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**THE STORY ABOUT THE
REDUCTION IN NUMBER OF
WINDMILL SAILS**

By Povl-Otto Nissen

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THE STORY ABOUT THE REDUCTION IN NUMBER OF WINDMILL SAILS

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This paper was presented 2011 at The International Molinological Symposium (TIMS) in Aalborg, Denmark.

Abstract: The discovery of the vacuum force on windmill sails superseded the idea of making the total front sail area of a rotor as large as possible. The Danish meteorologist, inventor and college professor, Poul la Cour (1846-1908), made a breakthrough in the understanding of the forces on windmill sails. His research with mill models in front of two wind tunnels took place over the period 1896-1900. He developed a concept called the “ideal” sail. How did he do that? What were the improvements? What were the consequences? Before his aerodynamic research, la Cour received state support to build the first electricity producing windmill in Denmark in 1891, which included the storage of wind energy by separating water into hydrogen and oxygen.

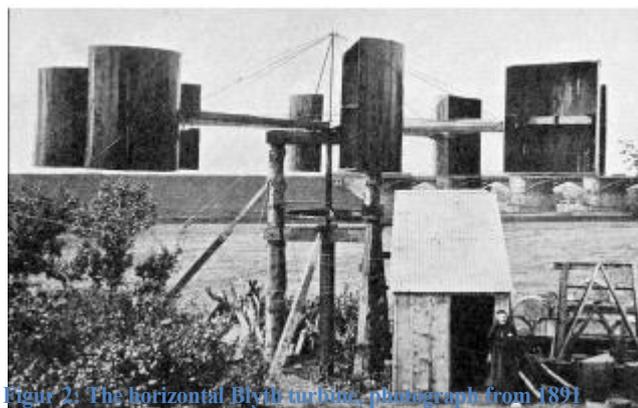
1. Introduction

This paper is based on studies of the surviving documents from the research carried out by Professor Poul la Cour over the period 1891 to 1900. Especially the report “*Forsøgsmøllen I og II*, Copenhagen, 1900. About 8000 documents remain in the archive at the Poul la Cour Museum, Askov, DK6600 Vejen, Denmark.

The Poul la Cour Museum researches and distributes the history of the technology of electricity producing windmills, - nowadays called wind turbines. The very first known electricity producing windmill with a vertical rotor was built in 1887-1888 at Cleveland, Ohio, by Charles F. Brush. It was huge with many blades and it delivered power to 240 lamps in the owner’s house. This system worked for twenty years. But old documents tell us that already the Scottish scientist William Thomson, later lord Kelvin, discussed the possibility already in 1881 and concluded that it was not profitable. Nevertheless the Scottish professor, James Blyth, built a windmill with a horizontal rotor for electricity production at his summer cottage already in 1887, and with acid metal battery storage.



Figur 1: The Brush turbine, Cleveland, 1888



Figur 2: The horizontal Blyth turbine, photograph from 1891

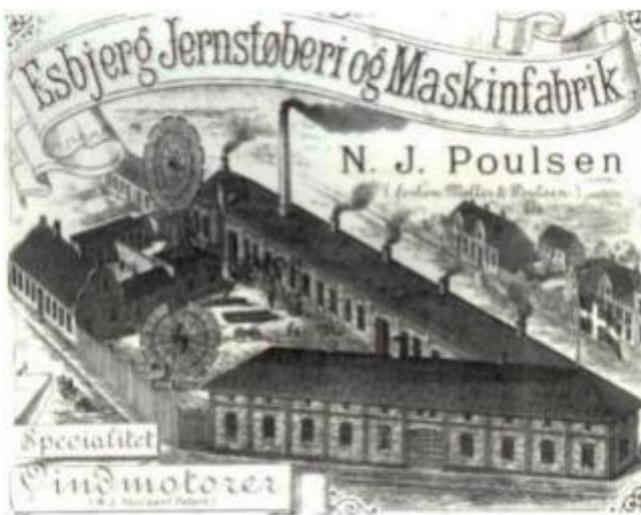
The American tradition of windmills utilised many blades. This type of windmill is very suited to pumping water. These mills also influenced Danish mill designs during the 19th century. The building of the railways provided an opportunity to use this type of windmill in conjunction with water towers on railway stations for pumping water for the steam powered locomotives.



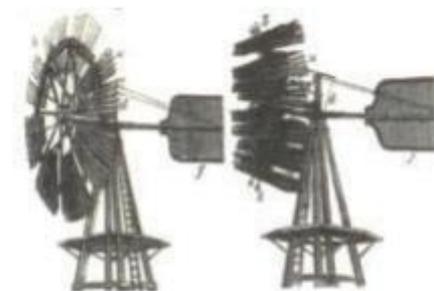
Halladay-mølle på Hjørring Station (Detalje af foto i Historisk Arkiv, Vendsyssel historiske Museum, Hjørring)

Figur 3: Typical railway station water pump system. Figur 4: Hjørring railway station with a Halladay Mill.

