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OSCILLATING-WING POWER GENERATION

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ABSTRACT

Numerical and experimental methods are described for the investigation of an oscillating-wing generator or *wingmill*. The numerical approach applies a previously developed, unsteady, incompressible panel method incorporating a non-linear, deforming wake model to compute the unsteady flow about an airfoil undergoing specified pitch and plunge motions. An experimental model is described which can duplicate much of the parameter-space available to the panel method. Numerical results are presented demonstrating configurations that yield high efficiencies. Results are compared to the wingmill experiments of McKinney and DeLaurier.

NOMENCLATURE

A area swept out by the wing, in terms of c^2
 C_D drag coefficient, $\text{drag}/(q_\infty S)$
 C_L lift coefficient, $\text{lift}/(q_\infty S)$
 C_M moment coefficient about x_p , $\text{moment}/(q_\infty S c)$
 C_P power coefficient, $\text{power}/(q_\infty S V_\infty) = C_L \dot{y} + C_M \dot{\alpha}$
 C_{P_I} ideal power coefficient, $P_I/(q_\infty S V_\infty)$
 C_{P_T} total power coefficient, $P_T/(q_\infty S V_\infty)$
 c chord length
 f oscillation frequency in Hz
 h plunge amplitude, in terms of c
 k reduced frequency, $2\pi f c/V_\infty$
 P_I ideal power, $16/27 P_T$
 P_T total power available, $q_\infty V_\infty A$
 q_∞ freestream dynamic pressure, $1/2 \rho_\infty V_\infty^2$
 S wing area
 t time

V_∞ freestream velocity
 x_p pivot location, in terms of c
 y plunge displacement, in terms of c
 α angle of attack (AOA)
 $\Delta\alpha$ sinusoidal pitch amplitude
 η_{P_D} efficiency based on drag, C_P/C_D
 η_{P_I} ideal efficiency, C_P/C_{P_I}
 η_{P_T} total efficiency, C_P/C_{P_T}
 ρ_∞ freestream density
 τ nondimensional time, tV_∞/c

INTRODUCTION

The phenomenon of wing flutter is well known to aeronautical and hydronautical engineers. If a wing is free to vibrate in both the pitch and plunge degrees of freedom, for example, then power may be transferred from the air or water stream to the wing, and explosive bending-torsion wing-flutter may occur. Oscillating wings therefore may be used to extract power. McKinney and DeLaurier (1981) performed wind-tunnel tests on an oscillating-wing windmill (which they termed *wingmill*) and claimed that the measured power-extraction efficiencies were competitive with those of some conventional windmill designs.

Numerical investigations using an unsteady panel code with a non-linear wake model were carried out by Jones and Platzer (1997) to compute thrust generation and power extraction for pitching and/or plunging airfoils. It was shown that thrust was generated for all pure plunging motions (in agreement with linear theory), and power was extracted for

combined pitch-plunge motions if the geometric pitch amplitude exceeded the maximum induced AOA due to the plunging motion for phase angles near 90 degrees. The dependence on pitch and plunge amplitudes, frequency, pitch axis and the phase angle between pitch and plunge were explored to some degree, but minimal effort was taken to determine optimal configurations and, as will be discussed in a later section, the performance criteria used there was more appropriate to thrust-generation investigations.

Little additional experimental or computational work seems to have been done to explore the more precise parameters governing the power-extraction capabilities of wing-mills. In particular, no direct comparisons of numerical and experimental results seem to have been performed, with the exception of linear theory. Additionally, no known experiments with a wingmill have been performed in water. The wingmill may offer several distinct advantages for power generation in water: a dam would not be required, minimizing the impediment to ship and fish traffic and avoiding the substantial infra-structural costs of a dam, they may easily function in relatively shallow water where a rotating propeller's diameter would be severely limited, they might easily be fitted between the pilings of existing bridges, and the flow of water in a river is typically more consistent than wind.

Therefore, in the present investigation the previously developed panel code is used to determine the parameter combinations which lead to optimum power-extraction from an air or water stream, and a model of an oscillating-wing power generator designed to be used in a low-speed water tunnel is described.

Unfortunately, due to an *act of God* involving a broken water main, the experimental facility was damaged, and experimental data could not be obtained in time to be useful here. The model was briefly tested prior to the flood, and the flutter condition was easily obtained. The model is illustrated here, and testing will begin in another facility in the near future.

APPROACH

A brief summary of the numerical and experimental approaches and a description of the configurations investigated in this study are included in the sections below.

