THE DESIGN INSTRUMENTATION AND USE OF LINEAR ORIFICES TO SIMULATE THE PERFORMANCE OF WELLS TURBINES.

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An orifice damper with a linear relationship between flow rate and induced pressure drop has been constructed to simulate the constant speed operation of a Wells turbine. The damper consists of a rotor with constant thickness unprofiled blades mounted on the shaft of a d.c. motor with speed control. The results obtained were in excellent agreement with predictions from a one dimensional momentum analysis, and were shown to agree with measured data from Wells turbine tests.

INTRODUCTION

In the modelling of small scale fluid systems it is often necessary to simulate the effect of a turbine on the system. It is not possible to use a similarly scaled turbine due to the relatively high mechanical inertia and the unrepresentative performance which is due to Reynolds number effects. A conventional turbine, Francis or Kaplan for example [1], in which the available energy is converted into kinetic energy and thence to a change in circumferential momentum can be adequately simulated by an orifice plate. The Wells turbine [2], however, exhibits a linear relationship between flow and pressure drop when operating at a constant speed and therefore requires a linear orifice. The most common device to exhibit linear characteristics is one utilising laminar flow. However, such a device would be impractical due to size and the problems of clogging.

Early tests on models of a wave energy device utilised two classes of linear damper. At 1/57th scale a flexible diaphragm with narrow slots cut along several diameters [3] was used, whereas at 1/11th scale a spring controlled variable area orifice permitted a larger dissipation of air power [3]. Despite their successful operation they had one major drawback which was that each damper had only one damping rate, and any system optimisation involving a change in damping rate would require a change of damper.

For subsequent tests [4] a linear damper with a variable characteristic was developed utilising a slotted disk attached to a d.c. motor with speed control. The pressure-flow characteristics obtained are in excellent agreement with results obtained from Wells turbine tests, and demonstrate the accuracy of the simulation.

As well as simulating the performance of the Wells turbine the linear dampers can be used as gas flow measuring instruments with the rotating damper especially being capable of accurate use in varying or reversing flows. As the pressure drop is linearly related to the flow then very little signal processing is required to convert the measured pressure drop across the device into a flow rate.

CONCEPT

The Wells turbine rotor has a number of blades with a symmetric aerofoil section and no camber which are arranged with their chords in the plane of rotation (90 degree stagger angle), and which can operate in the absence of guide vanes. A resolution of forces shows that a net unidirectional circumferential force results from air flow in either axial direction [2]. Two factors suggested simulating this turbine using a set of unprofiled blades driven by a variable speed d.c. motor. Firstly very little aerodynamic torque would be produced by the blades which had a constant thickness over their chord, (ie flat plates), which would imply that a small d.c. motor with a suitable control circuit could maintain a constant speed in a varying flow, or could be controlled to operate with a varying speed throughout a flow cycle and so mimic the performance of a low inertia turbogenerator. Secondly is the observation [2,5] that the linear relationship between flow and induced pressure drop at a constant rotational speed holds after the rotor has stalled, which suggests that the streamlined properties of the aerofoil in delaying stall and minimising the coefficient of drag are not significant in ensuring the linear damping characteristic.

By approximating a rotor blade to a smooth flat plate in an ideal fluid, figure 1, it is posssible to perform a one dimensional momentum analysis which demonstrates the linearity of the variation of the induced pressure drop with flow.

One dimensional momentum considerations give the forces on the plate when surrounded by a uniform pressure field as:

$$Fz = \dot{m}_1 V_1 \sin i$$

$$F_\theta = \dot{m}_3 V_3 - \dot{m}_2 V_2 - \dot{m}_1 V_1 \cos i$$

The force F_θ which is parallel to the surface of the plate can only be sustained by a shear force which is not possible in an ideal fluid, hence $F_\theta = 0$.

