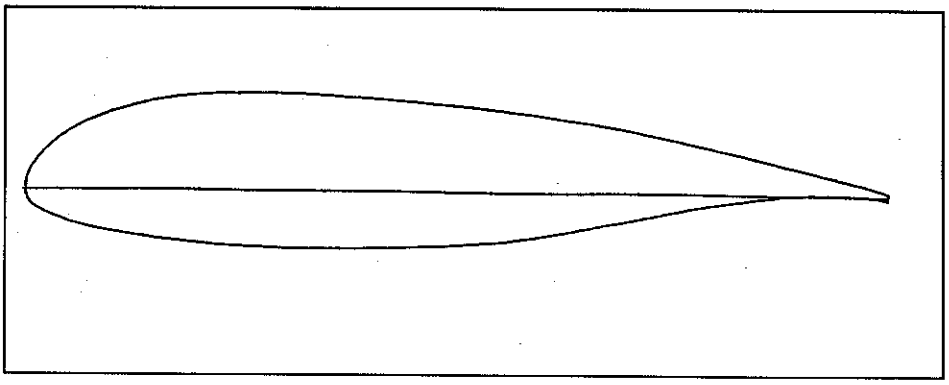
DESIGN AND CONSTRUCTION OF A ROTOR FOR FC 4000 WIND TURBINE



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INTRODUCTION

The FC 4000 Wind Motor is a 1.5 kW wind turbine, designed for low wind regimes. The cut in speed is rather low at 3 m/s. It is a multipurpose turbine which produces a.c. electric power that can be used for water pumping,grain grinding and battery charging. The WT (Wind Turbine) directly drives a Permanent Magnet Generator (PMG) which has 14 poles and reaches an efficiency as high as 88% at a rather low rpm of 200. The efficiency remains in the range of 88 -94% upto an rpm of about 430 and thereafter declines very gradually.

The present rotor of FC 4000 has a diameter of 4m and consists of 2 blades of Wortmann FX 63-137 airfoil cross-sections. In fact the cross-sections are artificially thickened, to be discussed later. The blades have a chord length of 230 mm at 30% radius from the rotor axis and 10 mm at the tip (100% radius). A pair of airbrakes, mounted on the hub, controls the rotational speed when the generator is unloaded(fig.1). The yawing and safety system consists of a side vane and a hinged main vane (Fig.1), held in position by a spring . Above the rated wind speed of 10 m/s, the aerodynamic drag on the side vane will outbalance the tension in the spring and the side vane will start turning the rotor out of the wind. The process is gradual and the rotor is completely out of the wind at 15 m/s (cut out speed). The cut out wind speed can be adjusted by varying the tension of the spring. The turbine has a survival wind speed of 45 m/s.

The present 2-bladed rotor needs to be described in some detail.Although initially it was decided that the rotor should have cross-sections of FX 63-137 airfoils, shown in Fig.2 ,the 13.7% thickness of this profile was inadequate to withstand the aerodynamic loads. The profile actually used on the rotor is artificially thickened by multiplying the ordinates by a constant factor greater than 1. Thus the tip section was made 18% thick and the root section 24% thick. The thickness was allowed to vary linearly from tip to root. Thus the rotor has different airfoils at different sections. However it retains the sharp and cusped trailing edge of the Wortmann profile. Another unconventional aspect of the rotor is that it has a high design tip speed ratio ($\lambda = 8$) but not the twist which normally goes with such high λ. It has no twist at all and is set at a blade angle of 7 degrees.

The production method that is to be employed influences the design choice of the rotor. Hence a brief description of the production method which is based on Copy Milling is given here. Two separate profiles for the upper and lower surfaces of the blade are made out of hard foam (commonly applied for floor insulation) by cutting with an electrically heated steel wire under tension. A wooden beam is prepared by glue-laminating pinewood under pressure. A profile cutting machine using the principle of copy milling is employed to cut the wood. Here a sensor roller transmits the airfoil pattern from foam profile via a parallelogram to the tool, curving out the blade out of the wooden beam (Möller 1991).

The present rotor exhibited 3 problems. First, the measured Power Factor (C_p) is as expected ,near about 0.44, at low wind speeds but drops to about half this value at higher wind speeds. In general the C_p values obtained are low. Second, the sharp and cusped trailing edge is impossible to produce out of wood. Third the rotor in operation makes a periodic whistling noise which is aerodynamic in nature. The noise is not a severe one but ,if possible, it should be eliminated.

CHOICE OF AIRFOIL

The FX 63-137 airfoil is essentially a laminar flow airfoil. It is assumed tentatively that in spite of artificial thickening this character is retained. The boundary layer remains laminar over a large extent of the airfoil starting from the leading edge, provided the airfoil is smooth and the turbulence in the naturally occurring wind does not trigger boundary layer transition (i.e., onset of turbulence). Both requirements are very stringent. First , the leading edge becomes rough due to dust particle and insect impingement. Second, the turbulence level in atmospheric wind is often very high. Under controlled ideal conditions the airfoil has a minimum C_D/C_L value of 0.007. But it is not obtained for most cases of operation in atmospheric wind and particularly when the leading edge becomes slightly rough. This may be the reason for its much lower C_p than the design value. Tangler et al (1990) have reported that NACA 23xxx and NACA 44xx series airfoils exhibit 30% to 50% drop in (C_L)max when their leading edge becomes rough due to insect accumulation. This leads to a similar drop in peak power of the wind turbine. It is also mentioned that NASA LS-1 and NACA 63xxx series are less sensitive to roughness and give improved results . Tangler et al (1990) have developed an airfoil called S807 which shows a high value of (C_L)max and at the same time even greater roughness tolerance than NASA LS-1 and NACA 63xxx series. This airfoil however has a sharp trailing edge. Out of all the afore mentioned airfoils only the NASA LS-1 series combines a high (C_L)max with roughness tolerance and blunt trailing edge. For the purpose of making an airfoil out of wood, the blunt trailing edge is a desirable feature.

NASA LS-1 series consists of several airfoils, both symmetric and cambered, of varying thicknesses. Recalling that structural considerations required 18 % thickness at the tip for the Wortmann airfoil, we choose a NASA LS-1 airfoil of approximately same thickness. Further a cambered airfoil is to be preferred for two reasons : (1) It has a lesser drag compared to symmetrical airfoils for the same lift at small angles of attack, and (2) for WTs operating at high λ , the required blade angle at the tip is usually very small for optimum operation (Durand 1965).For a symmetrical airfoil this may even turn out to be negative which is undesirsble as it may lead to poor starting torque. These considerations led to recently designed special purpose general aviation airfoils such as NASA LS(1)-0417 and its modified version called NASA LS(1)-0417 Mod. The latter was developed by McGhee & Beasley (1981).

