An analitical and numerical study of the Custer channel wing configuration

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ABSTRACT

The purpose of this paper is to offer an analytical optimization of the Custer channel wing (CCW) and also to numerically simulate the optimized configuration in order to validate the results trough computational fluid dynamics. The methods rely on the established set of equations to determine the pressure coefficient of a stream of air over a curved surface - due to the Coanda effect and also on basic geometric ratios used for optimization. Findings indicate higher section loadings and higher stalling angles for the channel portion of the wing, consistent with the Coanda effect. Further applications of Custer's principle could be conceived for both short take off and landing aircraft (STOL) and also for heavy air transport aircraft.

Key words: Custer Channel Wing, Coanda Effect, Super Circulation, RANS, CFD.

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INTRODUCTION

In the early 1950's, Willard Ray Custer immagined, designed and developped an innovative fixed wing aircraft which relied on a channel wing configuration. In Custer's design, the aircraft's propeller – which was located at the back of the wing, near the trailing edge- created a sucction effect over the top of the channel to increase lift.

Although his inspiration came from analyzing high speed wind gusts flowing over corrugated metal roof surfaces, the design relies on the concept of super circulation. Circulation is linked to the lift force trough Eq.1:

$$L = \rho_\infty v_\infty \cdot \Gamma \qquad (1)$$

where

v = aerial speed
G=circulation arround the airfoil
r= freestream density of air

Custer successfully tested his aircraft in 1950 and obtained a series of patents for variations on the theme Ref[1]. In his designs, the propeller can be placed both upwind and down wind of the wing channel, however in practice the down wind version is always prefereable. This is because for a stator-less propeller, the downwash is rotational and would generate uneven lift over the channel surface. Figure 1 depicts a drawing from one of Custer's early patents of invention.

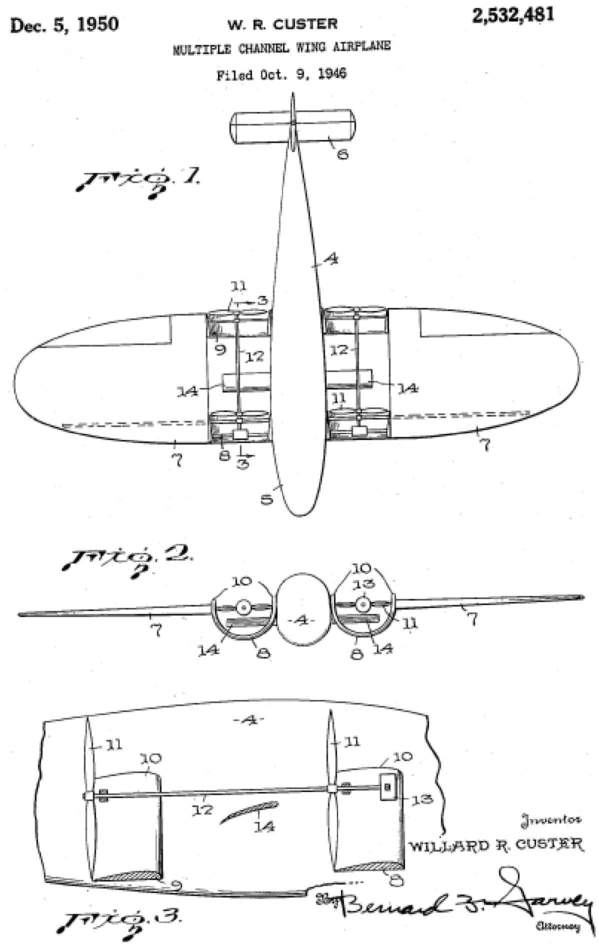

Fig.1 One of Custer's original designs, patented in 1950 (US Patent 2532481)Ref.[1]

THE CONNECTION TO THE COANDA EFFECT

The Coanda effect is ubicuos to most super circulation aerodynes, this is because by controlling the flow of air over any curved surface one can control the pressure drop over it and hence control lift. References [2] trough [5] offer analytical and experimental equations and methods for calculating the pressure drop over a Coanda surface.

