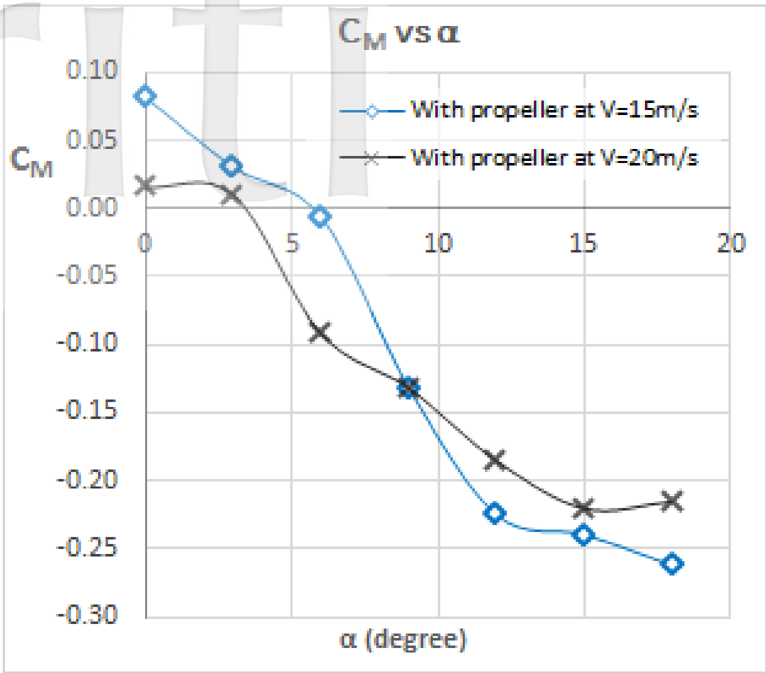

Figure 11 C_M-α for propeller configuration

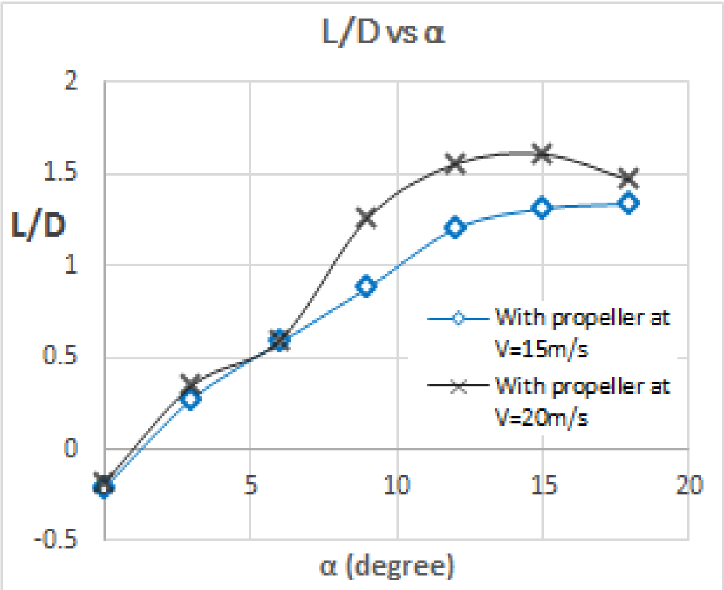

Figure 12 L/D-α for propeller configuration

3.2 Surface Pressure Measurement Data

A. Effects of Reynolds Number on Clean Configuration

The effects of Reynolds number for clean wing experiment on the pressure distribution is shown in Figure 13, Figure 14 and Figure 15. From the pressure distribution, a small increase can be observed in C_P when Reynolds number increases. This happens from the wing apex to the mid chord of the wing. Further aft of the wing, vortex breakdown is observed. The vortex breakdown can be expected to occur when there is a drop in the pressure coefficient in the region. The results here showed that the vortex breakdown occurs earlier at higher Reynolds number. At lower Reynolds number, the vortex breakdown is delayed. This observation is consistent with previous findings on non-slender delta wing studies [7-10]. For the non-slender wing, the formation of vortex breakdown is delayed if Reynolds number increases.

