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SUBSONIC FLOW STUDY AND ANALYSIS ON ROTATING CYLINDER AIRFOIL

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Abstract - *The concept of moving surface- boundary layer control is explored in this paper. A planned study was carried out on a conventional symmetrical airfoil 0012, of 100mm chord length. The study was complemented by numerical analysis and Computational fluid dynamics analysis through simulation. The moving surface was provided by rotating cylinder, located at C/8 and C/4 (where C is the chord length) distances from the leading edge. The diameters taken for the case were 13mm and 15mm respectively. The presence of rotating cylinder in a 0012 affects the airfoil lift characteristics. It provided the proper pressure variation and hence the lift at zero degree of angle of attack. Rotating cylinders at both the locations resulted in a significant increase in the lift through momentum injection by 100% and delayed the stall characteristics.*

Nomenclature:

C_D = *Coefficient of drag*
C_L = *Coefficient of lift*
D = Aerodynamic drag Force
L = Aerodynamic lift force
C= Chord length of airfoil
d = diameter of cylinder
t = maximum thickness of airfoil
r = radius of cylinder
ω_r = *angular velocity of rotating cylinder*
V_∞ = *Free velocity of air*
V_r = *Total velocity at any point (x, y)*
V_x, V_y = *Velocity in x & y direction respectively*
$P_0 = $ *total pressure i.e.* $103125Pa$
Re = *Reynolds Number*
P_s = *Static pressure*
q = dynamic Pressure
Ø = Velocity Ratio/ Factor
μ = *Kinematic viscosity of fluid (air) = 1.729 ×* 10^5*Kg/ms*
α = Angle of attack (AOA)
ρ = *Density of air = 1.225 kg/*m^3

1. INTRODUCTION

An airfoil is a basic element, which define the amount of lift and drag can be generated by a wing of an aircraft. As the airfoil is the basic key for lift generation. Thus enhancement in the design of an airfoil can also improve the lifting characteristics.

The major theory behind the generation of lift over an airfoil is that, when a flow passes over a surface of an airfoil a pressure difference is generated due to which lift is generated. For positive lift generation i.e. upward force the pressure over the upper surface has to be low compare with lower surface of an airfoil [1].

This pressure gradient or difference is made, either by varying AOA in symmetrical airfoil or by using camber airfoil. Mainly the airfoil's designing is done by observing the changes in parameters like lift, drag, pressure, temperature, velocity etc. at its surface. These changes has been observed at different air velocities and at different angle of attack.

1.1 Magnus Effect

When a side force is generated on a rotating cylinder or solid sphere immersed in a fluid (mainly air) due to its relative motion between the rotating body and the fluid. This phenomenon is known as Magnus effect [2].

By using. This principal is also work behind the working setup of Anton Flentter's rotating cylinder or Flettner's rotor. This defines that a rotating cylinder is able to generate's lift by creating pressure differences over its surface (as shown in Fig 1 [3]) by following Magnus effect principle.

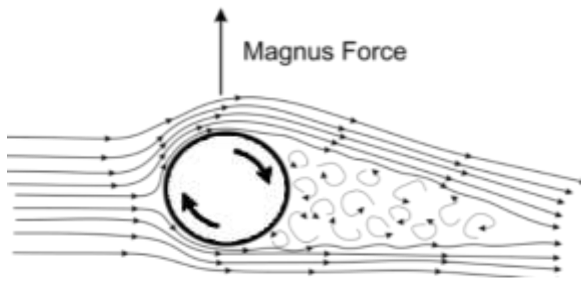

Fig -1: Rotating Cylinder (Sketch of Magnus effect with streamlines by Rdurkacz)

The airfoils which are the typical combination of both conventional and rotating cylinders (as shown in Fig 2 [4]). can be defined as complex airfoils or rotating airfoils. This study is also based on these type of airfoils.