N.J. Poulsen in Esbjerg DK, one of the bigger millwrighting companies in Denmark, built this type of windmill. They even built the very special type called Halladay turbines, where the blades could be turned parallel to the turbine axis. It was this factory, which also built the first Danish electricity producing mill of quite a different Poul la Cour design.



Figur 5: Advertisement factory logo.



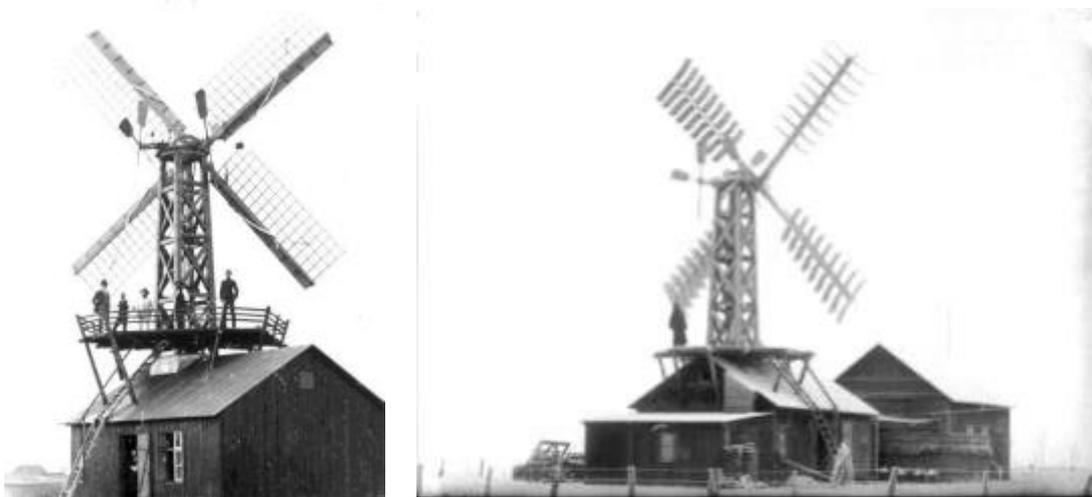
Halladay-mølle (efter Nordisk Conversationslexikon, 1894)

Figur 6: The Halladay mill in two positions.

2. The first Danish electricity producing windmill

There is no evidence that Poul la Cour knew about the Brush mill in Iowa, but its existence must be acknowledged. However, it is most important that the first Danish electric power generating stations were installed in the three cities of Køge, Copenhagen and Odense in 1891. The fuel used was coal or oil, which are not natural resources occurring in Denmark. La Cour wondered if it would be possible to use the ever-present wind over Denmark to drive turbines for making electricity instead of having to buy fuel from abroad.

Everybody told him that it could not be done. The wind does not blow all the time, so it was necessary to find a way to store the energy for use during periods with no wind. The technology of lead/acid batteries was known, but was too expensive. La Cour then had the idea of storing the power of the wind using electrolysis to separate water into hydrogen and oxygen so that the two gases could be used later for heating and lighting. Also it was known, from a firm in Italy, that these gases could be used in autogen welding, which usage could be useful for small industries in rural areas. With the help of his older brother, who was president of the Royal Danish Farm Household Society, the Minister of the Interior (Home Secretary) became interested in the scheme. La Cour was then granted the financial support of 4000 Dkr for research into the subject of wind energy. No doubt it helped that he was already known as a highly respected inventor of telegraph equipment. A new experimental windmill was built and ready to work in May 1891 in the southern part of the small village where the College of Askov had settled after the war with the Prussians in 1864.



Figur 7: Left: First photograph of the first electricity producing mill in Denmark with canvas sails, 1891.

Figur 8: Right: Second photograph of the first electricity producing mill with wooden shutters.

Poul la Cour chose the millwright N.J. Poulsen to build his new mill. However, it is obvious that it was quite a different design compared to what the factory were used to building. Just to prove that his concept was correct. La Cour only needed his mill to be as cheap as possible. So he chose the well known four bladed rotor design from the standard Dutch windmill design, but of course he had no use for the interior machinery for flour production. Instead he built a slim wooden tower, sufficient to carry the turbine and a vertical spindle down to the DC dynamo in the building. To begin with it could be used with canvas sails, but very soon these were changed to wooden flaps, which were

a well-known technology. For some reason the name of Poul la Cour is connected with this special design of mill building, but its appearance was not the big invention.