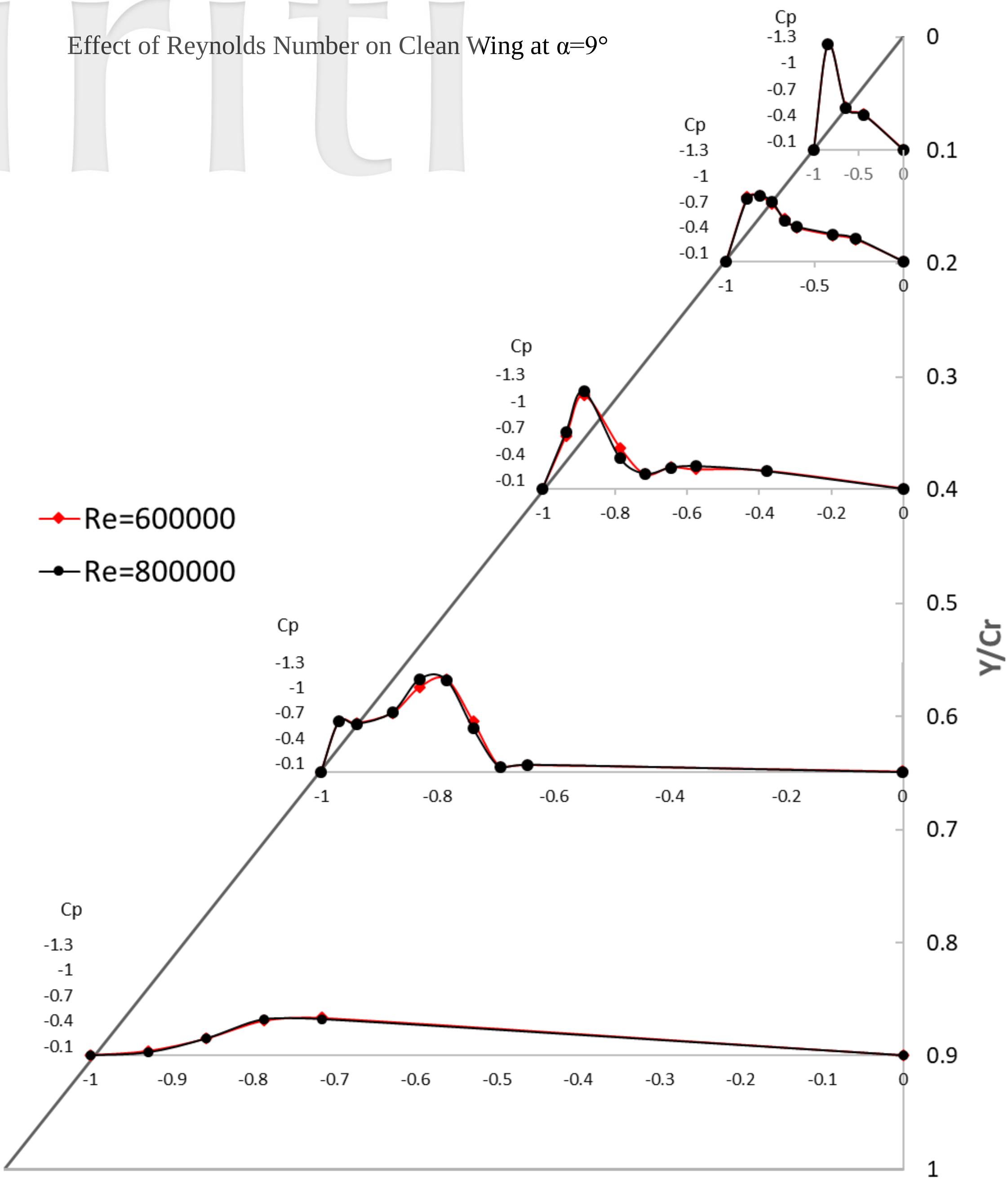

Figure 13 C_P plot at α=9° for clean wing

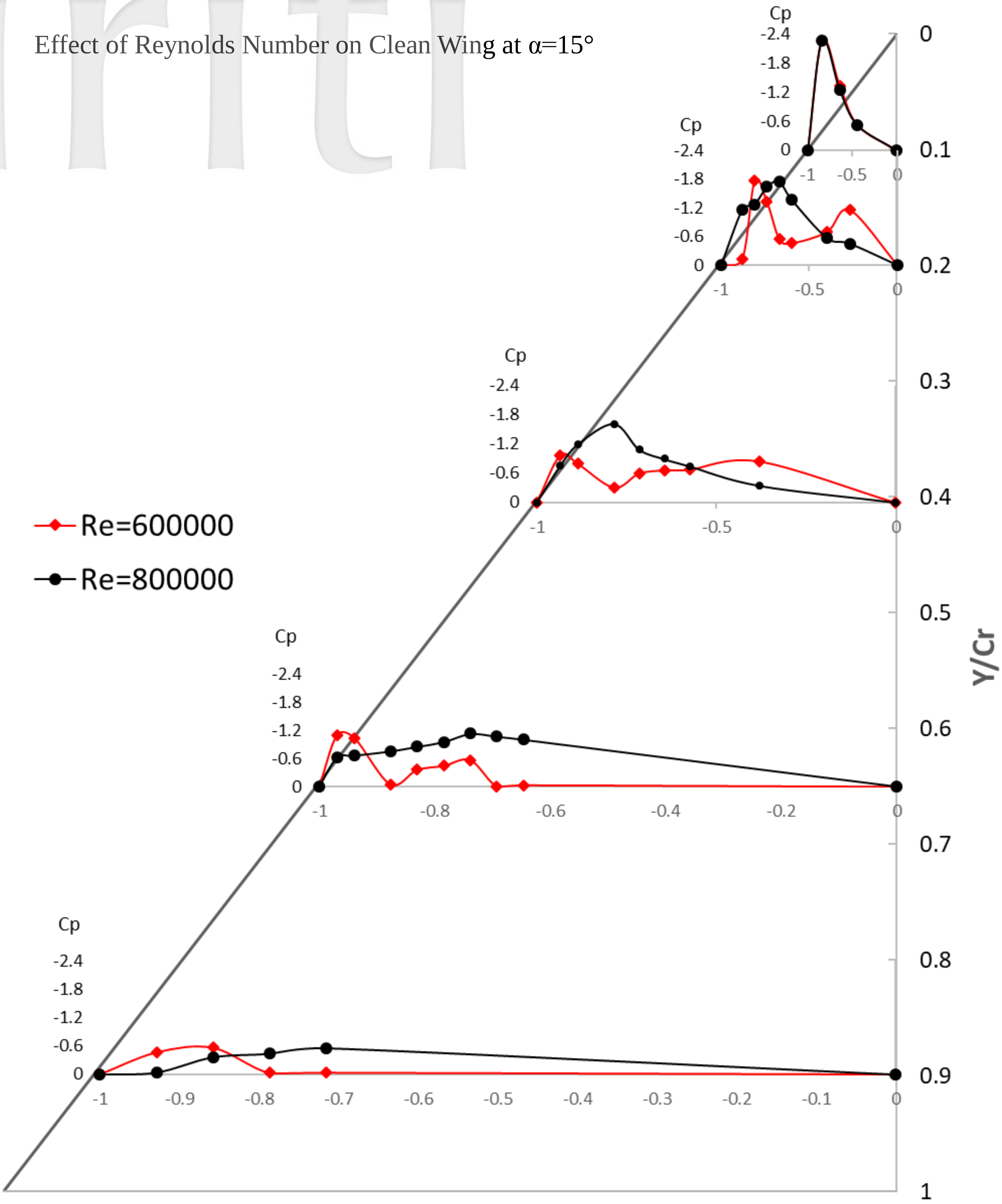

Figure 14 C_P plot at α=15° for clean wing

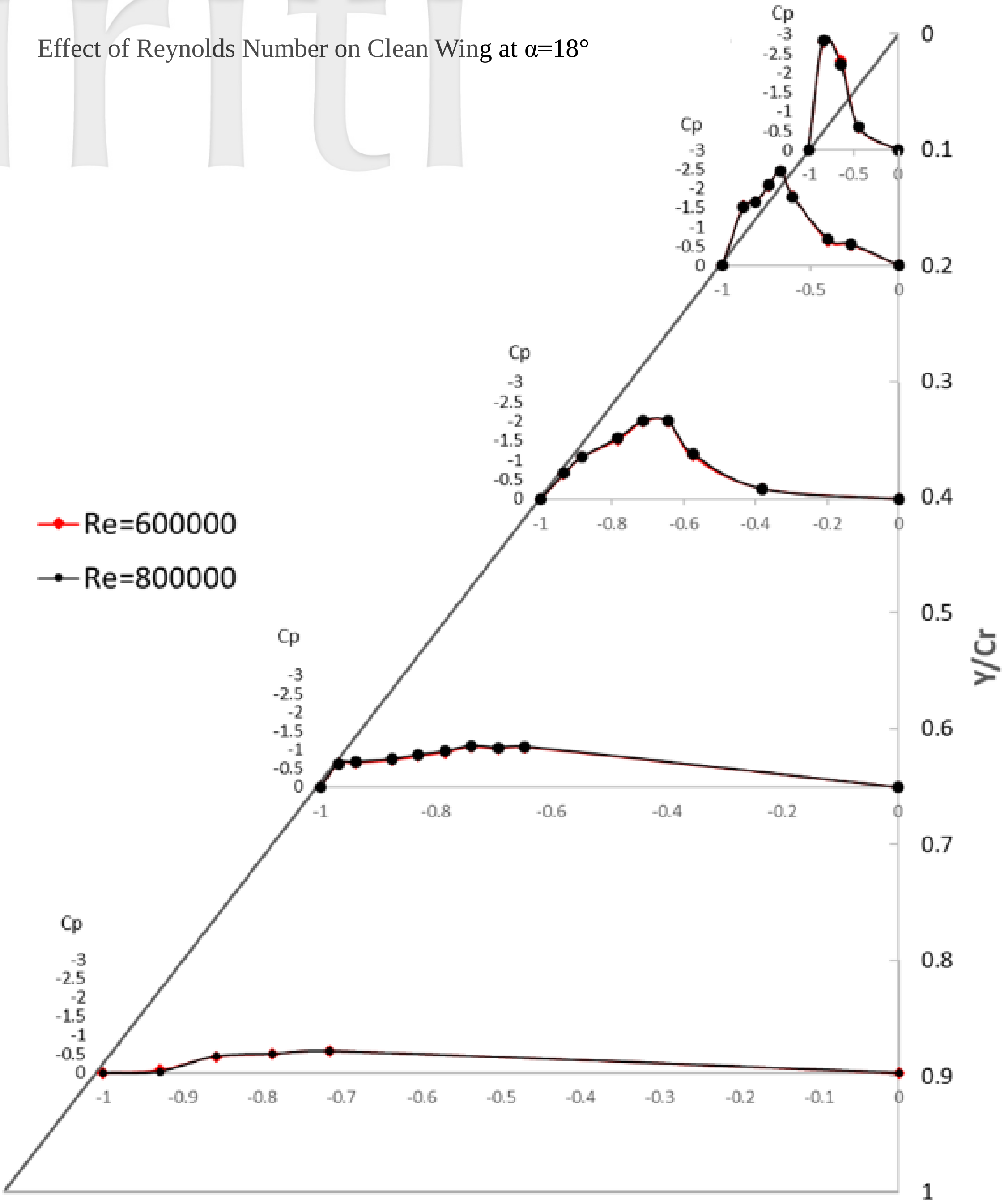

Figure 15 C_P plot at α=18° for clean wing

B. Comparison between Clean Wing and Propeller Configuration

Figure 16, Figure 17 and Figure 18 show the effects of propeller on the pressure distribution above the wing. In these figures, the results obtained from clean wing configuration were compared with those from propeller wing configuration. At lower angle of attacks, it can be observed in Figure 16 that the size of the primary vortex is smaller when the propeller is activated. This may link with a stronger primary vortex in the region. This happens because the flow is accelerated from the propeller, lowering the pressure distribution on the upper surface. At higher angle of attack, the induced flow from the propeller is unable to sustain the adverse pressure gradient and vortex breakdown is developed in the region.

