

DEVELOPMENT OF A NEW MEMBRANE AIRFOIL AND ITS APPLICATION TO THE WELLS TURBINE

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ABSTRACT

A new airfoil, which consists of a rigid airfoil wrapped around by a thin membrane, has been developed. Theoretical and experimental studies show that the membrane airfoil develops larger camber and hence larger lift than the rigid airfoil alone. This membrane airfoil has been applied to blades of the Wells turbine, which can extract energy from fluid moving to and fro. Steady-state experiments show that the turbine with membrane-wrapped blades excels in efficiency the turbine with conventional rigid and symmetric blades at lower wind speed. It is, however, shown that membrane-wrapped blades also yields larger drag than rigid blades and that this results in deficiency of the turbine at faster wind speed.

INTRODUCTION

Membrane airfoils change their shapes so that the structural stresses become in equilibrium with the air load. Hence their aerodynamic characteristics become nonlinear with respect to the change of incidence. The self-equilibrium of membranes usually yields larger aerodynamic forces than rigid and symmetric airfoils. Theories for membranes are concisely reviewed by Newman (1987). The present study introduces a new membrane airfoil: a rigid airfoil wrapped by a thin membrane.

The aim of our study is not only the development of a new class of membrane airfoils but also their applicability to an energy converting system called the Wells turbine. The Wells turbine is an engineering system that has a single set of turbine blades, rotating always in the same direction in their own plane, and that can extract energy from a motion of fluid across that plane either from the front or the rear (Lighthill 1989). Therefore the conventional Wells turbine has symmetric airfoil blades.

We have studied our new membrane airfoil theoretically as well as experimentally. We have also conducted experiments to compare the steady-state

characteristics of two turbines in one-way flow. One of the turbines has rigid and symmetric blades, and the other has rigid blades wrapped by thin membranes.

MOTIVATION

First we tried applying a single membrane airfoil to the Wells turbine, but it turned out in vain. When we set a single membrane at the right angle to the flow, it would not yield the force perpendicular to the direction of flow. This means that a single membrane airfoil will not yield the force to set the turbine blades start to rotate. That is why we developed the new membrane airfoil.

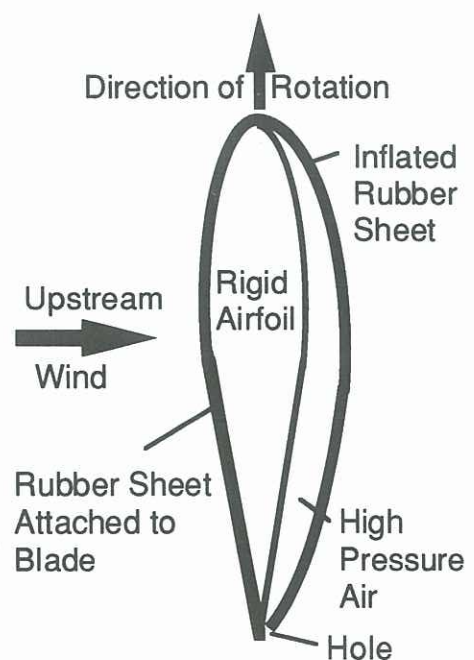


FIGURE 1. MEMBRANE-WRAPPED BLADE

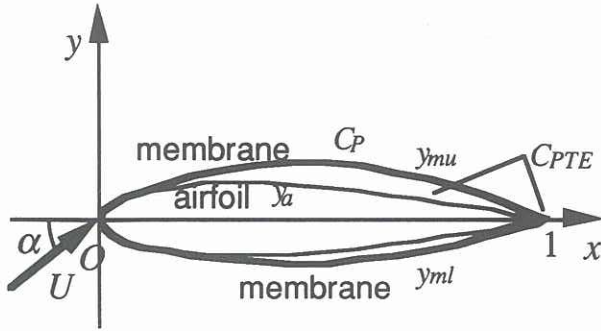


FIGURE 2. COORDINATE SYSTEM

Figure 1 shows the basic idea of our invention. Our membrane-wrapped airfoil has both camber and thickness. Since the membrane has holes along the trailing edge, the high pressure air in the vicinity of this edge can come into the space between the rigid blade and the membrane. The high pressure air inflates the membrane away from the blade on the leeward side, while the membrane stays attached to the rigid blade on the upwind side. This natural deformation yields the favorable camber and hence larger aerodynamic forces than rigid and symmetric airfoils. This effect can also set the turbine blades start to rotate. Our experiments assured this fact. It is also pointed out that this natural and favorable camber could be induced by the flow moving across the turbine either from the front or the rear.