By a resolution of forces

$$CL \propto F_\theta \sin i + Fz \cos i = K_1 Fz \cos i$$

$$CD \propto Fz \sin i - F_\theta \cos i = K_1 Fz \sin i$$

substituting for Fz gives:

$$CL = K_2 \sin i . \cos i$$

$$CD = K_2 \sin^2 i$$

The induced oressure drop, ΔP, is proportional to Fz (which is proportional to CL cos i + CD sin i) therefore:

$$\Delta P \propto \sin i.$$

Figure 2 shows sin i plotted against i which indicates that a linear relationship can be expected upto an incidence value of between 30 and 40 degrees. The excellent comparison between the above prediction and the measured results is discussed in the performance section.

The rotating damper constructed was to be flange mounted, for ease of rotor changing, and figure 3 shows the arrangement drawing and general construction details. Full detail drawings are given in [6]. The rotor is mounted directly onto the shaft of a d.c. motor which is fitted with ball bearings, and is capable of sustained speeds of upto 11 000 rev/min. The opto sensor for detecting the rotor speed is mounted on a bracket fixed to the end of the motor, and the signal leads are taken out through one of the supporting struts. Self adhesive reflective tape for use in conjunction with the opto sensor is fixed to the rotor.

INSTRUMENTATION

In our application, the rotating damper and its control electronics is housed in close proximity onboard a floating test rig. Remote operation at distances of up to 100 m is typical.

Control of the d.c. motor driving the rotating damper is implemented using the circuit shown in figure 4. In essence, an onshore buffered voltage representing demanded rotating damper speed is sent to the speed controller. The speed of the d.c. motor is ascertained using an infra red source and sensor housed in the nacelle of the rotor in conjunction with small reflective strips on the rotor disk. Feedback in the circuit is sufficient to maintain a required motor speed with the fluctuating air flows encountered, and a feedback signal is also provided onshore to confirm demanded rev/min. The circuit is equally applicable to laboratory rigs where, for example, gas flow measurement is envisaged.

PERFORMANCE

To accommodate the damping rates required a rotating damper with a tip diameter of 0.108 m and a hub to tip ratio of 0.6 was constructed as detailed in [6]. A series of rotors were tested over a range of speeds from 5 000 to 11 000 rev/min. The lower speed of 5 000 rev/min being selected to ensure that the angle of incidence remained below 30-40 degrees.

A unidirectional air flow test rig was constructed using an orifice plate, which was constructed and installed to BS 1042, to measure the rate of flow before it passed through the rotating damper. The justification for testing in unidirectional air flow and applying the results to an oscillating, reversing flow is based on the results obtained by Sea-Lanchester which demonstrated that the behaviour of a Wells turbine in oscillating flow could be predicted from results obtained in steady flow using a quasi-static approach [2], and on the work done by the Queen's University of Belfast [7] which shows very good agreement between the rms pressure coefficient for flow oscillations of 0 Hz upto 1 Hz for Reynolds numbers of 10^5 and rms flow coefficients of 0.08 which are comparable with the values experienced by the rotating damper unit under operational conditions.

Figure 5 shows a specimen set of results which exhibit the required linear characteristic and the onset of non linearity which begins when the incidence angle at mid blade span is 37 degrees, a value which agrees with that predicted.

When the results are plotted non dimensionally, figure 6, the linear characteristic is still visible, and the trend of increased damper stiffness with increase in solidity is apparent. By suitable choice of speed and rotor, damping rates in the range of 0.33×10^{-4} to 2.2×10^{-6} m^5/Ns could be achieved which would correspond to a maximum instantaneous air power of 260 w.

The reduction of the data using dimensional analysis techniques is shown on figure 6, however, there is still a dependence on solidity. Evaluation of the induced pressure drop [6] shows how a correlation of the form :

$$\frac{\Delta P}{\rho N^2 Dt^2} = K.\frac{Q}{NDt^3} \quad (Sa)^n$$

was found to hold.

Figure 7 shows that all the rotating damper information can be represented by this relationship. To further check the validity of using the rotating damper to simulate Wells turbine behaviour, the available performance data for Wells turbines tested by Sea-Lanchester and the CEGB have also been plotted on figure 7, and the agreement is excellent.