A comparative study of these two airfoils were made. The modified airfoil showed the following improvements over its predecessor. The L/D ratio is increased by 10% at C_L =1. Also (C_L)max is increased by 10 % for the Re No. range of 2 to 4 million. Both airfoils are tolerant to roughness but the Mod. airfoil is better below Re = 2 million. (C_D)min is the same for both airfoils , but persists over a greater range of incidences for the Mod

airfoil. All of these make the Mod airfoil a better choice. This conclusion is reinforced by the fact that this airfoil is currently used on such WTs as the Carter 250 and EST 80/200 in the USA (Tangler & Somers 1990).

The stall characteristics are worse (more sudden stall) for Re No. over 2 million, but comparable in the range 1 to 1.5 million. For the FC 4000 WT above a speed of 430 rpm the airbrakes are centrifugally activated which results in stall of the blades to cut power output. Sudden loss of power during overspeed control may not be a problem. However gust induced stall during normal operation is another matter. The design angle of attack which corresponds to (C_D/C_L)min is well away from the stall angle and the Re No. is likely to stay below 1 million,to be shown later. The NASA LS(1)-0417 Mod. airfoil has a maximum camber of 2.3% at 20% chord from the leading edge. Fig. 2(b) shows this airfoil with its notable features such as a blunt trailing edge and upper surface flatness near 40 % chord.

ROTOR BLADE DESIGN

It was decided at the outset that the computer program available on telephone link with a Company called "Energi og Miljo Data" at Aalborg will be used for detailed performance calculations. Now, this program is not really a design program because it has no built in optimisation procedure. It merely gives power and torque at different wind speeds and rpm, when the blade geometry is specified. Of course, the name of the airfoil has to be given as an input. Then the program calls up section characteristics, lift & drag vs angle of attack (alpha), from its airfoil library. It so happens that NASA LS(1) series was not part of its library storage. So the lift & drag data had to be retrieved from the paper (microfische copy) of McGhee & Bealey(1981) and fed into the computer library. They give data only over a small range $-7.5^\circ < \alpha < 19^\circ$, reproduced here in Table 1.

Table 1: Section characteristics of NASA LS(1)-0417 Mod Airfoil
Re No. = 1 Million

Alpha	C_L	C_D	C_L / C_D
-7.5°	-0.45	0.015	
-5°	-0.2	0.011	
-2.5°	0.1	0.009	11.1
0.0°	0.4	0.0095	42.2
2.5°	0.7	0.011	63.6
5.0°	1.0	0.012	83.3

7.5°	1.25	0.014	89.3
10.0°	1.4	0.016	87.5
12.5°	1.6	0.0225	71.1
14.0°	1.65	0.025	
15.0°	1.7	0.035	
16.0°	1.4		
18.0°	1.31		
19.0°	1.29		

The program with Energi Og Miljo DATA at Aalborg requires data over a range $-180^\circ < \alpha < +180^\circ$. Hence this data had to be artificially created. Data for NACA 4412 airfoil was readily available. It is known that lift and drag do not significantly differ from one airfoil to another when Alpha is large in magnitude, either positive or negative, since under these conditions the airfoil is no longer a streamlined body. Available limited data of the NASA LS(1)-0417 Mod airfoil was superimposed on the lift and drag curves (Figs. 3 & 4) of NACA 4412. A few points had to be extrapolated , shown by squares in the figures, and starting from the neighbourhood of $\alpha = \pm 40^\circ$ the NACA 4412 data were retained for the NASA airfoil . The drag curve has been conservatively drawn (Fig. 4) by maintaining the width of the "drag bucket" the same as for NACA 4412, although it is known that the NASA LS(1) airfoil is superior in this respect. Fig.5 shows determination of (C_D / C_L)min. for 0417 Mod airfoil and the corresponding value of Alpha. (C_D / C_L)min. = 0.01118 at $\alpha = 8.25^\circ$.

In comparison, FX 63-137 airfoil has a (C_D/C_L)min. of 0.007, but little roughness tolerance.

Selection of the design tip speed ratio was based on the following considerations. In the existing blade of zero twist made of Wortmann profile , the tip region makes a significant contribution to the starting torque because of the large blade angle of 7 degrees. In a twisted blade the blade angle at the tip is likely to be much smaller. This is more so because the airfoil selected NASA LS(1)-0417 Mod has a moderate camber and consequently the (C_D/C_L)min. occurs at a relatively high value of α . This is a price one has to pay for roughness tolerance since increased camber reduces it . Thus in the new design of the rotor the starting torque will have to come from the inboard region of the rotor and is likely to be small. This is usual for a high speed rotor. In general, the higher the tip speed ratio the lower is the starting torque. Secondly, a very high value of λ also means greater twist and may pose a problem for the profile cutting machine. Thus a moderately high value of $\lambda = 7$ was selected . Jansen & Smulders (1977) have given a procedure ,approximaate charts and formulas based on " Ideal Windmill " of Gluert (DURAND 1965). This procedure was used as a starting point and a few experimental computer calculations by the Mainframe computer with Energi Og Miljo Data were used to improve upon it.

Design parameters are :

Rotor radius	2m	(R)
No. of blades	2	(B)
Design tip speed ratio	7	(λ_0)
Angle of attack for (C_D/C_L)min.	8.25°	(α_0)
Design lift coeff. (at $\alpha = 8.25^\circ$)	1.3	(C_{L0})

The starting design calculations are given in Table 2. $\lambda_r = \lambda_0 * r/R$ is defined as the speed ratio at a radius r, ϕ is the wind angle and β is the blade angle.