THEORY

Figure 2 shows the coordinate system and nomenclatures for our theory. This airfoil consists of a rigid airfoil core and a membrane of natural rubber wrapping around it. Along the trailing edge there are holes in the membrane, which allow air to go into the space between the airfoil surface and the membrane. Since the high pressure air in the vicinity of the trailing edge becomes in equilibrium with the lower pressure air outside the membrane, the mechanical equilibrium yields camber for itself.

The flow is assumed steady, inviscid and two-dimensional. We have used the vortex-panel method (Kuethe and Chow 1986) to analyze aerodynamics. The number of panels used in our calculation was forty.

The membrane is assumed elastic, incompressible and two-dimensional. The treatment of elasticity is as follows. Let us introduce the aeroelastic coefficient $\bar{A}E$:

$$\bar{A}E = \frac{Et}{2\rho U^2 c}, \quad (1)$$

where E , t , ρ , U and c denote the Young's modulus, the membrane thickness, the air density, the undisturbed air speed and the chord length, respectively. Using this coefficient the stress-strain relation is given in non-dimensional form:

$$C_T = \bar{A}E \varepsilon, \quad (2)$$

where C_T and ε denote the tension coefficient, i.e., the tension divided by the dynamic pressure, and the strain,

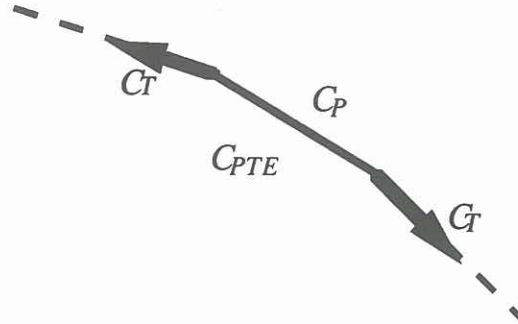


FIGURE 3. PANELS FOR A MEMBRANE

respectively. The strain is given by use of y_a , y_{mu} and y_{ml} , which are coordinates of the core airfoil, the upper membrane and the lower membrane, respectively:

$$\varepsilon = \frac{\int_0^1 \left\{ \sqrt{1 + (y'_{mu})^2} + \sqrt{1 + (y'_{ml})^2} \right\} dx}{2 \int_0^1 \sqrt{1 + (y'_a)^2} dx} - 1. \quad (3)$$

As is shown in figures 2 and 3, the equilibrium between the tension and the air load acting on the membrane element is described by

$$\frac{C_T}{R_{m\pm}} = C_P - C_{PTE}, \quad (4)$$

To derive the equation above, we assumed that the pressure in the space between the membrane and the airfoil surface is constant and equal to the trailing edge pressure. Indeed this assumption was verified by the measurement of surface pressure. In equation (4), $R_{m\pm}$ denotes the curvature of the membrane:

$$R_{m+} = \left\{ 1 + (y'_{mu})^2 \right\}^{3/2} / y''_{mu}, \quad (5)$$

and

$$R_{m-} = \left\{ 1 + (y'_{ml})^2 \right\}^{3/2} / y''_{ml}.$$

The equation (4) offers condition for the separation of a membrane from the wing surface:

$$\frac{C_T}{C_P - C_{PTE}} < R_a, \quad (6)$$

where R_a denotes the curvature of the core airfoil:

$$R_a = \left\{ 1 + (y'_a)^2 \right\}^{3/2} / y''_a. \quad (7)$$

The same panels were used for aerodynamic and elastic analyses. Prescribing the value of the tension, we solved the aerodynamic and elastic equations simultaneously by use of the Newton-Raphson method. We used the value of the tension as the criterion of convergence; iteration was repeated until the relative error of the tension became less than 0.01%. Initial value for the tension was guessed by use of the equation (6). The value of the tension was renewed for every iterative step by the relaxation: taking the mean between the former value and the new guess based on the equation (2).