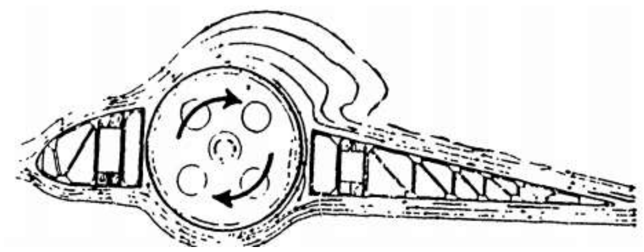

Fig -2: Rotating cylinder in wing (arrangement by Thompson)

2. LITERATURE RIVIEW

Magnus, was a physics professor at university of Berlin did an experiment in which he used a brass cylinder that could be rotated with the help of a string. It was placed on a freely rotatable arm, held between two conical bearings. And the air was blown towards it. They observed that when the rotating cylinder came in contact with the air blown towards it, it got laterally deviated. Magnus did not measure the magnitude of deflecting forces. Since then the phenomenon was called 'Magnus Effect' [2]. Rizzo compared and calculated the speed of Flettner rotor by applying fundamental principles of Kutta-Joukowski theory and by using wind tunnel data. He found out that the results obtained from wind tunnel data were closer to the actual speeds compared to those obtained by the theory. As a result Prandtl's boundary layer theory is more readily accepted in the explanation of Magnus effect [5]. Consequently Swanson explained the circulation as the result of a flow pattern determined by the boundary layer behaviour. That is, the circulation around a rotating cylinder is the result of the unsymmetrical flow pattern of the boundary layer at the lower and upper surface, separating at different positions [6]. Lafay's paper on Magnus phenomenon was among the first ones to discover the side force in the direction opposite to that predicted by Magnus, this force and phenomenon came to known as Negative Magnus force [7].

Swanson and Badalamenti did their researches and wrote in their papers about the dependency of Reynolds number on the magnitudes of lift and drag of the rotating cylinder at low velocity ratio. For low velocity ratios (ø < 1) the lift variation depends on the Reynolds number. Also in the case of Magnus rotors Reynolds number is based on cylinder diameter, this effect is quite pronounced at $Re > 6 \times 10^4$. The second region of Reynolds number dependency is ø>2.5 and $Re < 4 \times 10^4$[6, 8]. Tenant did an experiment on circulation for a symmetrical airfoil with a rotating cylinder present at its truncated trailing edge, the lift coefficient reached 1.2 with ø = 3 at zero angle of attack. It was found that lift coefficient values and the stagnation point location were linear function of velocity ratio (ø) [9].

Also, AL-Garni conducted the experiment and investigated the airfoil NACA0024 with rotating cylinder at its leading edge and a flap and the studies included variation of cylinder rotation and variation in flap angle deflection. The experiment was conducted at free stream velocity 5m/s and the rotation of cylinder was taken between 0 - 14400rpm. He observed that with increase in velocity ratio the lift and drag coefficients increase as well, but the lift coefficient curve remains unaffected. In their experiment the velocity ratio of 4 gave maximum value efficiency around L/D = 20 for α =0°. The addition of high lift devices like flaps greatly enhances the lift characteristics of a leading edge rotating cylinder airfoil [10]. Later on, Samani and Sedaghat of Isfahan University of technology, Iran did their research on the possible application of the Magnus effect using rotating cylinders. They used the concept of generation of Magnus force through treadmill motion of the aerodynamic bodies. Treadmill motion is the rotation of the skin of aerodynamic bodies at a constant circumferential speed. They expected that the treadmill motion of the wing may generate lift at zero air velocity which may lead to the MAV (micro aerial vehicle) configurations for vertical takeoff or landing [11].

3. METHODOLOGY

In this project, an airfoil NACA0012 has been considered as the base airfoil in which the lifting characteristics has to be vary by introducing the concept of rotating cylinder into it.

Following are the assume conditions on which this study is conduct:

i. The AOA of the airfoil is to be consider as zero (as symmetric airfoils are not able to generate lift at 0 degree of AOA thus give better results while comparing).
ii. The range of free stream air velocity (V_∞) is to be consider from 10-30m/s (of interval 5m/s) in horizontal direction only (subsonic range which can also be achieve in an experimental setup).
iii. The location of cylinder's center on the chord line is at the position C/8 & C/4 (where 'C' is the chord length) from the leading edge. Therefore,
    Case I: Center of cylinder is C/8 from LE having Diameter 13mm = 0.013m
    Case II: Center of cylinder is C/4 from LE having Diameter 15mm = 0.015m
iv. The value of velocity factor (ø) can be consider in range 1 to 2.5.
v. The angular velocity (ω_r) of rotating cylinder is to be decided on two factors 'ø' & diameter of the cylinder.

$$\omega_r \text{ (in rad/s)} = \frac{\text{Ø} \times \text{free stream velocity}\left(\text{in}\frac{\text{m}}{\text{s}}\right) \times 2}{\text{diameter (in m)}} \quad (1)$$

vi. While experimental testing the wing is to be consider as infinite wing.