Table 2 : Starting design calculations

r (m)	λ_r	phi(ϕ)	α_0	β	Re No. per unit wind velocity
0.3	1.05	30	8.25°	21.75°	$0.277 * 10^5$
0.4	1.4	23.5	8.25°	15.25°	$0.292 * 10^5$
0.8	2.8	13	8.25°	4.75°	$0.370 * 10^5$
1.2	4.2	8.75	8.25°	0.50°	$0.370 * 10^5$
1.6	5.6	6.7	8.25°	-1.55°	$0.370 * 10^5$
2.0	7	6.0	8.25°	-2.25°	$0.346 * 10^5$

The blade angles given in Table 2 were rounded off to the nearest whole number and the negative blade angles near the tip were increased to zero. This is necessary to avoid starting problem. Fig. 5 shows that C_D/C_L =0.0113 at $\alpha = 7^\circ$. This is an increase of 1% over the minimum value. Hence loss of peak power from the blade region at r = 1.6 m, due to increasing the blade angle, will be negligible. On the other hand at a tip speed ratio slightly below 7, this regionof the blade will be more productive resulting in a flatter $C_p - \lambda$ curve near the maximum. Note this region where r/R is 0.8 happens to be the most productive region. In fact, the computer calculations that followed threw up a pleasant surprise. It showed that best power performance is achieved if the tip is set at an even higher blade angle of 1 degree. This also improves the starting torque. The blade angle at the tip will from now on be called tip angle.

A few computer calculations were performed by changing the tip angle and twist from the values of Table 2. Neither the twist nor the tip angle given by the method of Jansen & Smulders (1977) turns out to be optimal, but an approximation.

The existing blade planform (chord distribution with radius) is retained except near the root. The best blade geometry arrived at is given below, where the twist angle is measured with respect to the tip :

Radius (m)	Chord length (m)	Twist (degrees)
0.3 (root)	0.243	22
0.4	0.235	15
0.8	0.190	5
1.2	0.160	1
1.6	0.130	0
2.0 (tip)	0.100	0

The following options were selected :

1st option

Tip angle = 1°

$(C_P)_{max}$ = 0.44
at λ =7

C_Q = $3.3 * 10^{-3}$
at λ=0.7

Where C_Q is the Torque Coefficient. Its value at λ as low as 0.7 gives an idea of the starting torque.

2nd option

Tip angle = 4°

(C_p)max = 0.42
at λ=7.7

C_Q =$6.1 * 10^{-3}$
at λ=0.65

The second option has a slightly lower (C_p)max but is preferred because it has a higher starting torque and the (C_p)max occurs at a higher λ, equal to 7.7 (see Fig.6). The latter feature gives a better match with pump characteristics (Fig.7), since it shifts the maximum to higher RPMs. Note the pump curves are required to intersect a little right of the maximum for best performance.

CONSTRUCTION

Copper backed glass fibre sheets (1.5 mm thick, used commonly in electronic industry) are used for preparing cut out of airfoils of different chord lengths , as required at different radial stations. The profile is first drawn on a paper by a P.C. controlled laser printer . This is pasted on a glass fibre sheet which is then cut by a small power saw leaving about 1mm of material around the profile. Finally a grinder is used to finish the surface within the thickness of the line drawn by the laser printer. Two such profiles, separated by a radial distance of 30 to 40 cm, are fixed on either side of a rectangular foam block with nails. Two persons hold one side each of the foam block and cut it with a hot wire under tension. The hot wire is made to traverse the glass fibre profiles nailed at both ends simultaneously. Several foam blocks glued together to replicate the whole length of the blade form a model for the profile cutting machine. Two separate models are required for upper and lower surfaces.

Certain problems were anticipated with a twisted blade. The highly curved leading edge of a twisted blade cannot be cut with a straight wire. This is because, in general for an arbitrarily selected axis of twist, no straight line can be drawn on the blade surface near the leading edge. To solve this problem the axis of twist was chosen to pass through the center of curvature of the leading edge and this axis must be perpendicular to the airfoil profile at any radial station. In this way the leading edge of the blade forms the part of a right circular cone whose generators are straight.Since the paper by McGhee et al (1981) does not give the location of the center of curvature, it was determined by fitting different circles to the leading edge. The one with the best fit gave the center of curvature at $x/c = 0.028$, $y/c = 0.003$, measured from the origin fixed on the leading edge (Fig. 2b).

It is generally felt that curving out both the blades and hub out of a single beam would be difficult because of the limited depth of cut and various physical interferences inherent in the present profile cutting machine. It is recommended that, at least to start with, each blade is made separately and bolted down on the hub. This gives the added advantage of changing the tip angle by inserting wedges . Then one has the freedom to do experiments in situ and find the best tip angle for the WT, or, at any rate verify the computer calculations.

AERODYNAMIC NOISE

It has been mentioned before that the existing rotor of the FC 4000 WT makes a periodic whistling noise which is like a turbulent jet noise. The time period of the intermittent noise is related to the RPM of the rotor. The side vane positioned normal to the wind is slightly downwind of the rotor plane and at a radial distance of 2.2m from the rotor axis. So the tip of a blade passes very close to it during rotation. Aerodynamic interference during a pass was suspected to be the cause of the noise. The side vane was rotated away from the rotor plane to increase distance between the vane and blade tip during a pass. This did not alter the noise at all.

Another probable source may be the tower, that is to say, the noise arises when the blade passes the tower. The existing blade is untwisted and set at a blade angle of 7 degrees. This means that the inboard region of the blade (say, from $r/R = 0.15$ and

0.4) has a high angle of attack even at high rotor RPM. So there is a wide and turbulent wake behind this region and when the blade passes the tower ther is a whistling noise (Fig. 8). If this be the cause then the new rotor, which is twisted and has a blade angle of 26 degrees at r/R = o.15, will not produce this noise.