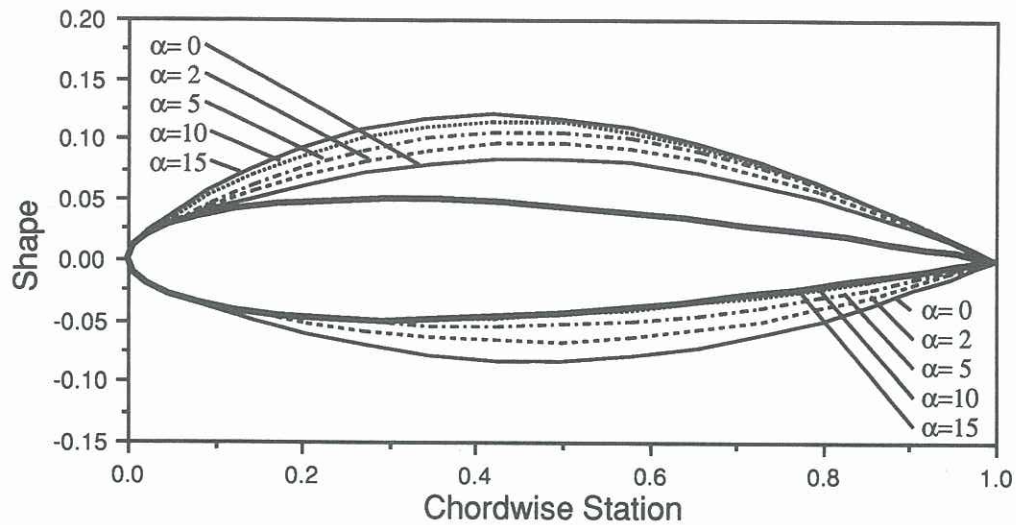
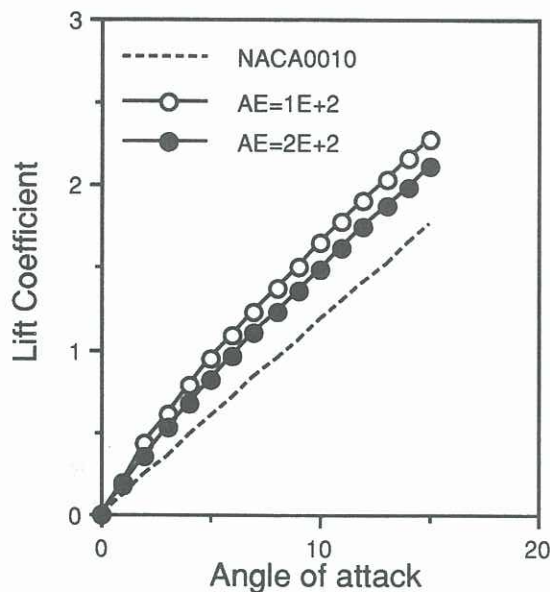
FIGURE 4. MEMBRANE SHAPES IN EQUILIBRIUM ($\mathcal{A}E=1 \times 10^2$)

FIGURE 5. LIFT COEFFICIENT VS. INCIDENCE

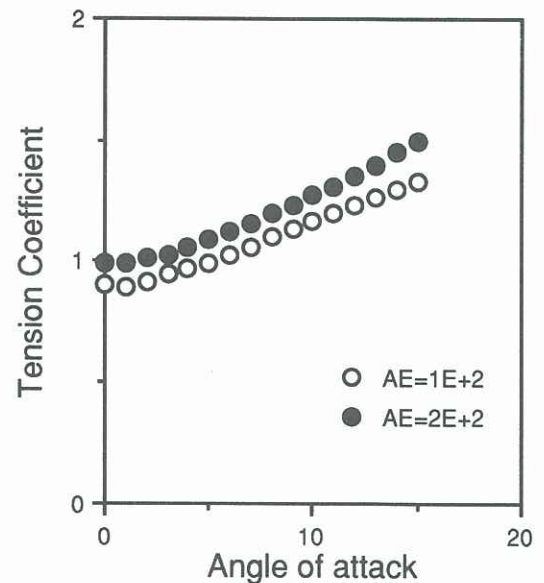


FIGURE 6. TENSION COEFFICIENT VS. INCIDENCE

EXPERIMENT

We have constructed the blow-down wind tunnel. The rotating speed of the fan is variable. We designed the turbine with four acrylic blades of the NACA 0010 airfoil. The solidity of the turbine is 0.57. The aspect ratio of a blade is 1.05. The turbine is set in the circular duct whose diameter is 0.3 m. We used a tachometer to measure the revolution rate of a turbine shaft as well as a multimeter to measure the electric power generated by a dynamo connected to the turbine shaft.

We used the same turbine to conduct the experiment on membranes. We wrapped each blade with a sheet of natural rubber whose thickness is 0.3 mm. Only edges of a rubber sheet are attached to a blade. This sheet has holes along the trailing edge of the blade. From now on we shall refer a rigid blade wrapped by a thin membrane as a membrane-wrapped blade.

Air speed ranges up to around 5 m/s. The nominal velocity of the relative wind to turbine blades is defined by the composition of the upstream wind speed and the rotating speed of a blade. This nominal velocity of the relative wind ranges up to around 50 m/s at the blade tip. The Reynolds number, defined by the blade chord and the relative wind speed at the blade tip, is up to 3.4×10^5 .

RESULTS AND DISCUSSION

Characteristics of membrane-wrapped airfoils

This section presents the analytical results and their annotation.