3.1 Equations Required & Calculations

NACA0012 curve equation: (here NACA0012 airfoil is consider as of a unit chord length):-

$$y = \pm 0.6(0.2969\sqrt{x} - 0.126x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4) \quad (2)$$

The symbol of '±' meant that, for a given value of x there will be two values of y in +ve side and in –ve side of y-axis.

Thus differentiating equation of both side w.r.t time (t), we get:-

$$\frac{dy}{dt} = \pm 0.6\frac{dx}{dt}\left(-\frac{0.14845}{\sqrt{x}} - 0.126 - 0.7032x + 0.8529x^2 - 0.406x^3\right) \quad (3)$$

For unit chord length airfoil the rate of change of 'y- axis' w.r.t 'x-axis' is given by the help of the equation (2). Thus by this it can say that for the unit chord airfoil the relation of 'y' velocity to 'x' velocity is given by the equation (3). Then if it assume that $\frac{dx}{dt} = V_x$ i.e. velocity in x- direction then similarly $\frac{dy}{dt} = V_y$ i.e. velocity in y-direction then for this case, V_y is given by for each point in x- direction by the relation:-

$$V_y = \pm 0.6V_x\left(-\frac{0.14845}{\sqrt{x}} - 0.126 - 0.7032x + 0.8529x^2 - 0.406x^3\right) \quad (4)$$

For total velocity at any point on curve i.e. V_r:-

$$V_r = \sqrt{(V_x)^2 + (V_y)^2} \quad (5)$$

For dynamic & static pressure at any point on curve:-

$$q = 0.5\rho(V_r)^2 \quad (6)$$

$$P_s = P_0 - q \quad (7)$$

For conducting following observation the value of ø & α is assume as to be 1 & 0° respectively. The other details regarding the rotational velocity of the cylinders for respective cases are shown in table -1.

Table -1: Rotational velocity of cylinders in case I & II

S.No.	V_∞ (m/s)	ω_r (rad/s) for case I	ω_r (rad/s) for case II
1.	15	2307.7	2000
2.	20	3077.0	2666.67
3.	25	3846.1	3333.33
4.	30	4615.4	4000

3.2 Geometry

As specified in problem that the cylinder is to be place at two location on the chord line i.e. C/8 & C/4, from the leading edge. Thus the study is also divided into two respectively. The Geometric specification which are going to remain same for both the cases are the following:-

i. The chord length 'C' of the airfoil is 100mm.
ii. The slot thickness between cylinder wall and airfoil section is taken as 0.5mm (to neglect the flow disturbance effect due to slot).

3.2.1 Computational specifications

i. For computational analysis, geometry is analyze in 2D.
ii. The far field is of dimension 480mm × 480mm for both cases (as shown in fig -3).

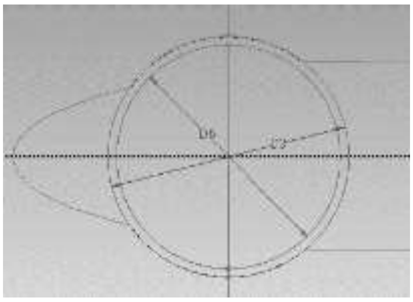

Fig -3 (a)

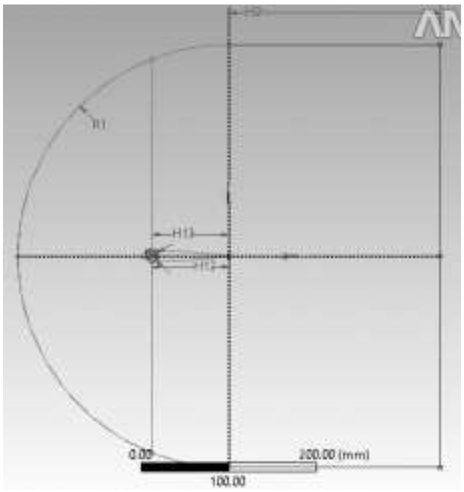

Fig -3 (b)

Fig -3: Computational geometry with its dimension's naming (a) cylinder and its domain (b) far field domain

3.3 Mesh Setup

For above geometry, C- Mesh Domain has been used to form a structure grid mesh. Structure mesh is easy when it's done for airfoil itself only. But due to the introduction of a cylinder geometry having a slot between cylinder and airfoil cut out wall in which the flow is also passing, makes the meshing for this case more complex.