Numerical Approach

Flow solutions are computed using an unsteady, potential-flow code originally developed by Teng (1987), with a Graphical User Interface (GUI) developed by Jones and Center (1996). The basic, steady panel code follows the approach of Hess and Smith (1966), where the airfoil is ap-

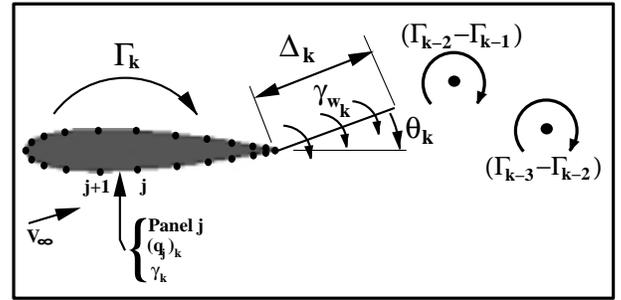


Figure 1. SCHEMATIC OF THE PANEL-CODE WAKE-MODEL.

proximated by a finite number of panels, each with a local, uniform, distributed source strength and all with a global, uniform, distributed vorticity strength. For n panels there are n unknown source strengths, q_j , and an unknown vorticity strength, γ . Boundary conditions include flow tangency at the midpoint of the n panels and the Kutta condition which postulates that the pressure on the upper and lower surfaces of the airfoil at the trailing edge must be equal.

The unsteady panel code adopts the procedure of Basu and Hancock (1978), where a wake panel is attached to the trailing edge through which vorticity is shed into the flow. The Helmholtz theorem states that the total vorticity in a flow remains constant, thus a change in circulation about the airfoil must result in the release of vorticity into the wake equal in magnitude and opposite in direction, given numerically by

$$\Delta_k (\gamma_w)_k + \Gamma_k = \Gamma_{k-1} \quad (1)$$

where Δ is the wake panel length, γ_w is the distributed vorticity strength on the wake panel and Γ is the circulation about the airfoil, and where the present and past time-steps are indicated by the subscripts $k, k-1$, etc.

The wake panel introduces two additional unknowns; the wake panel length and its orientation, θ_k , requiring two additional conditions for closure; the wake panel is oriented in the direction of the local resultant velocity at the panel midpoint, and the length of the wake panel is proportional to the magnitude of the local resultant velocity at the panel midpoint and the time-step size. The essential elements of this scheme are summarized in Fig. 1.

At the end of each time step the vorticity contained in the wake panel is concentrated into a point vortex which is shed into the wake and convected downstream with the flow, influencing and being influenced by the other shed vortices and the airfoil. Implementation of this approach requires an iterative scheme, since the velocity direction and magnitude used to define the wake panel are not initially known. Note that this deforming wake model is nonlinear.