For the sake of simplicity we will only present the reasoning given by Benner in Ref.[4]:

Assuming a volume element with an elementary mass dm in a Coanda jet, we can express the equilibrium of pressure and centrifugal forces that act uppon the element with the expression:

$$F_p = F_c \tag{2}$$

where

$$F_c = \frac{\rho R d\theta dR\ v^2}{R} \qquad (3)$$

$$F_p = R d\theta dP \qquad (4)$$

and $d\theta$ is the infinitesimal angular element

Benner expressed the pressure drop along the jet's span :

$$\Delta P = P_{static\ jet} - P_{atmosp\ heric} = -\frac{\rho v^2 h}{R} = -\frac{2h}{R} \cdot \frac{\rho v^2}{2} \qquad (5)$$

and then calculated the thrust of the elemental volume of height h:

$$T_H = \rho v^2 h \qquad (6)$$

therefore we can express

$$\Delta P = -\frac{T_H}{R} \qquad (7)$$

and since the pressure coefficient is deffined:

$$C_p = \frac{\Delta P}{\frac{\rho v^2}{2}} \qquad (8)$$

we arrive at

$$C_p = -\frac{2h}{R} \qquad (9)$$

Benner's equation works well only for small values of h (h<<R) however Roderick in Ref.[5] offers an aleternative equation for thick jets – in which h has the same order of size as R:

$$C_p = -\frac{2h}{R}\left(1 + \frac{h}{2R}\right) \qquad (10)$$

THE COMPUTATIONAL FLUID DYNAMICS STUDIES

In order to test the accuracy of the pressure coefficient analytical formula provided by Roderick, we sat out to design a simple computational fluid dynamics test in which a flow injected trough a slot of height h washes over a cyllindrical surface of constant radius R.

The velocity of the stream is in the high incompressible regime, the initial value being 100 m/sec. Reference [6] also presents a numerical study of the Coanda effect in which the viscosity model chosen is the Menter k-omega Shear Stress Transport (SST) this is deemed to be more accurate than other models since in the case of Coanda flows, the jet separation is an important parameter to be determined.

For this instance however, the angle of detatchment is of little importance since the ramp itself spans over only 90°. This value is far below the empirical established value for flow separation given by Newman Ref[7]:

$$\theta_{sep} = 245 - 391\frac{h/R}{1+1.125h/R} \qquad (11)$$

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Figure 2 presents the evolution of the pressure coefficient C_p, determined by the computational fluid dynamic test undergone with a pressure based solver for this two dimensional case.

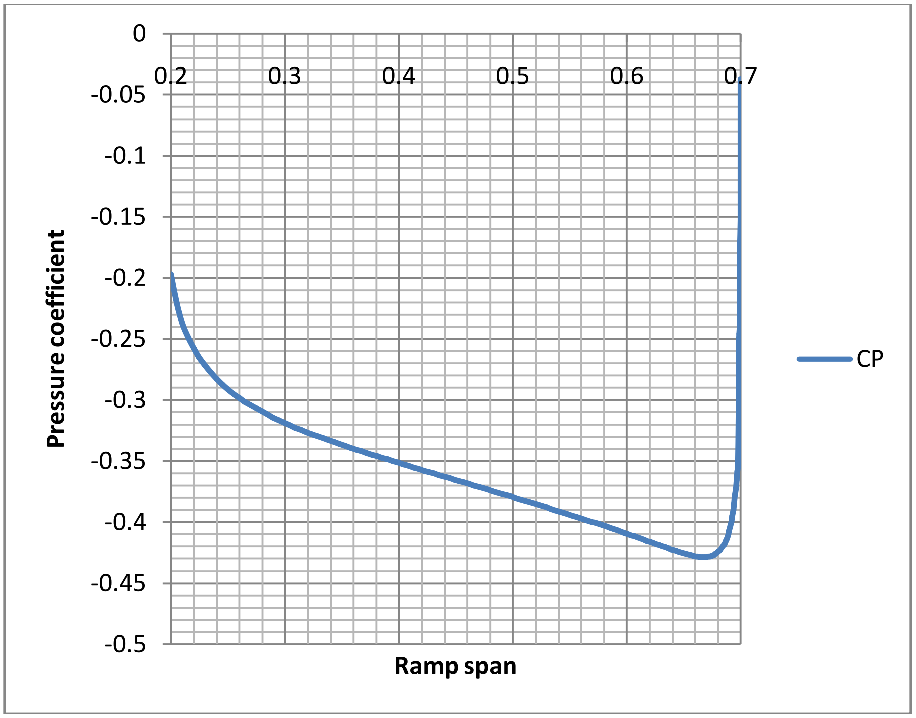

Fig.2 The pressue coefficient varies across the ramp span although the pressure drop is a constant Ref[9]. This is due to the fact that the total pressure has a liniar drop across the ramp.