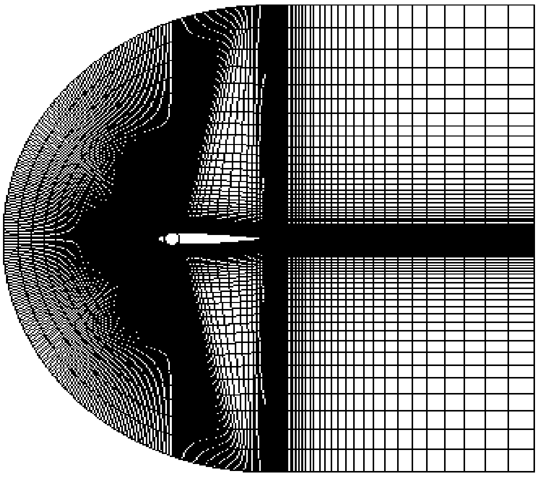

Fig -4 (a)

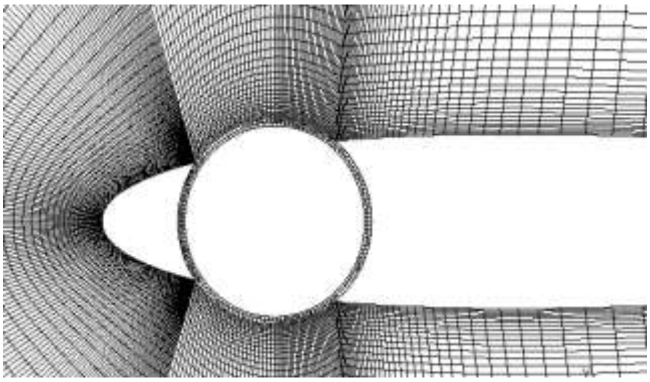

Fig -4 (b)

Fig -4: Meshing for Case I in: (a) outer domain and (b) near the cylinder's wall

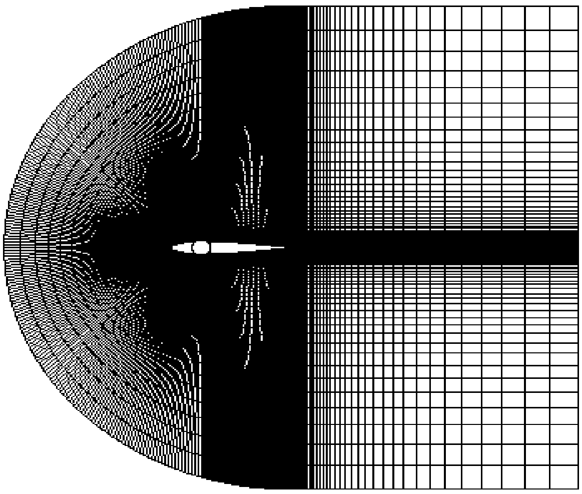

Fig -5 (a)

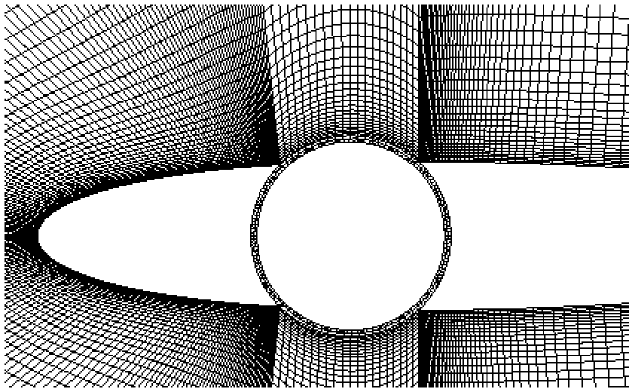

Fig -5 (b)

Fig -5: Meshing for case II in: (a) outer domain and (b) near the cylinder wall

3.4 Physics Setup

After finalizing the mesh in each case, the next process is to setup the physic i.e. define the physical values and boundary conditions of the simulating model.