CONCLUSIONS

A Wells turbine simulator based on a rotating disk with constant thickness, unprofiled blades has been constructed and tested. The results obtained are in excellent agreement with the effects predicted from a one dimensional momentum analysis and the observed performance of a Wells turbine beyond stall. Furthermore the results can be non dimensionalised, collapsed onto a single curve, and then shown to be in very good agreement with Wells turbine performance data.

The damper described has been successfully used at Loch Ness in optimising the performance of a model wave energy device (SEA CLAM) [4], and with the two passive devices previously described [3] could form the basis of a gas flow measuring system which can be used in reversing or fluctuating flows having an output which required a minimuum of data processing.

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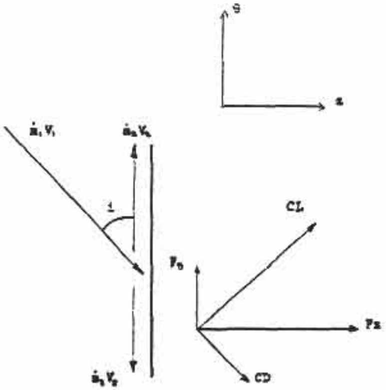
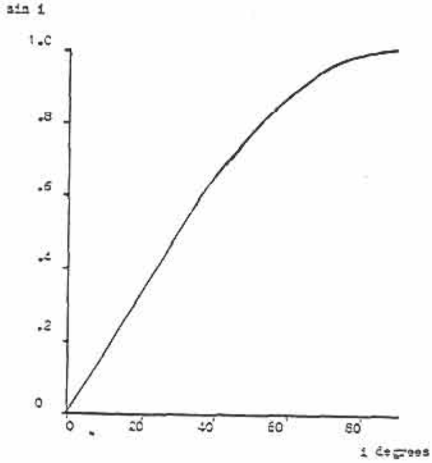


F_θ circumferential force on plate
Fz axial force on plate
CL plate coefficient of lift
CD plate coefficient of drag
V velocity
$\dot{m}$ mass flow