The electrolyzing vessels were placed in the larger building besides the mill building as well as two big gas containers in the ground. From here the two gases were transported through leadpipes 300 metres to the college buildings where they were used as lighting gas in very special lamps. The installation functioned for seven years from 1895 to 1902. This is quite another story, but is not the subject at this paper. It is important that this success released more financial support and made it possible to continue the research as The State Experimental Wind Laboratory with Poul la Cour as director.

3. An aerodynamic surprise

Millwrights were excited because a new market had appeared: The production of electricity and light using windmills. One millwright, Chr. Sørensen from Skanderborg, made contact with Poul la Cour in 1896. Sørensen had invented a new design of windmill rotor, *Keglevindfanget* (The Conical Wind Catcher), and he asked la Cour for help to produce documented test results in order to seek a patent. Chr. Sørensen himself had started research on models with different rotor types – all with same diameter - in front of a barrel with a blowing ventilator in one of the open ends. It was called a “blæsecylinder” (blowing cylinder) and possibly it was the first experimental wind tunnel. Until then windmill rotors most often were tested on a rotating merry-go-round (carousel) arm. Using this method it was difficult to create a constant air flow long enough to make reliable measurements, but la Cour now had suitable equipment. In 1902 he invented the *Kratostate*, a device which could smooth out the changing rotation of the mill to a constant rotation and driving force on a dynamo. Now it could be used to deliver a very constant air flow through the wind tunnel.



Figur 9: Left: This photograph from 1896 shows the "conic wind cather" with twelve sails.



Figur 10: Right: The conical wind catcher rotor as a roof mill with only six sails.

The first model Sørensen designed had twelve sails. La Cour found almost immediately that performance improved when some of the sails were removed. That was a surprise because the most common opinion at that time – even among millwrights - was that a mill should have as many sails as possible. This was supported by the hitherto accepted scientific formula:

$$L = 0.0338 F v^3$$

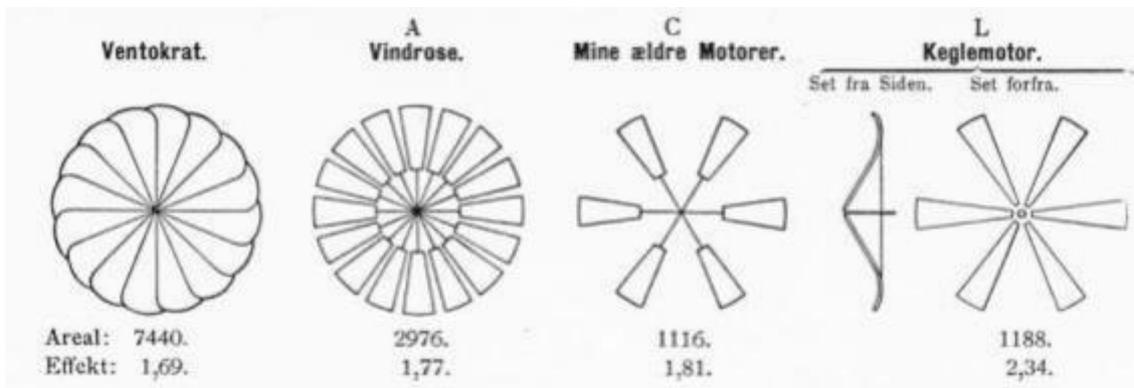
, where **L** is the power, **F** is the sum of the frontal area of the sails and **v** is the velocity of the incoming wind. The formula says that if the total front area of the sails is increased, then the power output will increase proportionally. La Cour proved that this was totally wrong. Only the term for the cube of the wind velocity is still valid from this formula.

La Cour presented his findings in a paper "Experiments with small mill models" at a meeting in the Danish Engineering Association and the paper was published in the magazine "The Engineer", (Ingeniøren) number 10, March 1897.

A quote from this paper, translated as precisely as possible, is as follows:

"So it is clear, that the rotor must collect energy from other wind streams than the ones hitting the sails. The rotor must also collect energy from the wind streams passing between the sails, and this collection must in certain cases, especially with open rotors, play an important role. The contribution in work coming from the space between the sails, appears to increase with increasing velocity. The experimental findings show that the wind passing between the sails is highly active in driving the sails. It can easily be understood, when it is considered that the air particles shortly after passing through the spaces, take up a position behind the sails where they cause a vacuum by their inertia, which accelerates the sails and at the same time decelerates the air particles."

As can be seen he had discovered the importance of the vacuum lift on windmill sails.



Figur 11: Drawings showing some of the test models and measurements.