Following are the boundary conditions of the both the cases:-

Table -2: Physics setup information for both cases of cylinder

S. No.	Parameters	For case I	For case II
1.	Type	Pressure-based	Pressure-based
2.	Y plus	Min value = 0	Min value = 0
		Max value = 539.299	Max value = 1015.546
3.	Energy	on	on
4.	Model	K-ω SST	K-ω SST
5.	Cylinder	Moving wall	Moving wall
6.	Airfoil	Stationary wall	Stationary wall
7.	Inlet	Velocity inlet (only x velocity component)	Velocity inlet (only x velocity component)
8.	Outlet	Pressure outlet (Gauge Pressure=1013 25Pa)	Pressure outlet (Gauge Pressure=1013 25Pa)

3.5 Validation

For validating the results which are obtain from the simulation. The help of the mathematical method has been taken. For validate the results of the simulation, it has decided to validate the results of a NACA0012 airfoil. Under this an airfoil NACA0012 of same dimensions is to design and simulate under same model conditions in which the required study is to be observed. Thus once the verification of the NACA0012 is done correctly, then it will work as a reference verification for our complex geometry's design. Thus first, the data of pressure parameters from simulation of NACA0012 has collected. Under this, major focus of data collection of the parameter's value at the surface of the airfoil while moving from LE to TE in x-direction. For this the particular interval in x-position is taken as 10mm (10mm=1cm=0.01m).

Once simulation data is collected, the value of pressure data by mathematical method using the equations (mentioned in article 3.1) has been found out. Now comparing the pressure data of respective location, which has been getting from simulation and mathematically can be use to validate the model. The comparing is done on the basis of %error. This %error should be minimum (can less or upto 1%) for the pressure values of respective locations.

4. RESULTS & DISCUSSIONS

As after following the procedure of validation. The results of NACA0012 airfoil has been taken on assuming the following parameters as constant i.e. V_∞ = 15m/s; ø = 1; α = 0°. Thus for this case following are the result for NACA0012 at different position of x:

Table -3: Static Pressure & %error Values at the surface of NACA0012

S,No,	Surface Point location in X- axis	Surface Point location in Y-axis	Static Pressure		% error
			Mathematically, P_m (Pa)	Simulation, P_s (Pa)	$\frac{P_s - P_m}{P_m} * 100$
1.	0	0	101325	101454	-0.127
2.	0.01	0.0046	101183	101269	-0.084
3.	0.02	0.0057	101186	101271	-0.083
4.	0.03	0.0060	101187	101278	-0.089
5.	0.04	0.0058	101186	101284	-0.096
6.	0.05	0.0052	101186	101293	-0.105
7.	0.06	0.0045	101186	101299	-0.111
8.	0.07	0.0036	101185	101308	-0.120
9.	0.08	0.0026	101185	101316	-0.129
10.	0.09	0.0014	101185	101326	-0.139
11.	0.1	0.0001	101184	101341	-0.154

Thus from table -3, It can observe that the error percentage of static pressures (in NACA0012) between mathematical and simulation are very less. Thus it can say that the simulation results for NACA0012 at given simulation conditions are considerable and valid. Thus this also validate the simulation setup for this case study too.