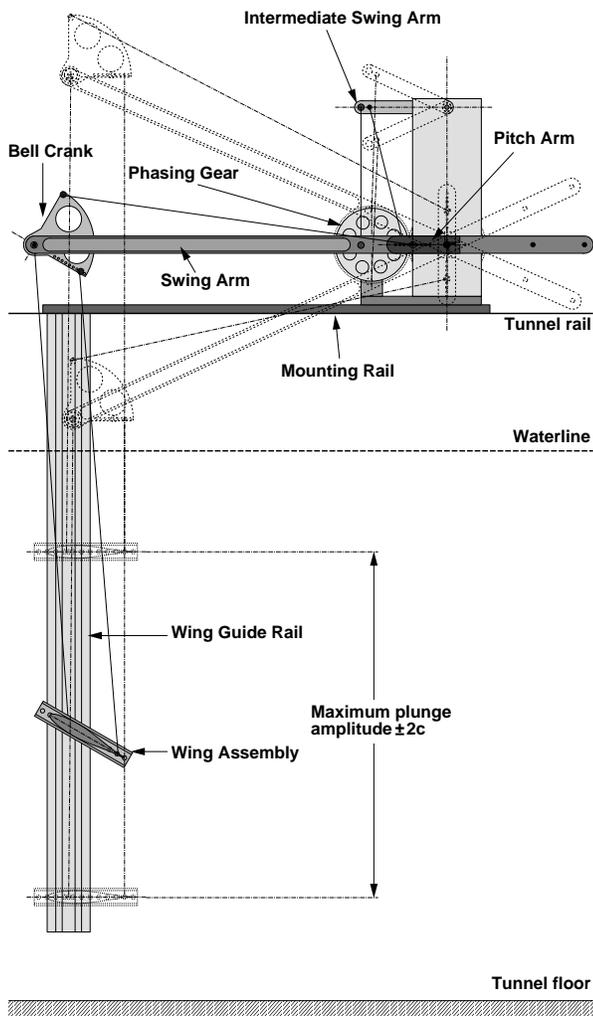


Figure 2. FLUTTER ENGINE - SIDE VIEW

Experimental Approach

An oscillating-wing flutter generator model was developed (Figs. 2 and 3) for testing in the Naval Postgraduate School water tunnel. The model was designed to span the tunnel, and provide plunge amplitudes of up to $\pm 125\text{mm}$ and pitch amplitudes of up to ± 65 degrees. The phase is variable, although not while in operation. This could be included using a differential gear setup, but this would increase the mechanical drag of the model substantially. The wing is a section of a model helicopter rotor blade with a 62mm chord length. The symmetric wing is approximately 14% thick, with the maximum thickness at about $0.35c$ and with a cusped trailing edge. The composite blade has a thin, very smooth graphite-epoxy skin over a light foam core. The wing has a span of 350mm , resulting in an aspect ratio of about 5.6 and a wing area of 0.0217m^2 .

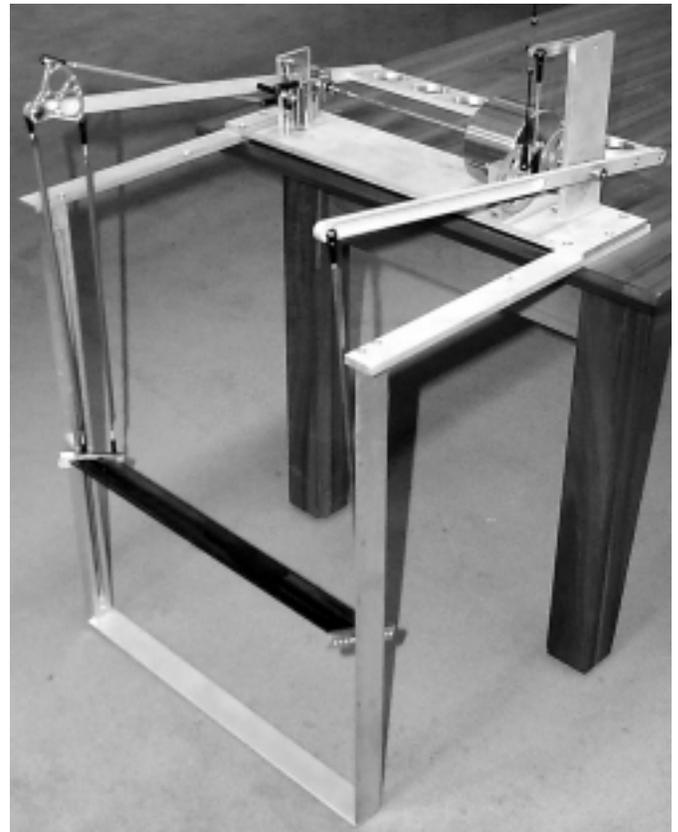


Figure 3. FLUTTER ENGINE - PHOTOGRAPH

The mechanism has two rails that extend vertically from the top to the bottom of the tunnel, flush with the side walls. These rails have grooves cut in them, and bearings attached to the wing slide up and down in these grooves guiding the plunge motion. Thin, airfoiled pushrods attach to the bearings on each side of the wing and couple to the swing-arms via ball-joints. As the wing plunges, the swing-arm is forced to rock. Through a series of linkages, the rocking swing-arm rotates a phasing gear which rotates a shaft driving the pitch-arm. A linkage from the pitch-arm drives the bell-crank back and forth, which in turn pitches the foil.

The model is designed to operate in the Naval Postgraduate School Eidetics water tunnel, a closed circuit, continuous flow facility with a contraction ratio of 6:1 and horizontal orientation. The test section is 38cm wide, 51cm high and 150cm long with glass side and bottom walls permitting optical access and an open top providing simple access to the model. The side walls of the test section diverge slightly to compensate for boundary-layer growth and to maintain uniform flow velocity. The facility has a maximum flow velocity of about 0.5 m/s .

As mentioned previously, the water-tunnel was recently damaged due to a flood, and could not be repaired in time to obtain data for this manuscript. However, a few days before the flood the model was briefly tested in the facility, and its operation was confirmed.