The first row of numbers is the sum of the front areas of the blades. The second row is the corresponding power. Millwright Sørensen received his patent which was the best known at the time. This encouraged him to build the new mill on top of a new stone building. The building itself was designed by a young architect, P.V. Jensen-Klint, who later became famous as church architect. Today the stone building houses the Poul la Cour Museum.



Figur 12: Left: Photograph of the wind laboartory mills, 1897.
 Figur 13: Right: Photograph of the wind laboratory mills, 1900.



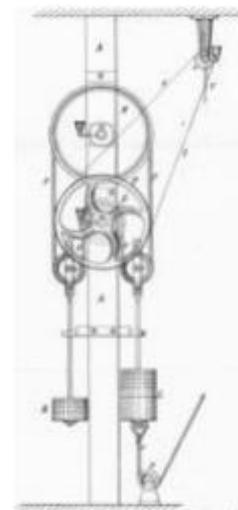
4. Further aerodynamic research

Poul la Cour aimed to continue his research in order to find what he called the ideal sail. He wondered why in earlier times mathematicians and physicists such as Bernoulli, Maclaurin, d'Alembert, Euler, Lambert and Smeaton had all propagated a completely incorrect formula. An example of what will go wrong, he claimed, when *“the starting point is rational thinking followed by trying to force the real world to fit into a formula with the best choice of constants”* (0.0338). Their excuse of course was that they did not have the unique test facilities that Poul la Cour had developed.

In the machinery hall he installed two wind tunnels of his own and invented a unique apparatus for measuring the wind pressure on different sail profiles. With his Kratostate he was able to produce a constant air flow through the wind tunnels with a deviation of only one per thousand.



Figur 14: Left: Photograph of the wind tunnels. One with diameter 1 m and one with diameter 0.50 m.
 Figur 15: Right: Drawing showing the Kratostate.



Both wind tunnels were 2.20 metres in length. The mill model for testing was placed in front of the big wind tunnel with a friction dynamometer. The pressure measure instrument was in front of the small tunnel.

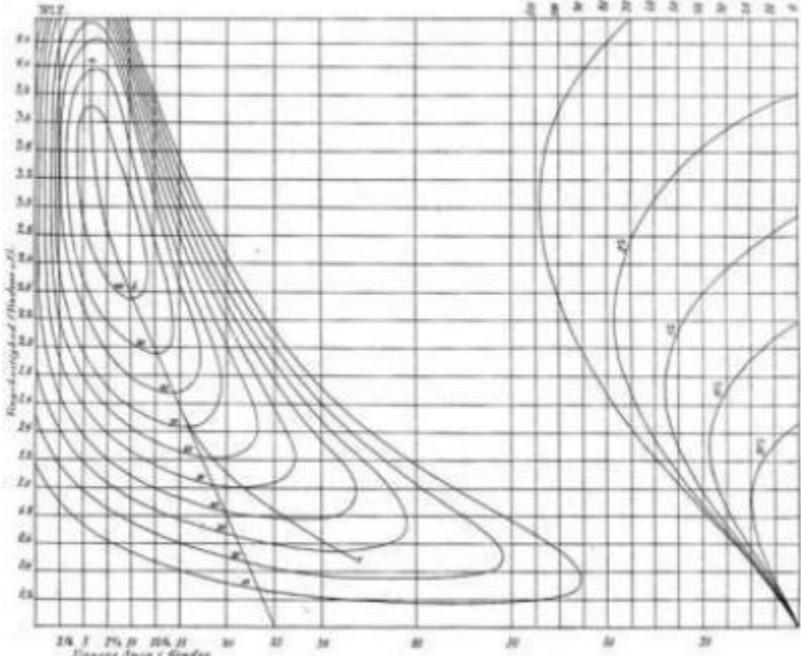


Arbejdsevnen af en Kæmpeplade paa 1 m. med 1 m. Vindhastighed med forskellige Smig og forskellige Pladehastigheder. Tallene ere g. m. pr. Sek.