Figure 4 shows membrane shapes in equilibrium in case $\mathcal{A}E$ equals 1×10^2 . The core airfoil is NACA 0010. Membranes are inflated where the local flow is

accelerated. At zero angle of attack both upper and lower membranes are inflated. In accordance with increase of the incidence the upper membrane becomes more and more inflated while the lower membrane becomes less and less inflated. Therefore camber of this membrane airfoil is getting bigger as the angle of attack is getting bigger.

The aerodynamic characteristics are summarized in figure 5. Lift acting on membrane airfoils is larger than that on a rigid airfoil. The governing parameter is the aeroelastic coefficient \bar{A} , which shows the relative elasticity to the dynamic pressure. If \bar{A} is small, a membrane is *soft*. Clearly a *soft* membrane yields larger camber and larger lift than a *hard* one.

Figure 6 shows the relation between the tension and the angle of attack. Apparently there is a positive correlation between the tension and the incidence. At zero angle of attack, however, the tensions do not become zero, because membranes are inflated on both sides of airfoils at smaller angles of attack.

Performances of turbines having rigid and membrane-wrapped blades

Figure 7 shows the experimental apparatus; figure 8 is the summary of the experimental results: the relation between the generated power and the upstream wind speed. The turbine with membrane-wrapped blades starts to rotate and hence can generate electricity at lower wind speed than the turbine with rigid blades, because larger lift acts on blades with air-induced camber than on rigid and symmetric blades. On the other hand at higher wind speed the performance of the turbine with rigid

blades excels that of the turbine with membrane-wrapped blades. This fact is presumably attributed to the poor lift-to-drag ratio of the turbine with membrane-wrapped blades due to larger drag brought by the excess deformation of the membrane at higher speed.

CONCLUSIONS

We have developed a new class of membrane airfoils: rigid airfoils wrapped around by thin membranes. This airfoil has variable camber due to self-equilibrium, and the lift acting on this airfoil is greater than that on the rigid airfoil alone.

We applied the new membrane airfoil to the Wells turbine. The turbine with membrane-wrapped blades has a better performance than the turbine with rigid blades at low wind speed. Since the application of the Wells turbine is proposed to use low speed motion of sea wave, our membrane-wrapped turbine is a promising innovation.

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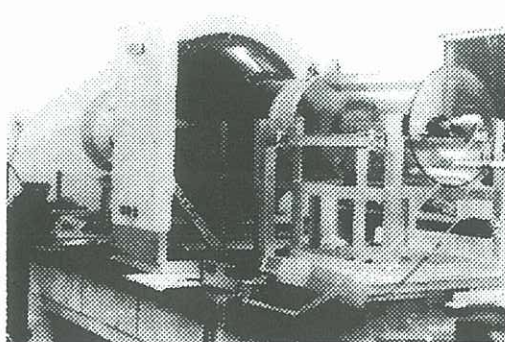


FIGURE 7. EXPERIMENTAL APPARATUS

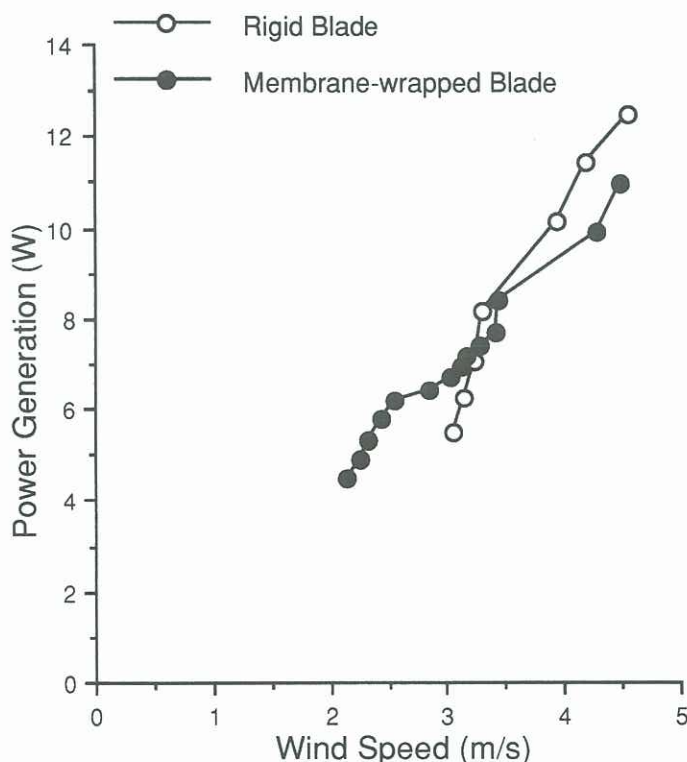


FIGURE 8. POWER GENERATION VS. WIND SPEED