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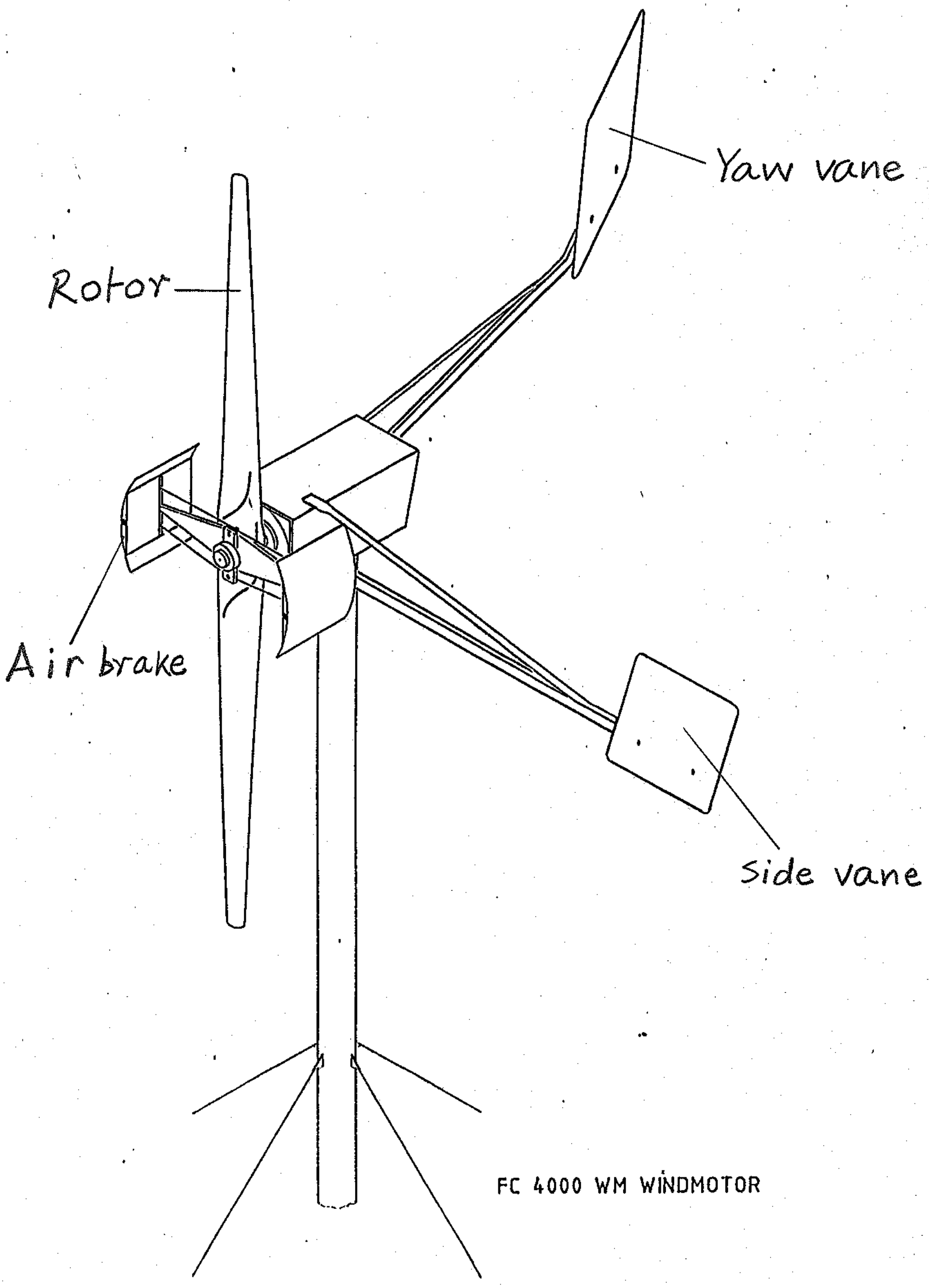