Equations of Motion and Performance

In the numerical model the airfoil is flapped sinusoidally, with the motion described by the equations

$$\alpha(\tau) = \Delta\alpha \sin(k\tau) \quad (2)$$

and

$$y(\tau) = h \sin(k\tau + \phi) . \quad (3)$$

Here τ is the nondimensional time, and k is the reduced frequency, and the motion is driven with a prescribed angular velocity.

While the experimental model does maintain a fairly rigid constraint on the pitch and plunge amplitudes and phasing, the experimental model will generally not have a fixed angular velocity due to the sinusoidal power-stroke. The motion of the experimental model is smoothed using a flywheel to even out the sinusoidal power-stroke, tuned springs that trade the kinetic energy of the reciprocating mass for potential energy to smooth out the top and bottom-dead-center points where the power is at a minimum and a spring *override* coupling that allows the plunge amplitude to under/over-shoot the prescribed value slightly, compensating for miss-tuning of the springs.

Performance is generally evaluated in terms of efficiency, however, there are several definitions of efficiency that may apply. In propulsion studies it is common to measure the efficiency as the ratio of the propulsive power obtained to the power put into the system. Following the same philosophy, for power extraction the efficiency should be the ratio of the mechanical power generated to the power actually extracted from the flow. This definition of efficiency maximizes the extracted power while minimizing the disturbance to the flow. This philosophy might be appropriate if a minimal disturbance to the flow is desired, or if a series of generators is used (like a multi-stage compressor), each extracting a relatively small percentage of the energy remaining in the flow.

However, the usual philosophy taken in power-generation studies is that the efficiency should be the ratio of the mechanical power extracted from the flow, to the total power flowing into the control volume, η_{P_T} . Thus, a perfect generator would leave the downstream flow completely stagnant. The power flowing into the control volume is proportional to the area swept out by the airfoil, and this

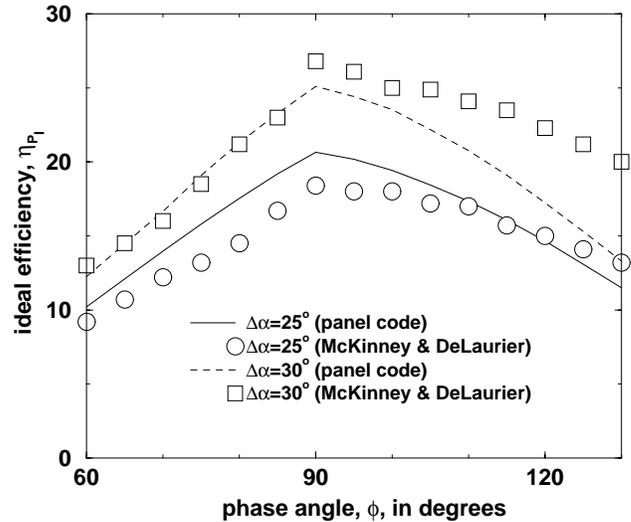


Figure 4. PANEL CODE VERSUS EXPERIMENT

area is determined either by the leading or trailing edge, depending on the various motion parameters.

Actuator disc theory predicts that at most 16/27 of the power flowing through the control volume can be extracted (Johnson, 1985). The coefficient, 16/27, is referred to as the *Betz coefficient*, and McKinney and DeLaurier define a further efficiency, based on this coefficient, as the ratio of the power extracted to the ideal power available, η_{P_I} .

Unless otherwise noted, efficiencies plotted in the results are the total efficiency, η_{P_T} .

RESULTS

Numerical predictions by the described panel code are first compared to the experimental measurements of McKinney and DeLaurier in Fig. 4. The conditions of the experiment were duplicated by the panel code for two curves, one with an AOA range of ± 25 degrees, and one with an AOA range of ± 30 degrees, Figs. 13 and 14 in McKinney and DeLaurier (1981), respectively. The panel code over-predicts the measured values slightly at the lower AOA, as expected, due to flow separation, three-dimensionality and mechanical losses affecting the experiment, which are not included in the numerical simulation. Interestingly, the panel code under-predicts the measured values at the higher AOA, particularly at the higher phase angles, but is in better agreement with the linear theory data in McKinney and DeLaurier's report.