	0°	2½°	5°	7½°	10°	12½°	15°	20°	25°	30°	40°	50°	60°	70°
0.1	0.1	0.2	1.1	2.1	2.2	3.1	4.1	5.1	6.1	8.1	11.1	11.1	11.1	1.1
0.2	0.2	1.1	3.1	5.1	6.1	8.1	10.1	12.1	17.1	21.1	22.1	18.1	6.1	
0.3	1.1	3.1	8.1	9.1	13.1	18.1	20.1	25.1	29.1	31.1	28.1	17.1		
0.4	2.1	7.1	12.1	18.1	23.1	28.1	32.1	38.1	40.1	39.1	28.1	7.1		
1.0	5.1	13.1	21.1	28.1	35.1	38.1	44.1	49.1	49.1	41.1	21.1			
1.1	9.1	21.1	31.1	40.1	47.1	52.1	56.1	58.1	54.1	42.1				
1.2	15.1	29.1	41.1	51.1	58.1	63.1	67.1	65.1	53.1	34.1				
1.3	20.1	37.1	51.1	62.1	71.1	74.1	73.1	68.1	48.1	18.1				
1.4	25.1	45.1	61.1	72.1	79.1	82.1	82.1	66.1	37.1					
2.0	30.1	53.1	70.1	82.1	89.1	90.1	85.1	61.1	29.1					
2.1	34.1	59.1	78.1	90.1	97.1	95.1	85.1	50.1						
2.2	36.1	65.1	85.1	98.1	102.1	95.1	82.1	32.1						
2.3	38.1	69.1	91.1	104.1	103.1	93.1	76.1	15.1						
2.4	30.1	72.1	96.1	108.1	103.1	89.1	64.1							
3.0	34.1	77.1	102.1	108.1	102.1	83.1	45.1							
3.1	31.1	78.1	104.1	108.1	97.1	73.1	25.1							
3.2	26.1	80.1	104.1	104.1	91.1	56.1	7.1							
3.3	21.1	76.1	99.1	100.1	80.1	30.1								
3.4	15.1	73.1	94.1	92.1	67.1	7.1								
4.0	8.1	66.1	85.1	83.1	49.1									
4.1		57.1	78.1	73.1	19.1									
4.2		43.1	67.1	56.1										
4.3		27.1	52.1	37.1										
4.4		9.1	37.1	13.1										
5.0			21.1											

Figur 16: Left: Photograph of the unique wind pressure messurer.
 Figur 17: Right: Table with Poul la Cour's measurements on a bend wing profile.

Poul la Cour did not develop a new formula, but he developed a diagram to determine the best design of a sail based on very careful and precise measurements. It is called the "mussel" diagram. With this available a millwright should be able to complete the practical work to an optimum of efficiency. With the wind flow of 1 m/sec determined from the small wind tunnel, he measured the influence successively on a plane, a curved and a bent profile with dimensions 10 cm x 10 cm.

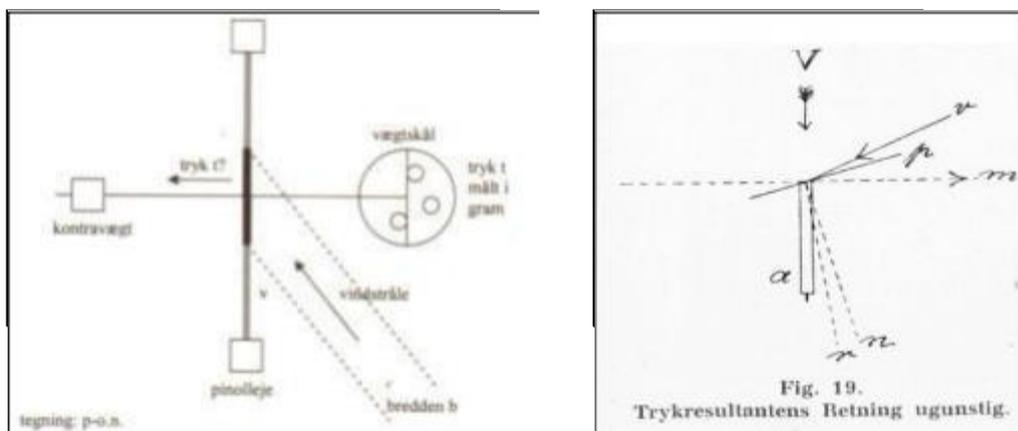


Figur 18: Graphical representation of the measurements, The "Mussel" diagramme

The origin of the diagram is the rotational centre of the sail. The numbers on the horizontal axis are the bevel angles of the sail to the rotation plane. The numbers on the vertical axis are the velocity factors for that particular point of the sail compared to the velocity of the incoming wind. The diagram gives the impression of a hill on a map with height contour curves. In this case it has a maximum power [gram-metres/sec] at the velocity factor 3. Reading the corresponding angle on the horizontal axis gives $7\frac{1}{2}$ degrees. To make the best possible sail, take the least steep path from the top of the hill, which gives the path a-c. Obviously it means that the sail should be slightly twisted with large angles near the centre and smaller ones further out. The curved path a-c could not be followed at that time using materials such as wood and iron. Today with glass fiber this is possible. Consequently, from about the velocity factor 1.4 it is necessary to compromise with a straight line hitting the horizontal diagram axis near the rotation centre at 25 degrees.