FIG. 1 : FC 4000 WIND MOTOR

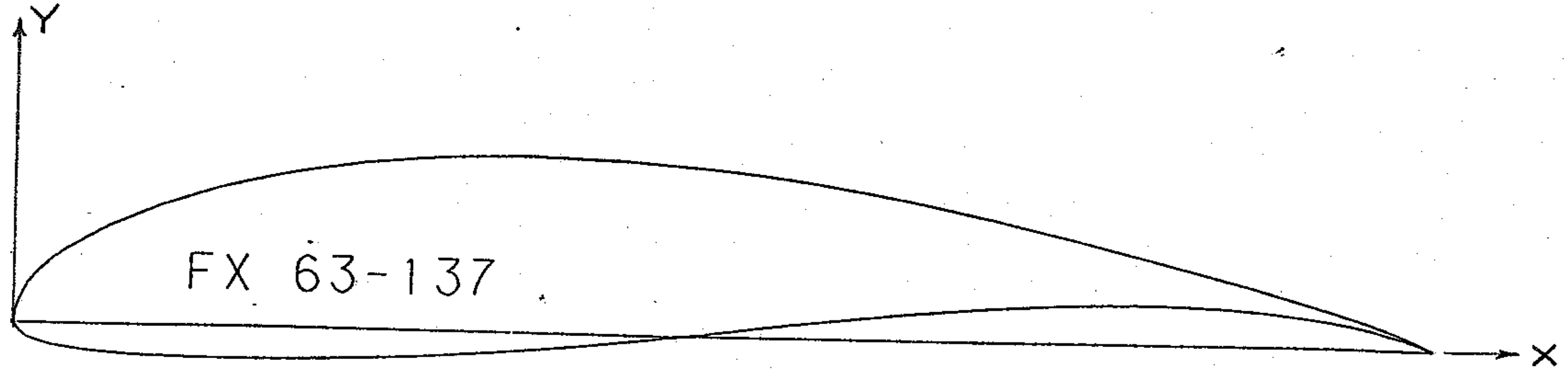


Fig2(a): Wartmann Profile

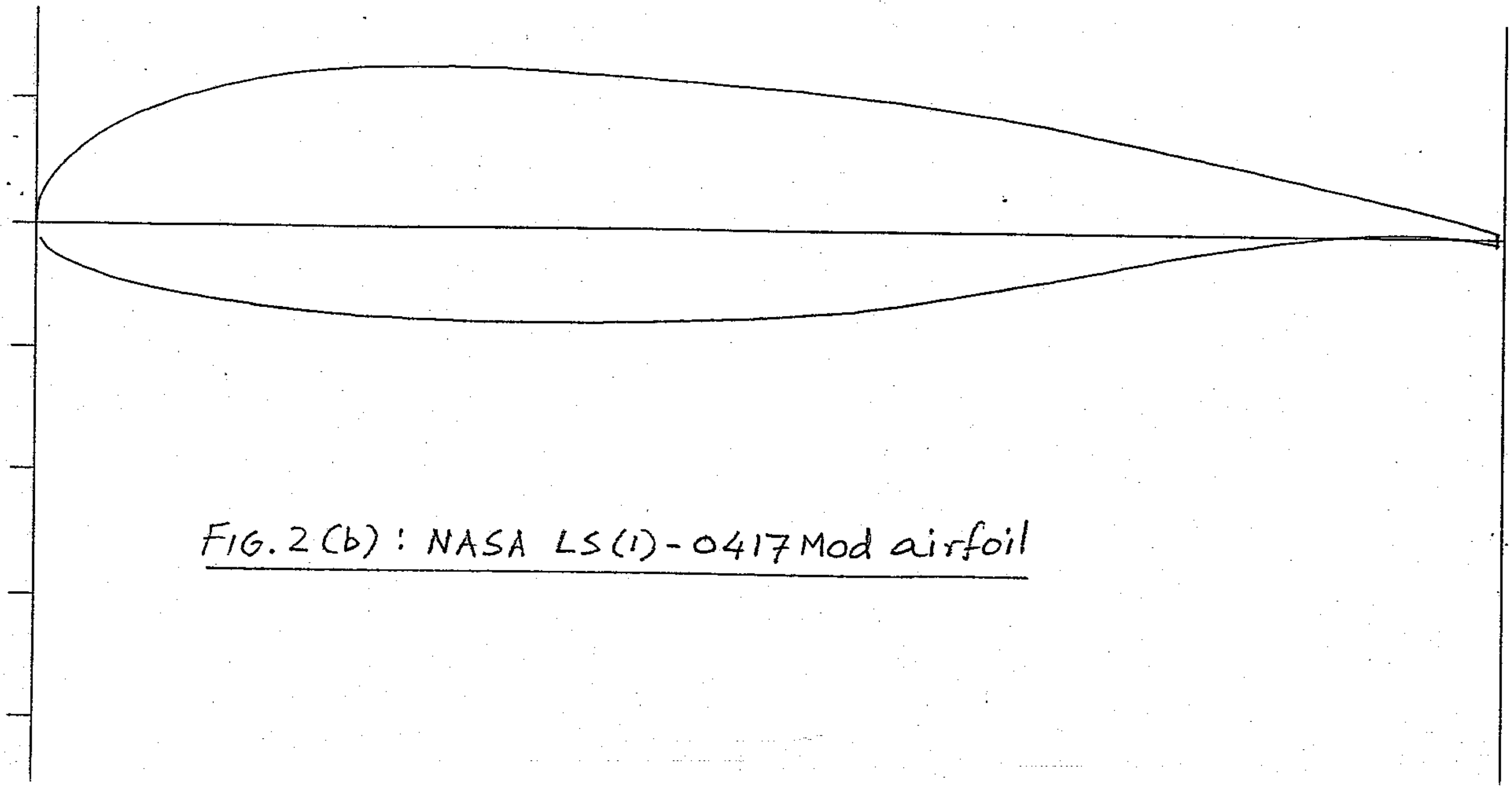


FIG. 2 (b) : NASA LS(1)-0417 Mod airfoil