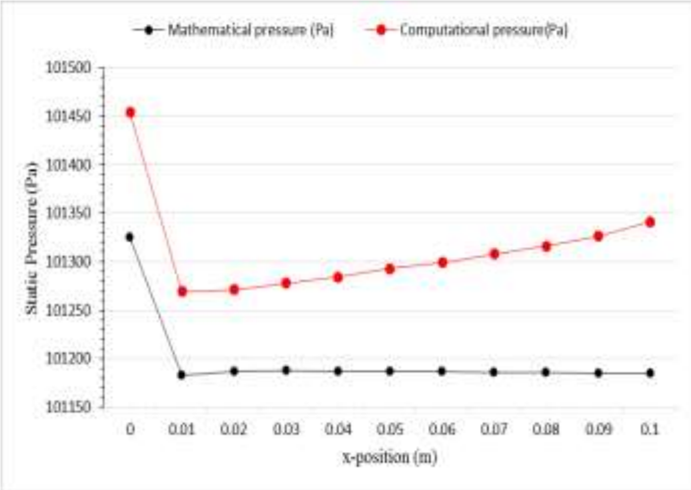

Chart -1: Static Pressure V/s x- position curve for NACA0012

After validating, the comparison is to be done between the case study's model to the conventional base design of its airfoil i.e. Rotating cylinder airfoils V/s NACA0012 airfoil. For comparing, the one should know the generalized data of NACA0012 at any assumed conditions (which must be similar in the study results too). Thus for both cases (i.e. I & II) of the concentrated study (along with NACA0012) the value of C_L & C_D along with their ratio's i.e. C_L/C_D at V_∞ = 15m/s; ø = 1; α = 0°, are given below (in table -4):

Table -4: Data comparison b/w NACA0012, Case I & II

Aerodynamic Parameters	For NACA0012	For Case I	For Case II	% change between Case I & 0012	% change between Case II & 0012
lift force, L (N)	-0.00070 ~ 0	0.566	1.33	100.01	100.005
Drag Force, D (N)	0.31746	0.560	0.787	43.37	59.65
C_L	-0.0011	0.003	0.009	128.2	111.9
C_D	0.5183	0.004	0.005	-99.2	-98.89
C_L/C_D	0.00223	1.011	1.696	99.77	99.87

As from above table-4, it can be easily observe the percentage increase in lift & drag in both cases (i.e. I &II) from the conventional airfoil at same physical conditions. Thus the percentage error for above cases are:

5. CONCLUSIONS

As from above study as compared to conventional airfoil, the airfoil's consisting of a rotating cylinder is able to provide high lift (nearly 100%) at zero degree of AOA too. Thus the rotating cylinder airfoil can be use in STOL flights, for generating high lift in short interval of time. The major factor over which the whole study depends is the overall change in aerodynamic forces with respect to conventional airfoil (NACA0012). For both cylinder cases, the aerodynamic lift force has been increased nearly 100% as compared to conventional airfoil. But for aerodynamic drag, differences are observable for both cases. There are nearly 43% and 60% increment in drag forces for cylinder at the position of C/8 and C/4 respectively (at same physical conditions).

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REFERENCES

[1] Fundamentals of Aerodynamics, Book by John D. Anderson.

[2] Magnus HG. on the ¨ deviation of projectiles; and on a remarkable phenomenon of rotating bodies. Taylor's Foreign Scientific Memoirs, Berlin 1853:804–10.

[3] By Rdurkacz, Sketch of Magnus effect with Streamlines and turbulent wake, https://commons.wikimedia.org

[4] Thompson, Rotor on Wing adds to Plane's Power, Popular Science Monthly~, Vol. 120, No. 2, February 1932, p. 50.

[5] Rizzo F. The Flettner rotor ship in the light of the Kutta–Joukowski theory and of experimental results, TM-228. NACA Technical Memorandum; 1925.

[6] Swanson WM. "An experimental investigation of the Magnus effect". Case Institute of Technology. Final report. 1956.

[7] Lafay A. "Contribution expe´rimentale a l'ae´rodynamique du cylinder et a´ l'e´tude du phe´nomene de Magnus". Revue de Me´chanique, 1912; 30:417–42.

[8] Badalamenti C, Prince S. "Effects of endplates on a rotating cylinder in crossflow", 26th AIAA applied aerodynamics conference, Honolulu, Hawaii. 2008.

[9] Tennant JS, Johnson WS, Krothapalli A. , "Rotating cylinder for circulation control on an airfoil", Journal of Hydronautics,1976;10(3):105,

[10] Al-Garni AZ, Al-Garni AM, Ahmed SA, Sahin AZ, "Flow Control for an Airfoil with Leading-Edge Rotation: an Experimental Study", Journal of Aircraft 2000;37(4):622,

[11] Novel on MAVs explaining the treadmill motion on wing by Ahmad Sedaghatb and Iman Samania, Isfahan University of Technology, Isfahan 84156-83111, Iran published online 10 November 2013