Next, the panel code is used to explore the rather large parameter space in search of local and/or global optima. The panel code does not model flow-separation, so effective

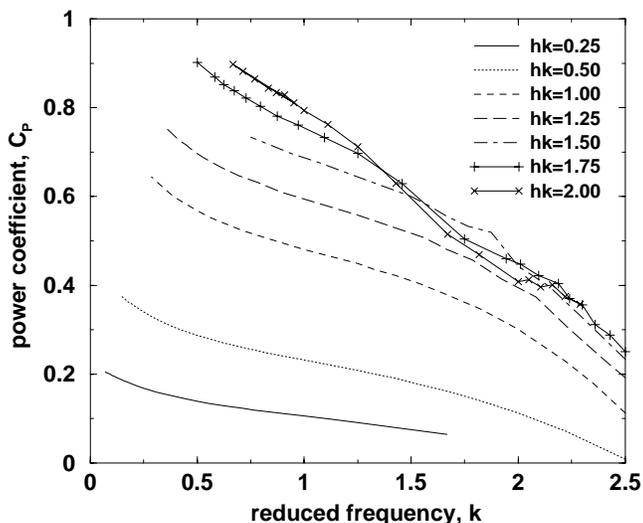


Figure 5. POWER COEFFICIENT VERSUS REDUCED FREQUENCY

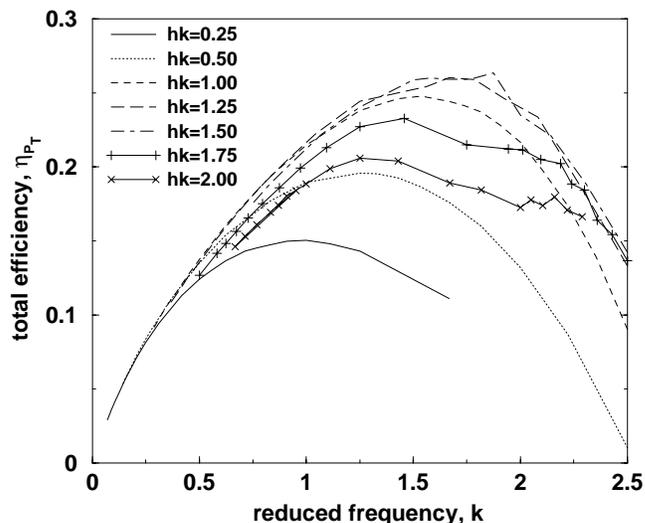


Figure 6. EFFICIENCY VERSUS REDUCED FREQUENCY

angles of attack are limited to 15 degrees for the data presented in Figs. 5, 6 and 7. McKinney and DeLaurier's experiments went to effective angles exceeding 25 degrees, but they noted rather significant hysteresis loops in their experimental measurements in these cases, which they attributed to dynamic-stall effects. In Figs. 5, 6 and 7 $x_p = 0.5$ and $\phi = 90$ degrees.

In Fig. 5 the effect of reduced frequency and the product hk , a measure of the Strouhal number, on the power coefficient is shown. Note, hk is the maximum non-dimensional plunge velocity, such that the maximum induced AOA due to plunge is $\arctan(hk)$. Higher power output is obtained for lower reduced frequencies and higher Strouhal numbers. McKinney and DeLaurier used reduced frequencies in the range $0.5 < k < 0.8$, and plunge velocities in the range $0.15 < hk < 0.25$, which are at the bottom end of this scale. It is apparent that maximum power output occurs for k approaching 0, thus driving the plunge amplitude to infinity.

A large plunge amplitude has a detrimental effect on the efficiency, however, as seen in Fig. 6, where the efficiency is plotted as a function of k and hk . A maximum efficiency is indicated for $k \approx 1.5$ and $hk \approx 1.5$. The panel code predicts efficiencies more than 50% greater than McKinney and DeLaurier's measurements for hk values 6 to 10 times greater than they tested. Note, for the optimal reduced frequency, this required plunge amplitudes of \pm a full chord length or more, which was apparently not mechanically feasible in their model, as all their results used $h = 0.3$. For the small plunge amplitude they investigated, they appear to have operated at near optimal reduced frequencies, as indicated

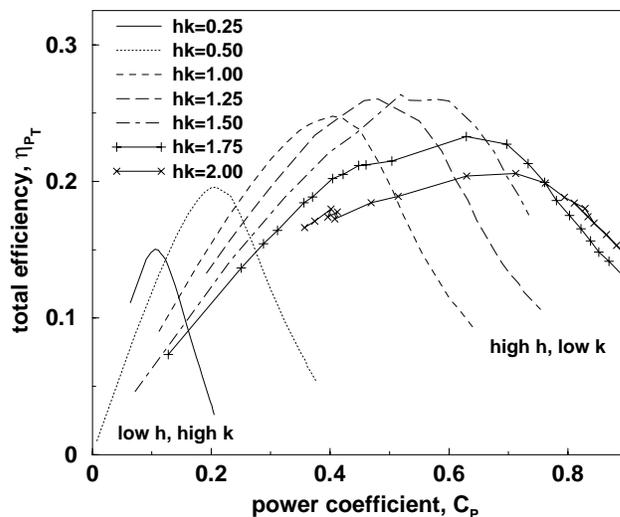


Figure 7. EFFICIENCY VERSUS POWER COEFFICIENT

in the curve for $hk = 0.25$ ($h = 0.3$ and $k = 0.83$) in Fig. 6.