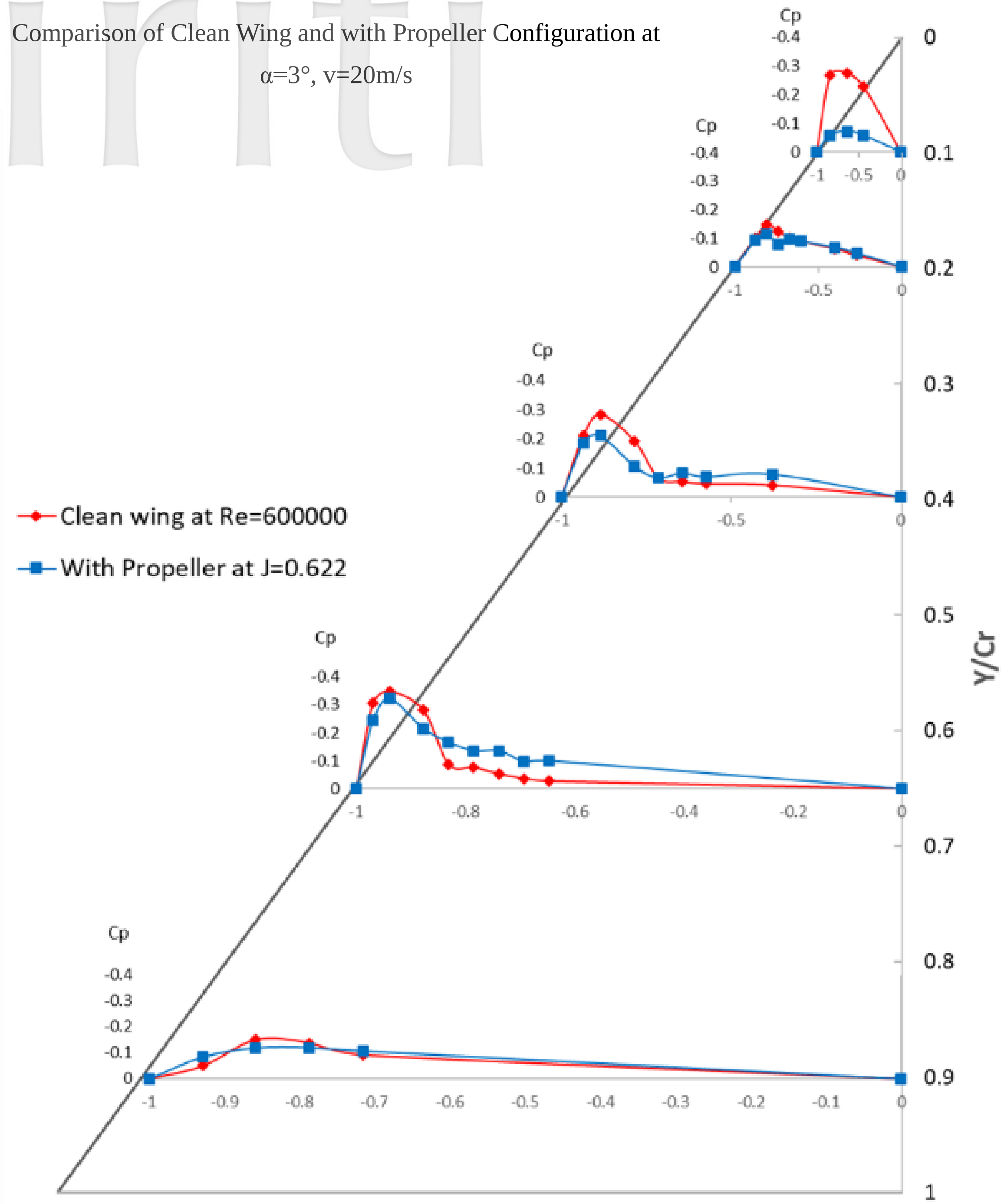

Figure 16 Effects of propeller on C_P distribution at α=3°

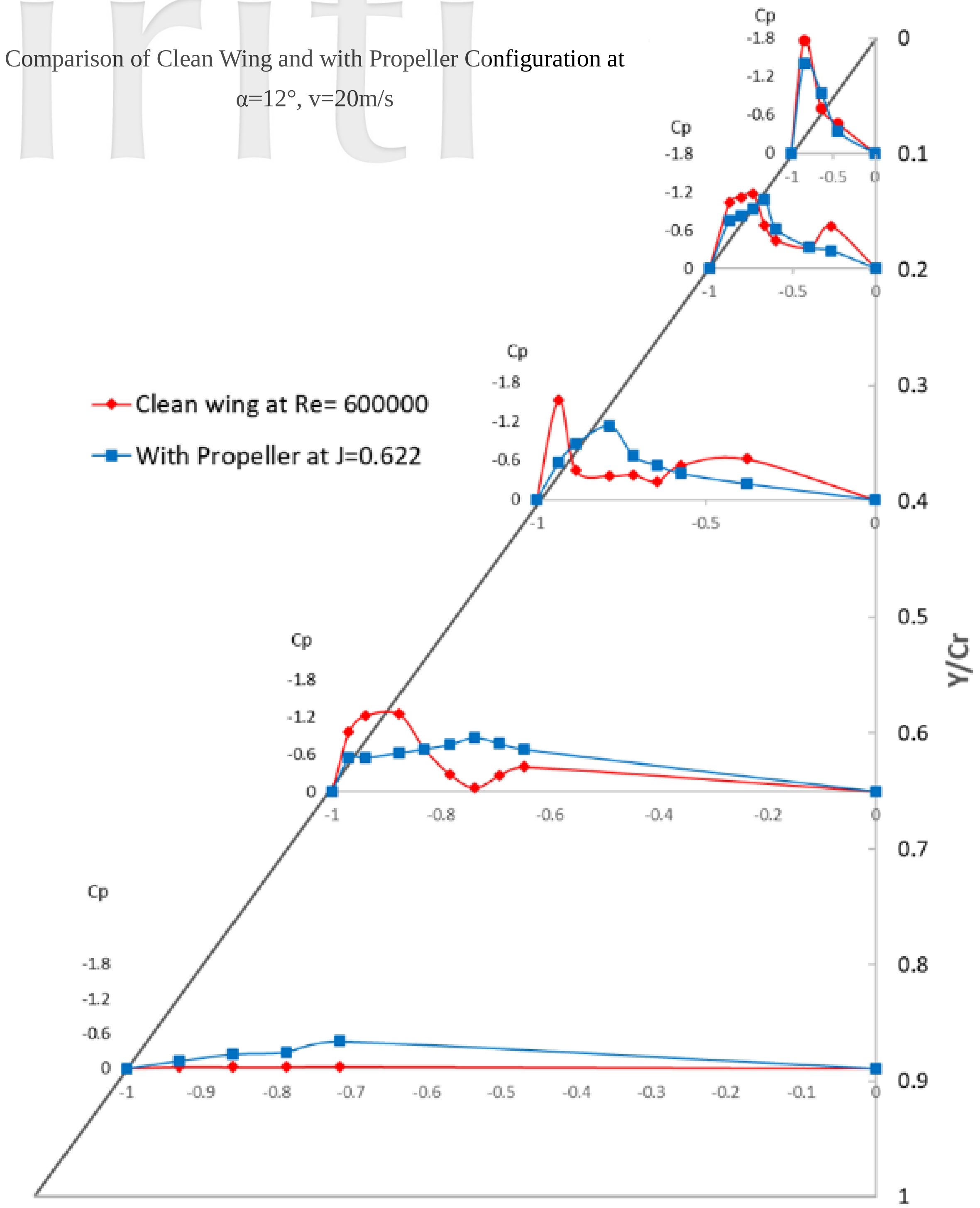

Figure 17 Effects of propeller on C_P distribution at α=12°

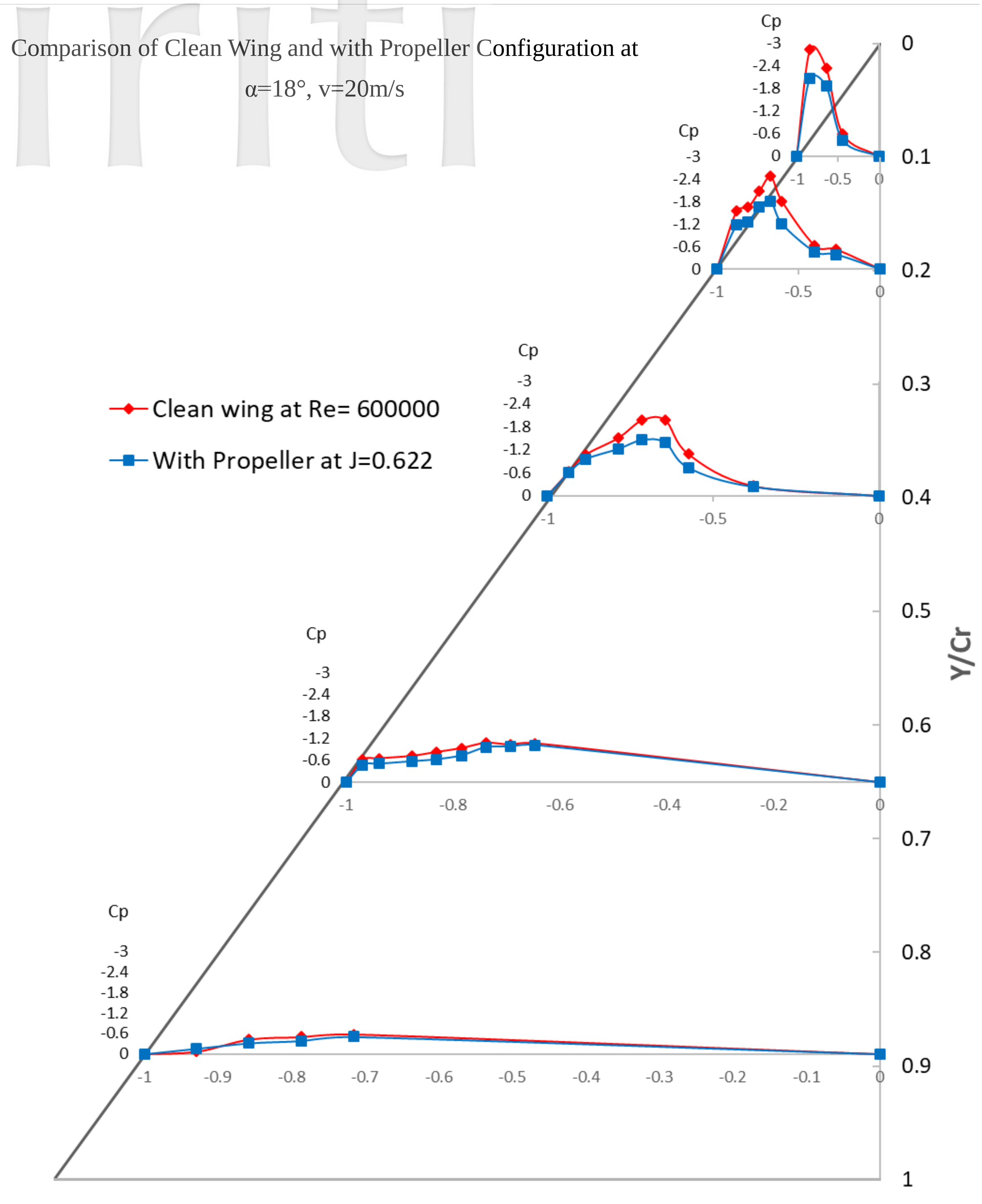

Figure 18 Effects of propeller on C_P distribution at α=18°

C. **Effects of Advance Ratio on Propeller Configuration**

The effects of propeller advance ratio on vortex above the wing are shown in Figure 19, Figure 20 and Figure 21 below. The figures show that the propeller advance ratio is more dominant at lower angle of attack. The result at lower angle of attack of $\alpha = 9^o$ showed that the size of the primary vortex is decreases. The results here showed that the vortex breakdown is delayed at lower advance ratio. Another observation from Figure 20 is that that vortex can be enhanced when the propeller speed is increased. The results obtained here consistent with the earlier literatures on propeller effects [11,12]. However, at higher angle of attack of 18° (Figure 21), there is no change in vortex strength for both propeller advance ratio tested in this experiment.