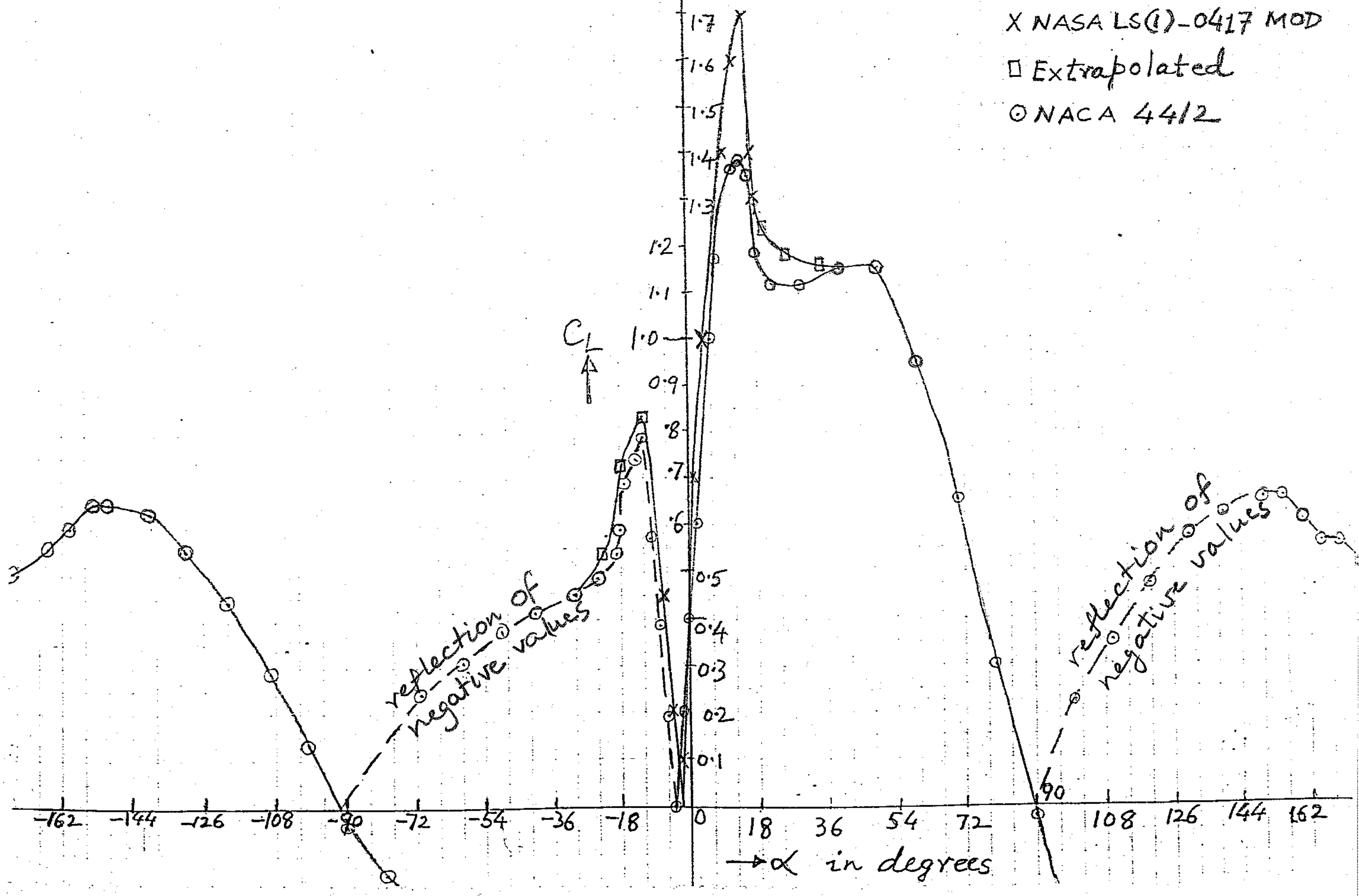


FIG. 3 : LIFT VS α

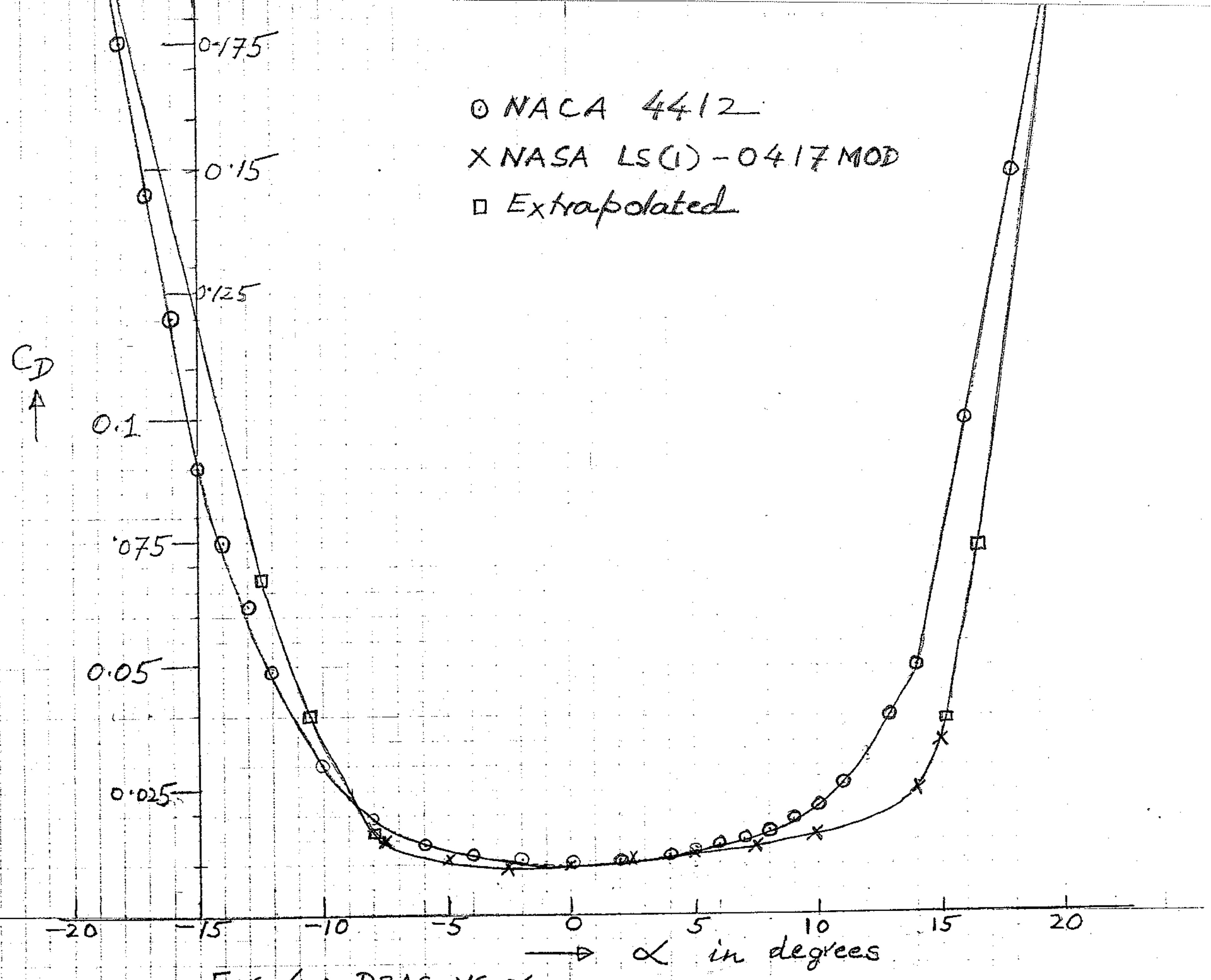
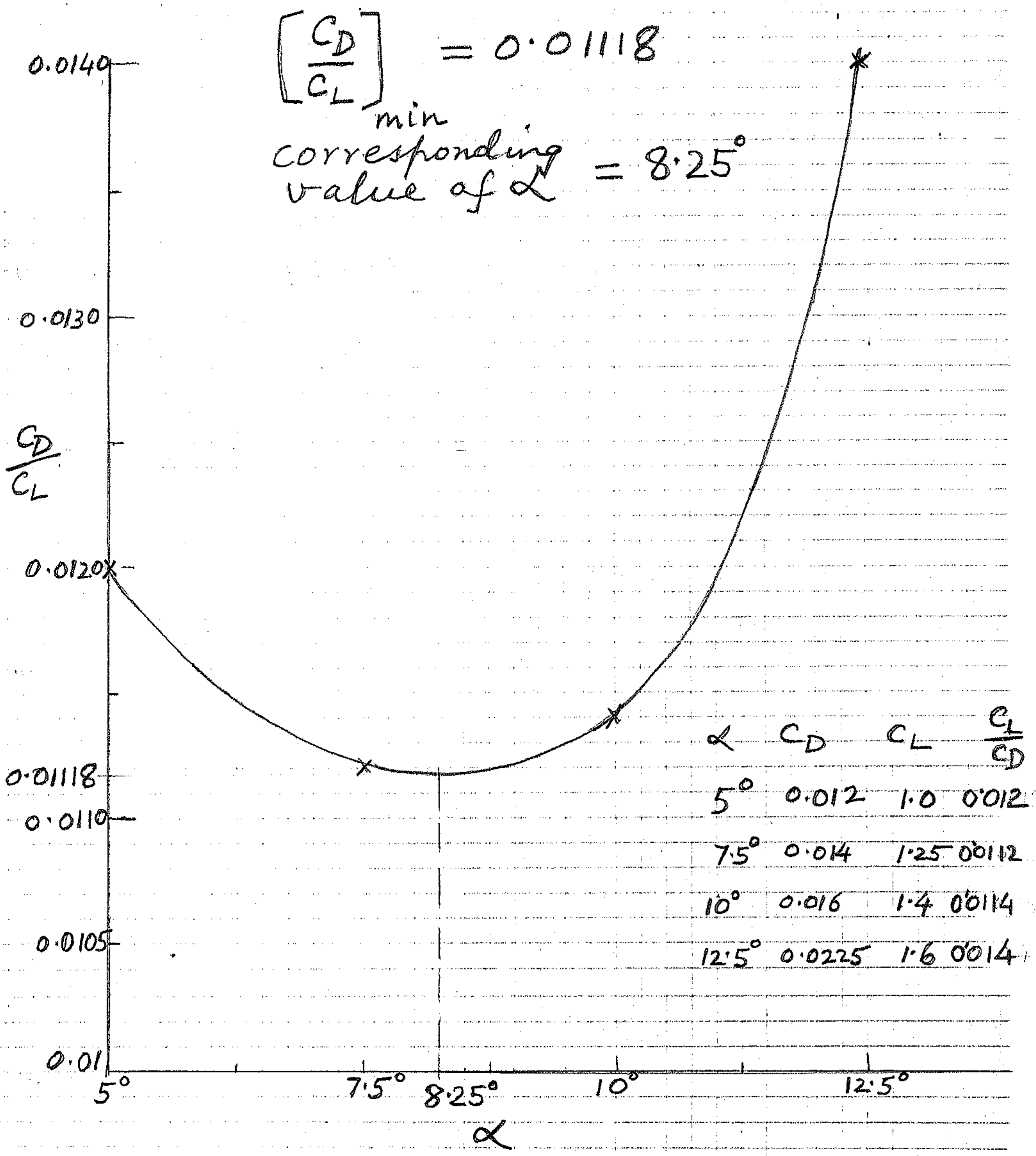