In Fig. 7 the effect of hk on both the efficiency and the power coefficient is plotted. The irregularity of the panel-code results at high values of hk , especially at higher values of k , are due to extreme non-linearities in the wake which induce non-periodic wake structures.

The panel method is very nearly a linear solution at these relatively low reduced frequencies. Consequently, it predicts essentially a linear increase in the power coefficient with increasing effective AOA. Clearly, at sufficiently high AOA the flow will separate over part of the cycle, and the

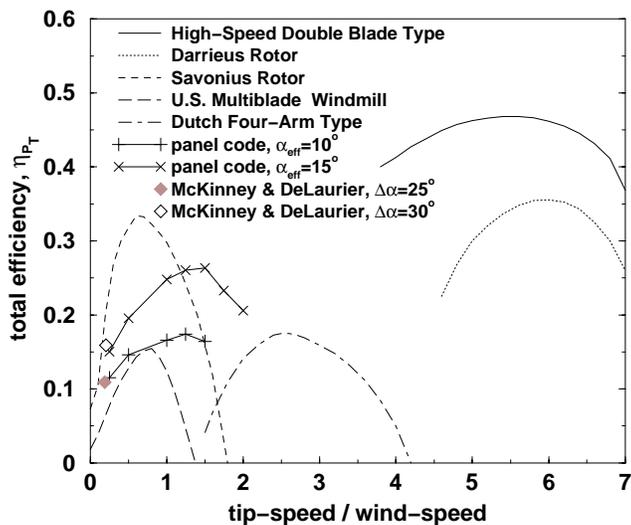


Figure 8. TYPICAL WINDMILL EFFICIENCIES (Cheremisinoff 1978).

performance will suffer. The panel code is of little use in predicting this, but dye-injection in the water tunnel will allow some indication of this in future experimental investigations with the described apparatus.

Typical efficiencies of various windmill types were reported by Cheremisinoff (1978), as shown in Fig. 8, with the efficiency plotted as a function of tip-speed. For a wingmill the tip-speed is oscillatory, but using the maximum plunge velocity as the tip speed, the maximum values from the two curves shown in Fig. 4 from McKinney and DeLaurier are included in Fig. 8, as well as data from the panel code for effective angles of attack of 10 and 15 degrees.

McKinney and DeLaurier's *wingmill* operates at exceptionally low tip-speeds ($0.15 < hk < 0.25$), and appears to be competitive with the U.S. multi-bladed windmills (commonly found on farms in the U.S. to pump water out of the ground) and the Dutch four-arm type windmill (classically used to grind flour). The other three windmill types are reported to have efficiencies 2 to 3 times greater than McKinney and DeLaurier's. Their model was small, and they suggested that problems of scale may have led to lower efficiencies. The panel code results indicate that considerably greater efficiencies are possible for higher plunge amplitudes and reduced frequencies. Future experiments will test this.

CONCLUSIONS

An unsteady panel method was described for the performance analysis of a flutter generator. Numerical predictions of the panel code were directly compared to the experimental measurements of McKinney and DeLaurier's wingmill.

Good agreement was found at lower angles of attack and flow speeds, but the numerical results under-predicted the experimental measurements for the higher angles of attack and flow speeds.

For a given maximum effective angle of attack there was an optimal plunge velocity, and an optimal ratio of h and k . The optimal plunge velocity increased with increasing effective angle of attack, operating at both higher frequencies and higher plunge amplitudes. For a maximum effective angle of attack of 15 degrees, an efficiency of 0.26 and a power coefficient of 0.58 was predicted at a reduced frequency of 1.6 and a plunge amplitude of 0.95.

An experimental wingmill was designed and built for operation in a low-speed water tunnel, and preliminary tests have confirmed its function in flows as low as $0.3m/s$. The model will be used in the future to investigate the accuracy of the panel code, and to explore the parameter space for optimal performance.

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