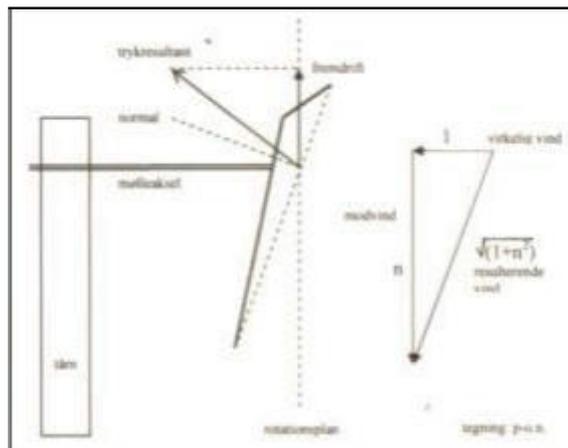
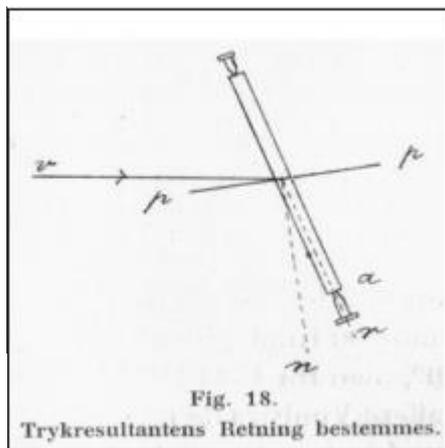
The research procedures for these findings were as follows:

1. Initially it is assumed that the flow pressure perpendicular to the plane is proportional to the area of the plane.
2. Secondly, it is determined that the pressure perpendicular to the plane is proportional to the velocity of the wind flow squared.
3. After that, the pressure perpendicular to a plane profile from a flow directed from different angles of 1 to 90 degrees on the plane is measured. The surprise was that these results did not fit with the values calculated in advance using Newtonian physics. They were not proportional with the width of the impacting air stream. It must be concluded that the resulting pressure mysteriously turned out to have other directions than perpendicular to the plane.



Figur 19: Two drawings showing the pressure of a flow from different angles on a plane surface. Left my description, right la Cour's own description.

4. To determine the directions of the resulting pressure on the plane from the air streams coming from different angles, the rotational axis of the plane is turned in every case until it is balancing back and forth in a regular manner. For given wind angles to the plane the angles between the directions of the resulting pressure and the direction perpendicular to the chord of the sails are measured.

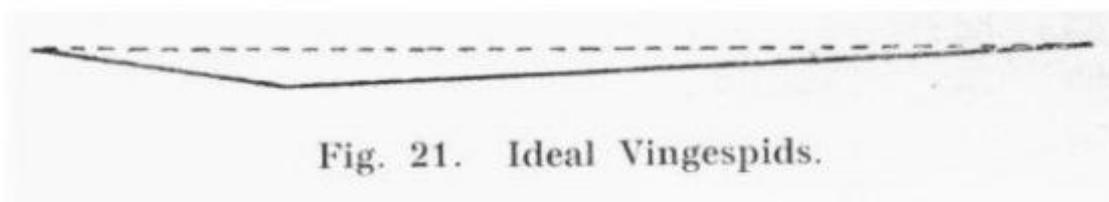


Figur 20: Drawing showing the pressure resultant over the axis, la Cour's description.

Figur 21: Drawing showing the pressure resultant lying on the favourable side of the profile normal.

Repeating the same with a curved profile and a bent profile it was concluded that the pressure resultant under certain circumstances (bevel and shape) lies to the "favourable" side of the perpendicular direction to the chord of the sail, sometimes to the "unfavourable" side. "Favourable" means the case where the resulting pressure has a component which causes the sail to rotate in the right direction. The task was then to find the right shape and give it the right bevel angle.

5. The "ideal" Mill



Figur 22: Drawing of the ideal shape of a wing profile.

The specifications of the ideal mill, translated as precisely as possible, is as follows:

- 4 sails with as few resistant surfaces as possible, especially near the tip of the sail.
- The width of the sail to be nearly $\frac{1}{4}$ or $\frac{1}{5}$ of the length of the sail, and almost same width all over.
- The surface of the sail starts at a distance from the axis of about $\frac{1}{4}$ of the sail length, so the surface is $\frac{3}{4}$ of the sail length.
- The cross section of the sail profile is not a straight line, but bent at a point, which is $\frac{1}{4}$ or $\frac{1}{6}$ from the fore edge and the fold is so strong, that it is 3 to 4 % of the chord of the profile, especially at the tip of the sail, however, near the axis it can be straight.
- The bevel angle is calculated from the profile chord, not from the large sail surface, nor from the small sail surface. It is 10 degrees at the sail tip and increases regularly so it is 15 degrees at $\frac{2}{3}$ of the distance from the axis and 20 degrees $\frac{1}{3}$ from the axis and would be 25 degrees at the axis.