Because Roderick's analitical equation estimates an average pressure coefficient of 0.44 for the particular case described here, we can conclude that the analytical expression correlates well with the preliminary numerical study, although the CFD plot suggests a higher pressure drop.

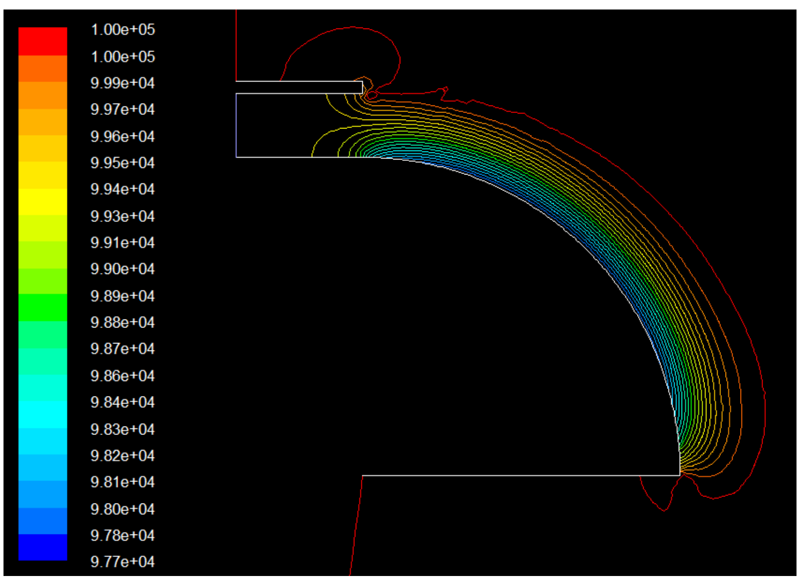

Fig.3 The Static pressure contours calculated for the Coanda effect ramp

Further, a geometrical optimisation of the channel wing was sought. By this we considered that the airfoil section will be normal to the director circular arc at all points across the channel's circumference. Therefore the pressure distribution will be the same across all radial locations of the channel and hence lift will present the same behavior. A representation of this is shown in Fig.4.

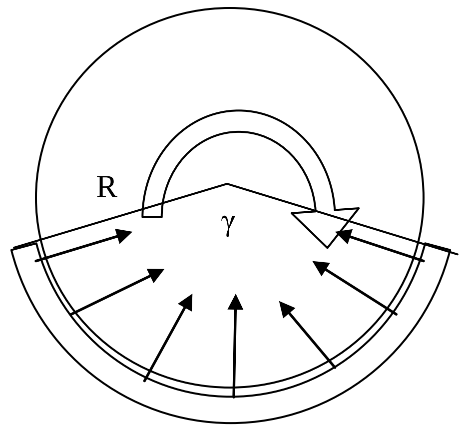

Fig.4 The spinning propeller behind the wing's channel and the lift force directions for each radial location for a channel of radius R and angle γ

If we deffine an efficiency factor as a function of the channel's angle γ such that we factor in the vertical components of all the individual lift vectors, sin(γ) but also the losses due to missorientation of the vectors cos(γ) and the surface aria of the channel (represented by the length of the arc):

$$\eta = \frac{2R\sin\left(\frac{\gamma}{2}\right)\cos\left(\frac{\gamma}{2}\right)}{2\pi R\frac{\gamma}{360°}} \tag{12}$$

which can be re-written:

$$\eta = \frac{R\sin(\gamma)}{2\pi R\frac{\gamma}{360°}} \tag{13}$$

By derrivation we can obtain the extremum point of the function:

$$\eta' = 0 \tag{14}$$

or,

$$\frac{\frac{2\pi x}{360}\cos(x) - 0.0054\cdot\pi\cdot\sin(x)}{\left(2\pi\frac{x}{360}\right)^2} = 0 \tag{15}$$

Further we will investigate the case where $\gamma = 180°$, which is also Custer's initial design concept and present the computational fluid dynamics simulation results for a CCW design similar to that in Ref [10]. The pressure ratio of the propeller is considered to be 1:1.2.