FIG. 4 : DRAG VS α

NASA LS(1) - 0417 Mod.



$\left[\frac{C_D}{C_L}\right]_{min} = 0\cdot01118$

corresponding value of α = 8·25°

α	C_D	C_L	$\frac{C_L}{C_D}$
5°	0.012	1.0	0.012
7.5°	0.014	1.25	0.0112
10°	0.016	1.4	0.0114
12.5°	0.0225	1.6	0.014

FIG.5 : Determination of $[C_D/C_L]_{min}$

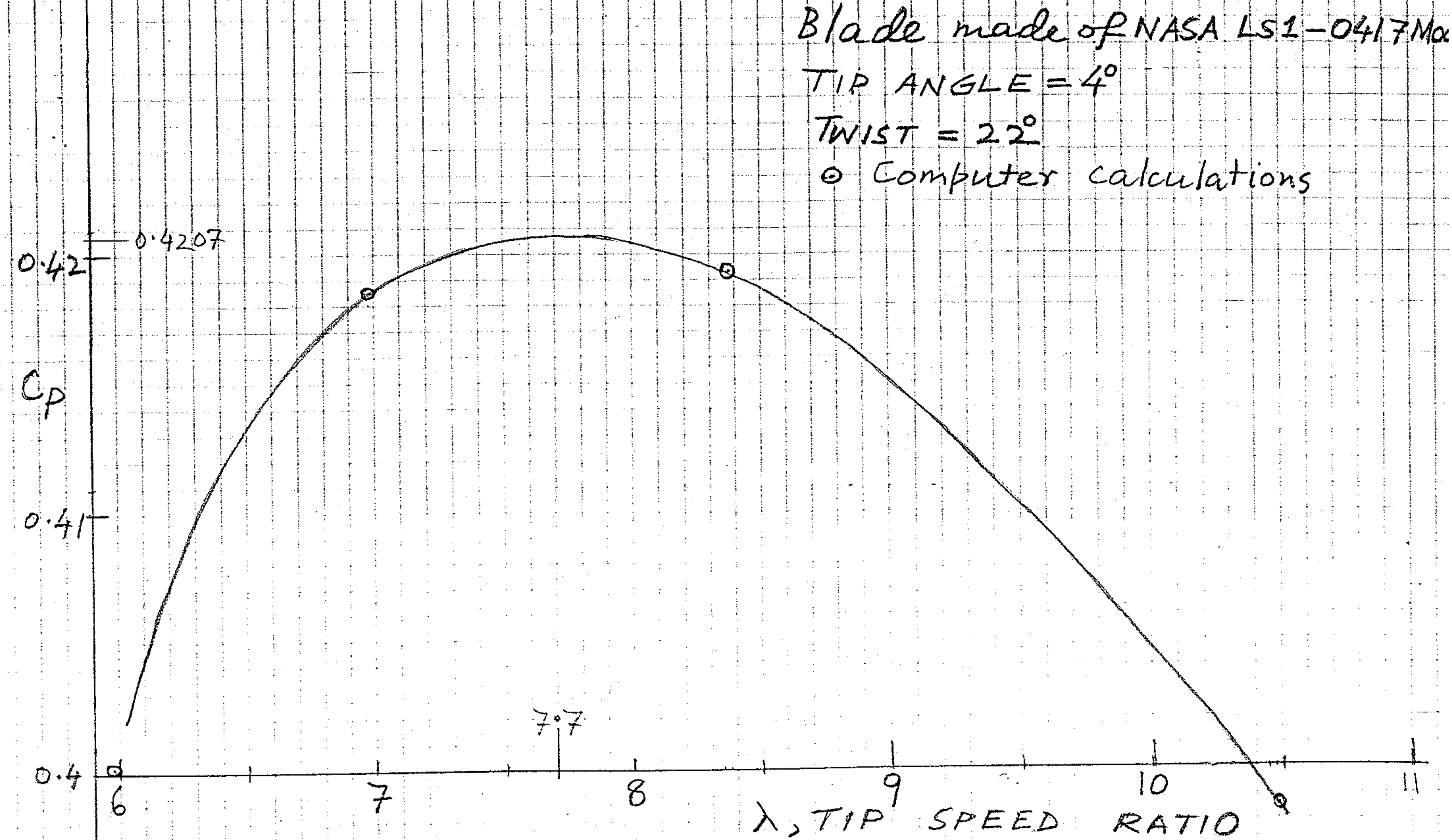


FIG. 6: $C_P - \lambda$ curve

3x380/motor 1,1 kw
3X220

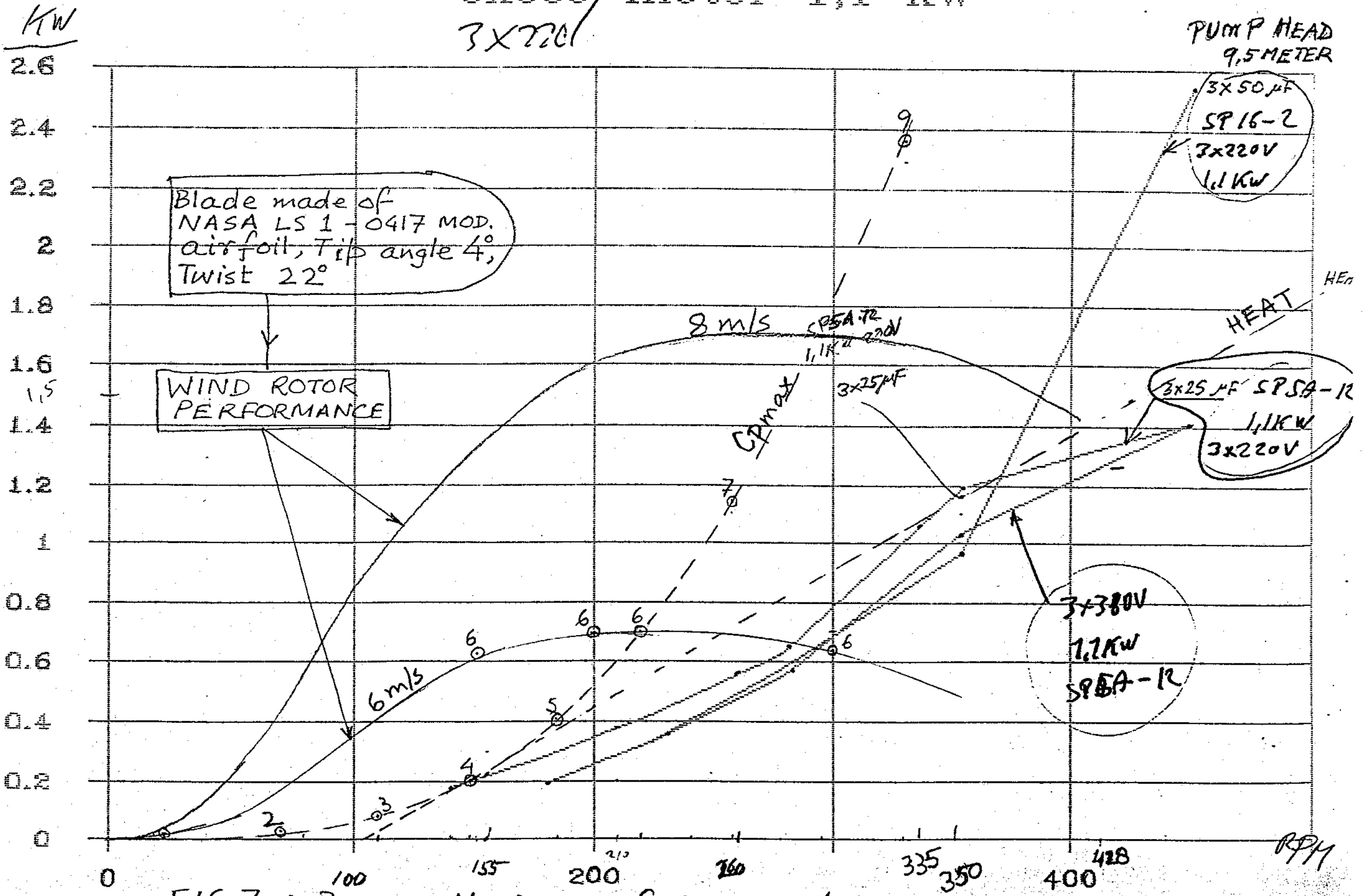


FIG.7 : Power Vs RPM of WT and pumps.

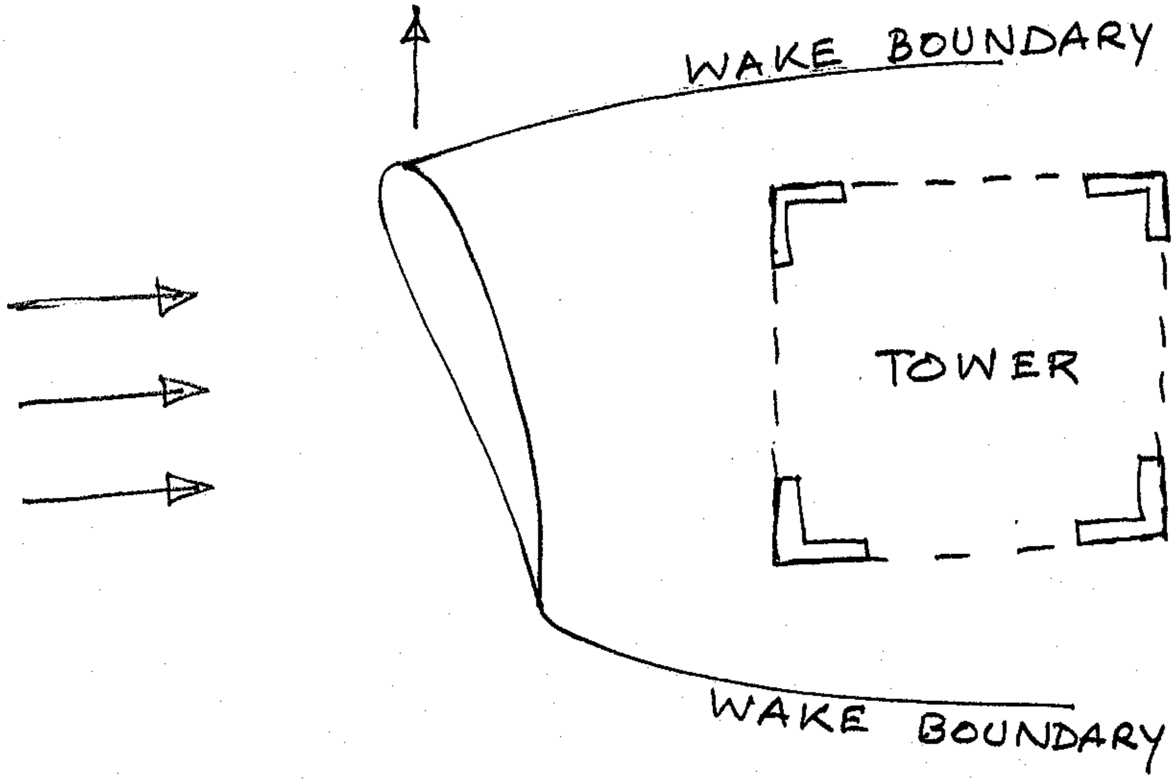


FIG. 8 : Blade-WAKE-tower interference