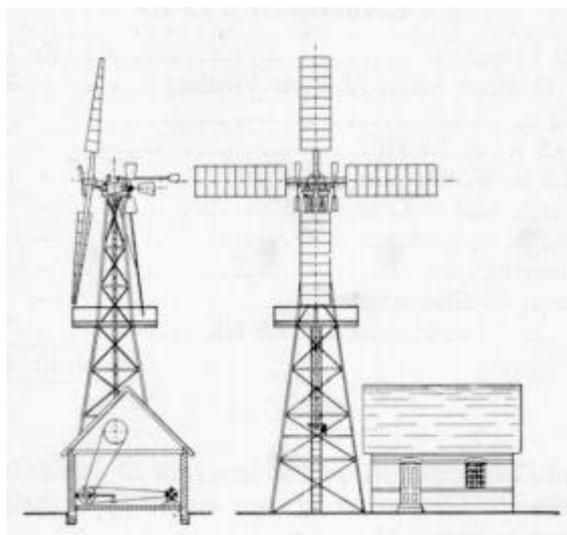
- f) The mill should be arranged so that the tip of the sail runs with a velocity factor of 2.4 the velocity of the incoming wind, out of which it is desirable to extract the greatest possible power. (It will most commonly be near to 6 or maybe only 5 metre/sec).
- g) The work that such a mill produces can be calculated as the research shows, by the fact that there is 60 gram-metre per square metre sail surface at a wind velocity of 1 metre/sec. The work will be a factor 60 of the total sail area in square metres multiplied by the wind velocity cubed and will be expressed in gram-metres. By dividing this number with 1000 the value in kilogram-metre per sec will be determined. Divided again by 75 will give the answer in horse power. Example: If the 4 sails have a length of 8 metres and a width of 2 metres and the power at wind velocity of 6 meters per sec is to be determined, then the tip velocity is 6 times 2.4 = 14.4 metres/sec. And while the circumference will be about 50 metres, this mill will make $(14.4 \times 60)/50 = 17.3$ turns per minute. Its sail surface is $4 \times 6 \times 2 = 48$ square metres, and its power with the aforementioned wind is $60 \times 48 \times 6^3 = 622080$ gr. m. = 622 kg. m. = 8.3 hp.

After publishing his research report "Forsøgsmøllen I og II" (The Research Mill I and II) in 1900, la Cour initiated a contest urging millwrights to build the ideal mill. Some of them became very angry as they were convinced they were already doing that! Millwright Chr. Sorensen was especially angry, because his attractive conical rotor on the laboratory building had, in the meantime, been exchanged for an ordinary 4 sail rotor (Figures 7 and 8). The problem was that the conical rotor in this large size had been too heavy and unstable. But Sorensen would not accept the removal and caused a lot of trouble in public, which finally involved the Danish parliament.

The end result was that in future the State Wind Laboratory should be a centre for information about the use and development of electricity in the rural areas of Denmark. A Danish Wind Electricity Society was formed and a consultant office was established. A magazine "Tidsskrift for Vind-Elektrisitet" was published 4 times a year. And finally, the training of so-called "Country Electricians" (Landlige Elektrikere) began in 1904 and was repeated every year until 1916.



Figur 23: Left: Photograph of the first class of Country Electricians from 1904.



Figur 24: Right: Design of an electricity producing wind mill for farms, recommended by la Cour.



Figur 25: Left: Johannes Juul. enlarged from the 1904 team photograph.



Figur 26: Right: Photograph of the Gedser turbine. The first 3-wing AC mill with tip safety brakes.

One of the students, Johannes Juul, was only 17. But the number 7 of his birth year 1887 looked very much like a 4 (1884) on his application, so the impression was given that he was old enough to participate. Of course this was discovered and after an extra year of practice he also received his diploma. He carried out further studies and became high voltage engineer, invented electric household equipment, and finally, in the 1950s, he developed the first 3-sailed AC wind turbine, the Gedser turbine. This was the “mother” of what is seen all over the world today, showing the influence from Denmark on the rest of the world.

3. Conclusions

Poul la Cour published “Forsøgsmøllen III and IV” in 1903, as a supplement to his report of 1900. He admitted that his expression “The ideal Sail” was unfortunate, because it could be misunderstood as a claim to its invention which would upset some people. The phrase was only used to point out the importance of the right shape and the right bevel angle. He also admitted that hundreds of years of millwrighting experience provided sails that were close to the ideal, but seldom 100% correct. He invited mill owners to send him descriptions and dimensions of their mills and offered to advise them on any improvements. He also discussed the ratio between the length and width of the sails compared to the space between them. However, it was not until 1919 that a new formula was presented by Albert Betz. He showed that the power of a mill depends on the proportion of the circle area covered by the rotor – not the frontal area of the sails. Betz also calculated that the theoretical and practical limit would be 59% of the wind power available.