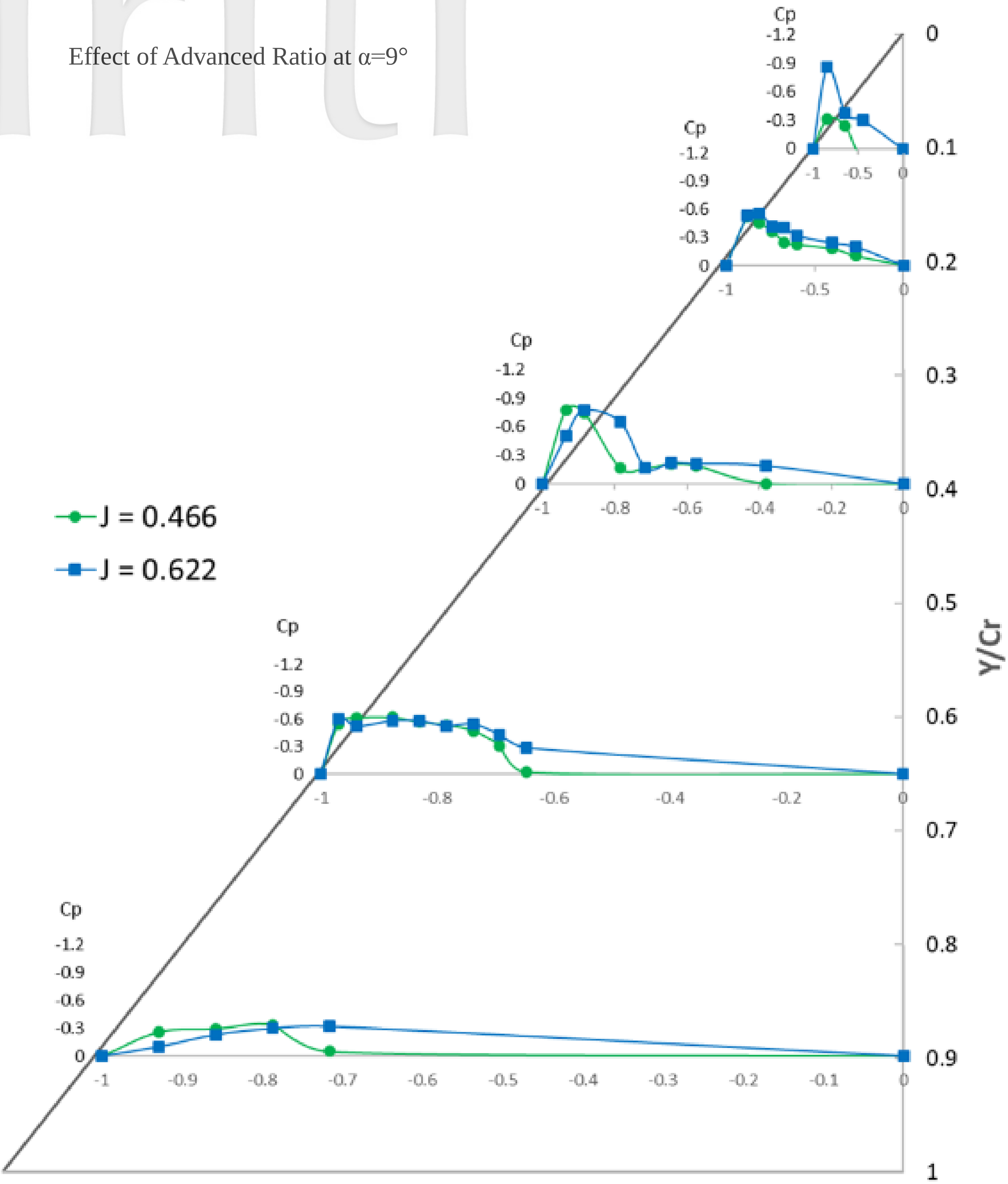

Figure 19 Effects of J on C_P distribution at α=9°

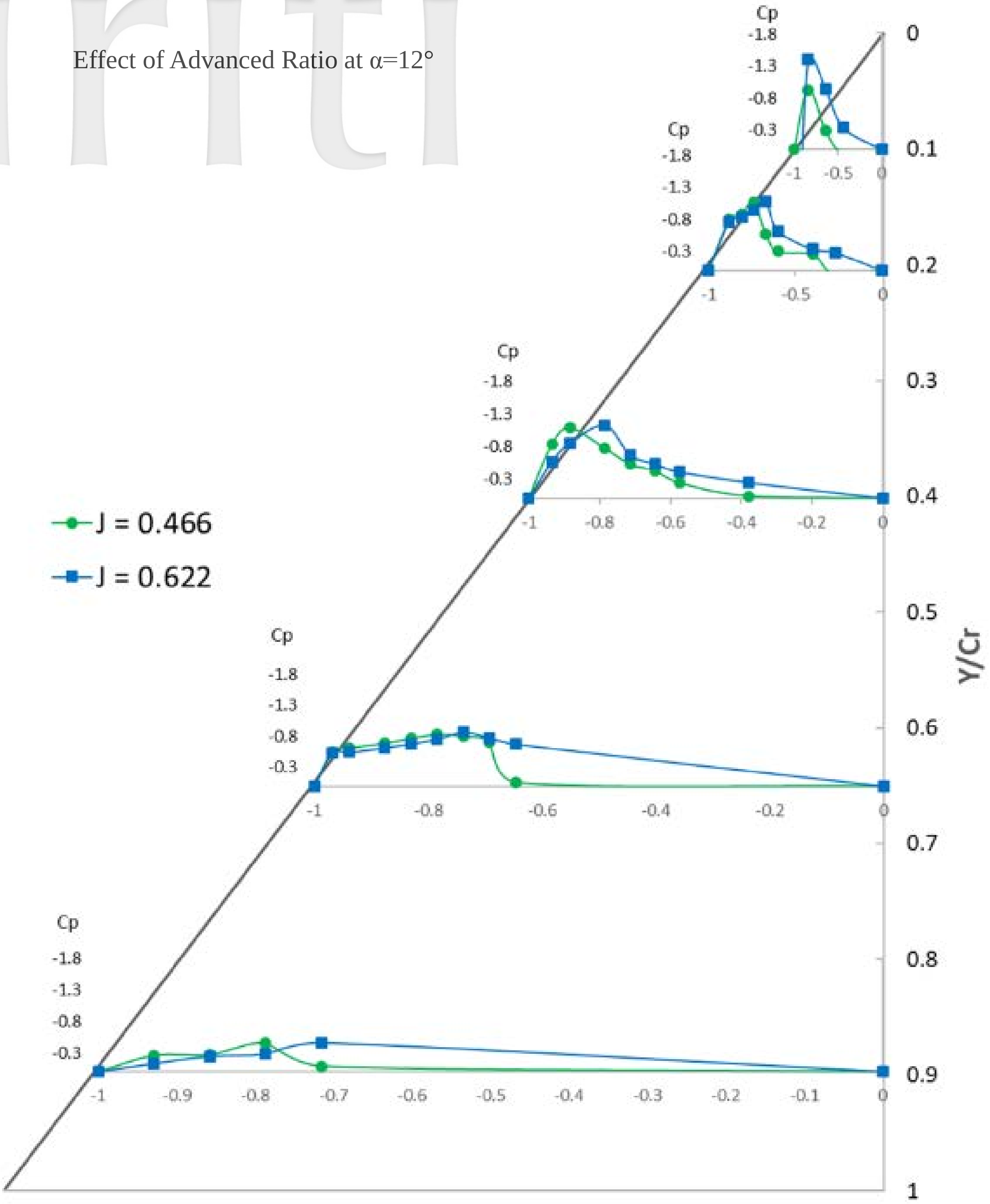

Figure 20 Effects of J on C_P distribution at α=12°

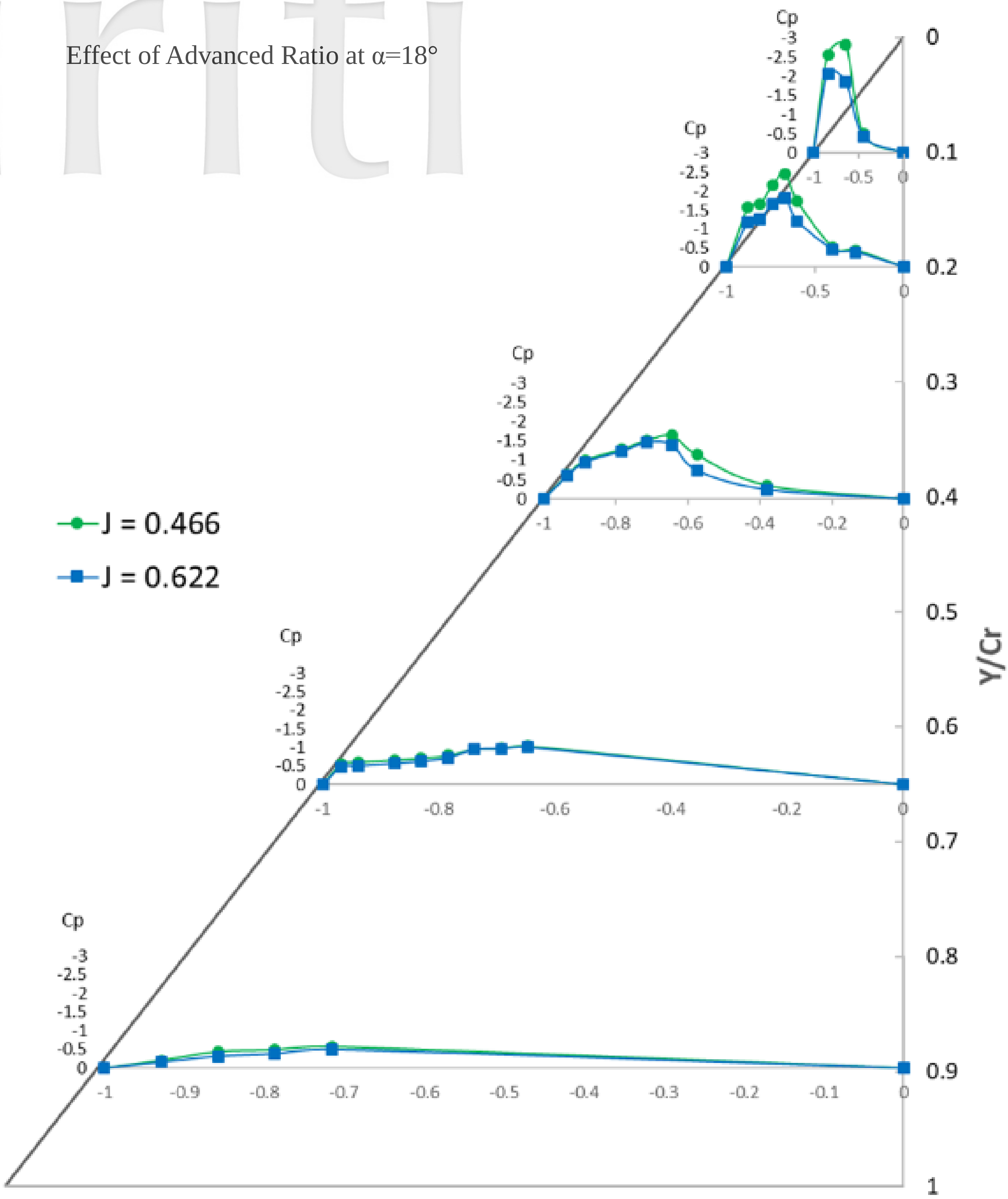

Figure 21 Effects of J on C_P distribution at α=18°

IV. CONCLUSIONS

The results obtained from this study has shown that the installation of propeller on the delta wing has influenced the lift, drag, pitching moment and pressure coefficients. From the pressure distribution plot, the vortex breakdown was observed on the wing before the maximum lift is achieved. The value of propeller advance ratio also plays crucial role in vortex development above the wing. Meanwhile, the effect of Reynolds number is insignificant on the aerodynamic coefficients of non-slender delta wing. From the surface pressure distribution study, the propeller flow has affected the vortex breakdown of delta-shaped wing model. The advance ratio is an essential contributing factor to the formation of primary vortex above the delta wing. The vortex strength is higher at lower advance ratio. At higher angle of attack, the influence of propeller on the flow above the wing was observed to be insignificant.

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