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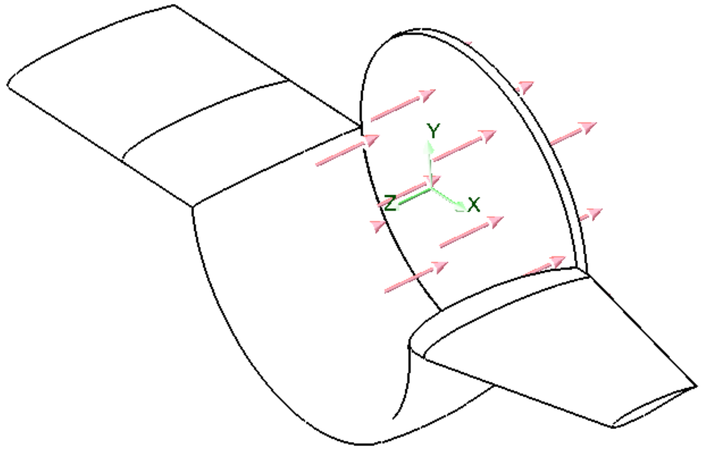

Fig.5 A CCW model with suction propeller and super critical airfoil

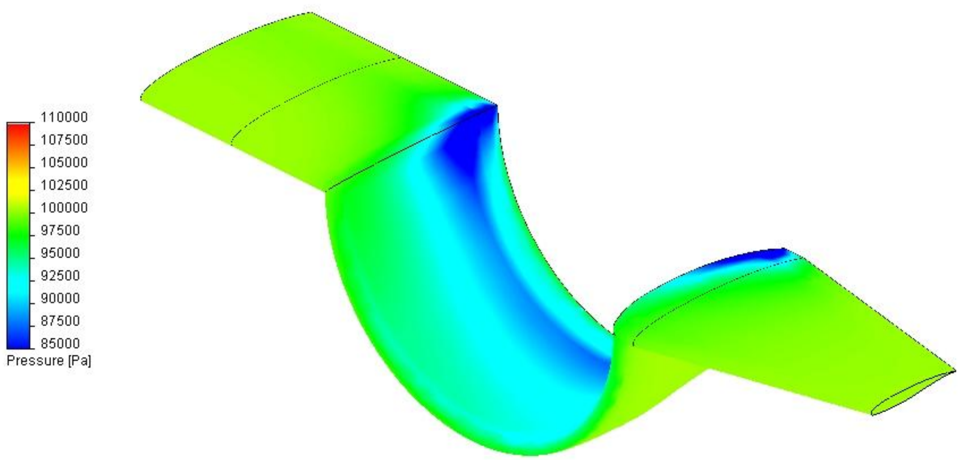

Fig.6 Pressure field around the top of a suction channel wing

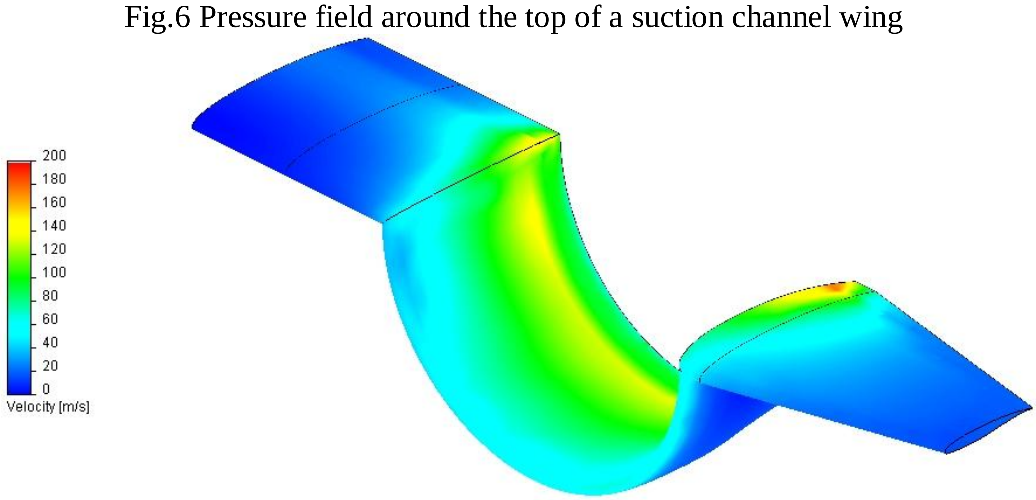

Fig.7 Velocity distribution around the top of a suction channel wing due to the suction Coanda effect

CONCLUSIONS

The CFD simulations presented here show that the lift in a Custer Channel Wing is the result of the accelerated air over the curved surface of the airfoil i.e. the channel only directs the flow to the propeller but plays no role in accelerating it. All cases tested are synthesized in Table 1 and graphically illustrated in Fig.8.