The contribution of Poul la Cour was an important step on the road to understanding the force of vacuum lift on mill sails. It was discovered on mill sails 5-6 years before the Wright brothers started flying, although it is the same force that keeps an aeroplane in the air. As far as we know the “musseldiagram” was constructed by Poul la Cour and thereby introduced the new concept of the tip velocity ratio, which is commonly used in descriptions of modern wind turbines.

Poul la Cour died from a lung infection on 24th April, 1908. His contribution to knowledge in many fields was outstanding. He covered every step from fundamental theoretical to practical research, making inventions and implementing his ideas for the good of society. In addition he was the author of several text books such as “Historical Mathematics” and “Historical Physics”. As well as being a scientist, he was also a very religious man and felt no contradiction in that. His epitaph, carved in a memorial stone a few kilometers south of Askov, expresses that:

“As Light from Heaven gives Light to our Eye
Thoughts are inspired by Light from on High”.



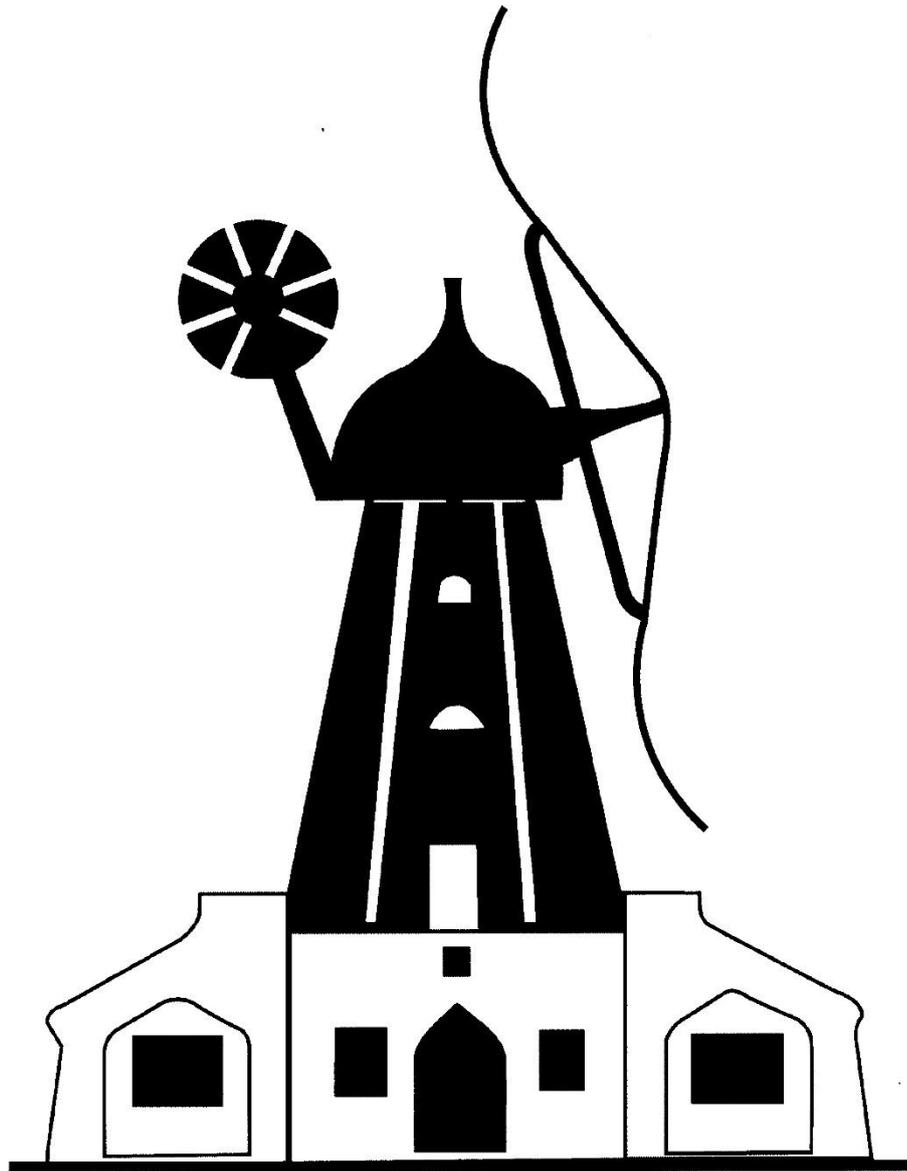
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Informations from documents in the archive of the Poul la Cour Museum.

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