Table I

case 150 m/s prop speed	load CCW	load CCW corrected	load wing	L/D
TAS 50 m/s, 0 grd,	5571.094034	3548.468	1523.062	7.029671853
TAS 0 , 0 grd	5291.591279	3370.44	1028.454	5.554313213
TAS 0 , 5 grd	5524.785434	3518.972	845.0282	8.522333581
TAS 0 , 10 grd	4405.226153	2805.877	785.1697	3.935441392
TAS 0 , 15 grd	4193.883679	2671.263	767.3453	3.480187855

The correction factor applied accounts for the curvature of the channel wall. In other words it shows what the wing loading would have been if the wing would have been straight and had the span equal to that of the circular arc of the channel,

$$L_{CCWcorrected} = \frac{2R\sin\left(\frac{\gamma}{2}\right)}{2\pi R\frac{\gamma}{360^\circ}} L_{CCW} \quad (16)$$

In this case, the correction factor is $2/\pi$;
The optimisation of this correction factor can be obtained by solving:

$$\frac{0.5\pi\frac{\gamma}{360}\cos\left(\frac{\gamma}{2}\right)-2.8\cdot10^{-3}\pi\cdot\sin\left(\frac{\gamma}{2}\right)}{\left(\pi\frac{\gamma}{360}\right)^2} = 0 \quad (17)$$

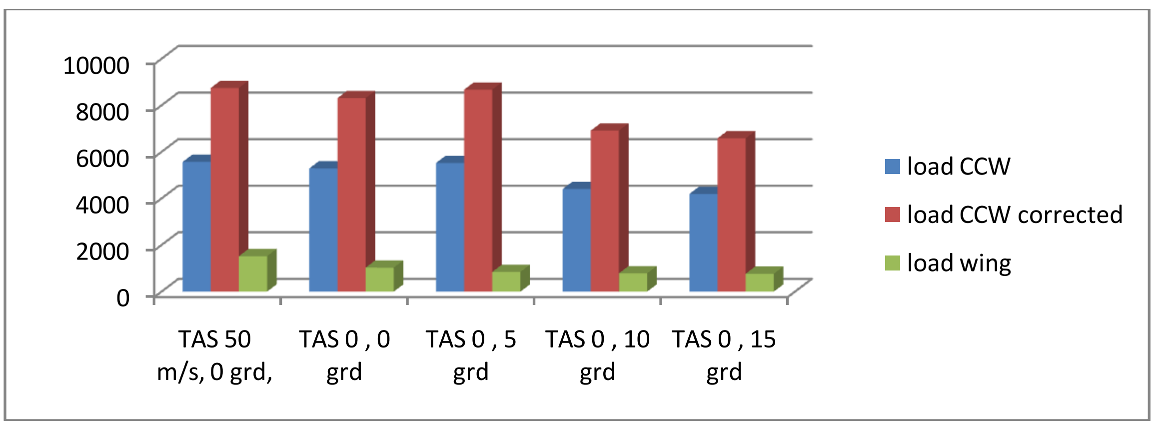

Fig.8 The dependency of loading for the channel and the parasitic lift of the rest of the wing.

From the data presented here we can conclude that although the channel wing can operate beyond the stall angle of the airfoil, this cannot be practically done because the regular wing surface cannot maintain a decent lift to drag ratio.

Another conclusion is that the true air speed (TAS) has a relatively low impact on the total lift of the channel itself. In Fig.9we can see that the optimum L/D is achieved at a larger than 0 angle of attack and also that the TAS has a positive influence on this parameter

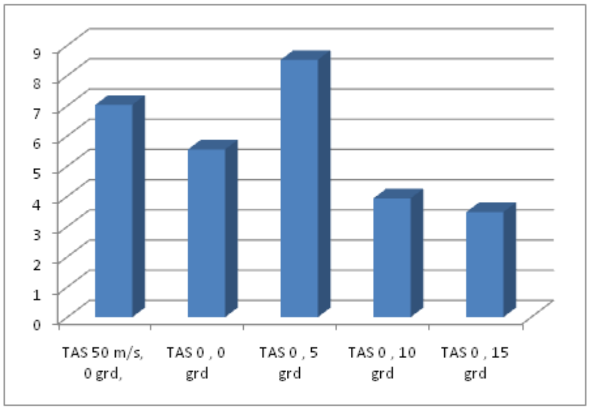

Fig.9 Lift to drag ratios versus angle of attack for a Custer Channel Wing

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