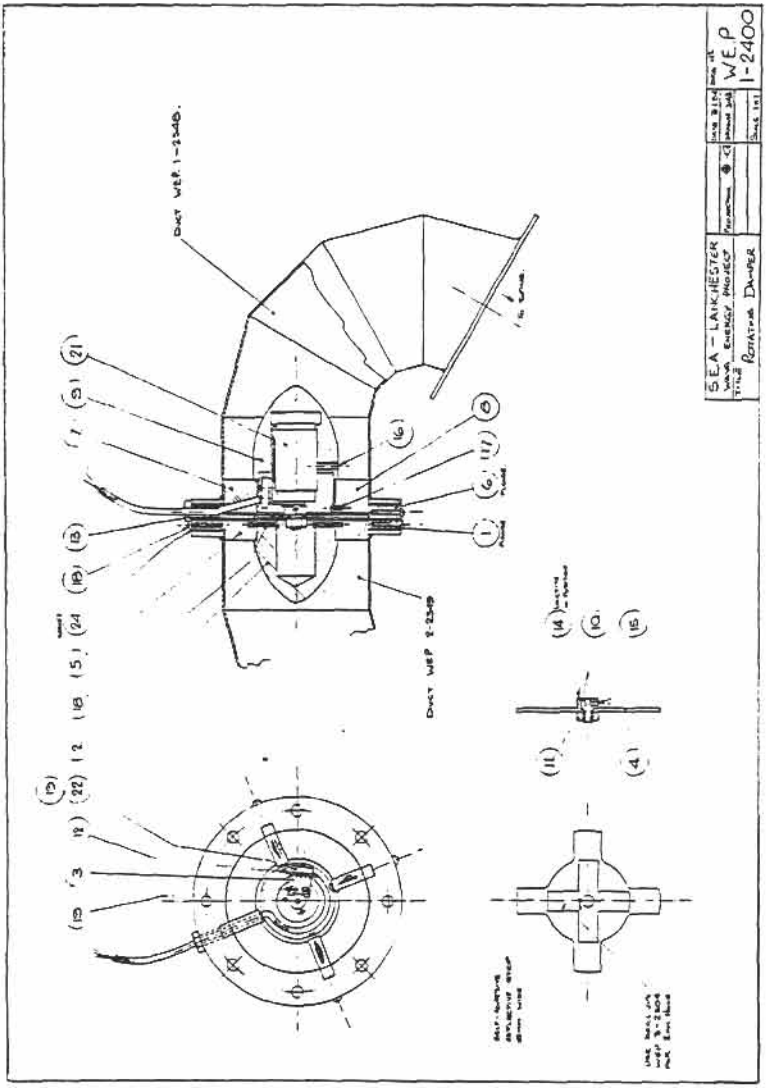
Smooth flat plate in an ideal fluid

Figure 1



sin i versus i

Figure 2



Rotating damper - assembly drawing

Figure 3

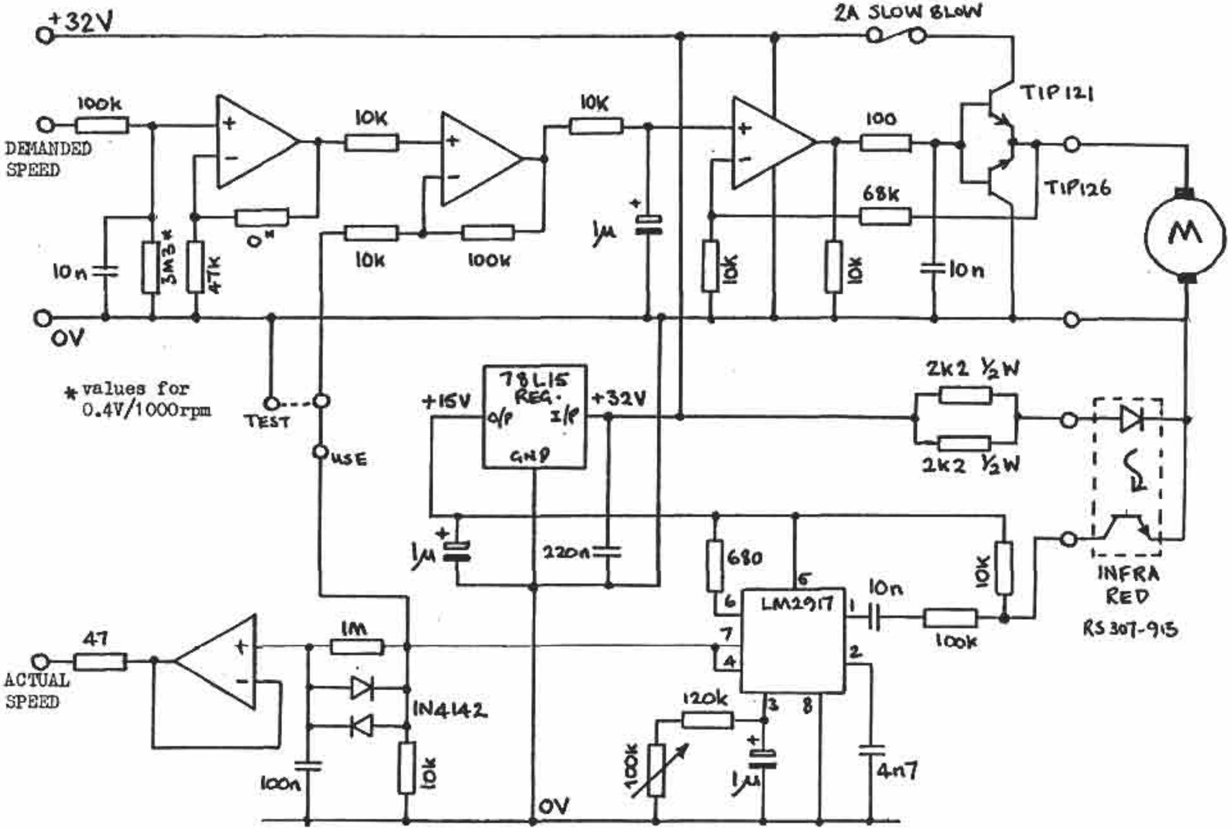
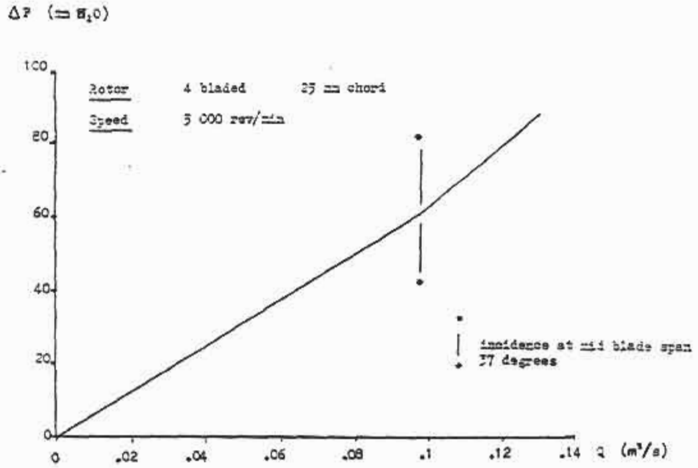
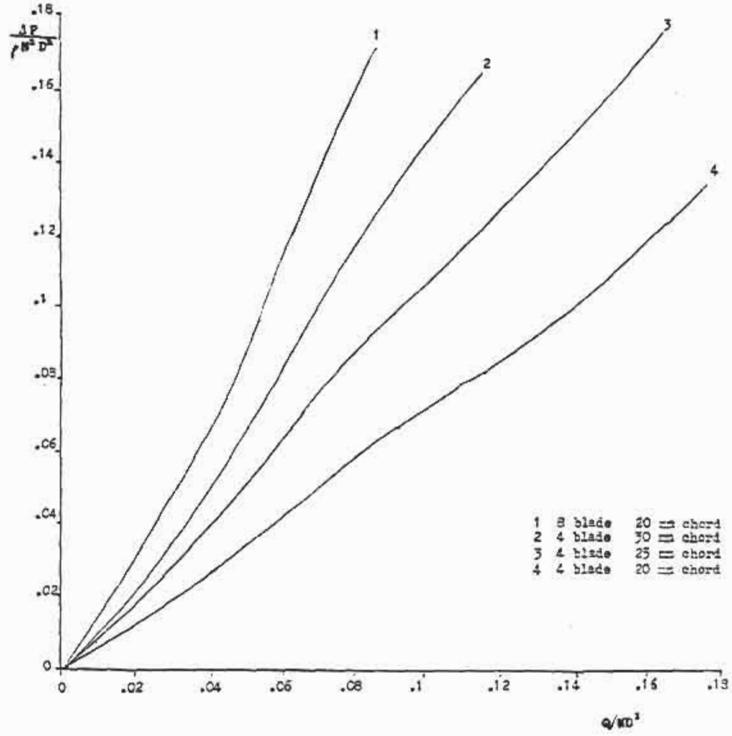

+32V
2A SLOW BLOW
TIP121
TIP126
100k
DEMANDED SPEED
10K
10K
100
68k
0"
10n
3M3*
47K
10k
100K
1μ
10K
10K
10n
M
0V
* values for 0.4V/1000rpm
TEST
USE
+15V
78L15 REG.
O/P
I/P
GND
+32V
2K2 ½W
2K2 ½W
1μ
220n
680
LM2917
5
6
1
10n
10K
100k
7
4
2
3
8
INFRA RED
RS 307-915
47
ACTUAL SPEED
1M
IN4142
100n
10k
0V
120k
100k
1μ
4n7

Figure 4



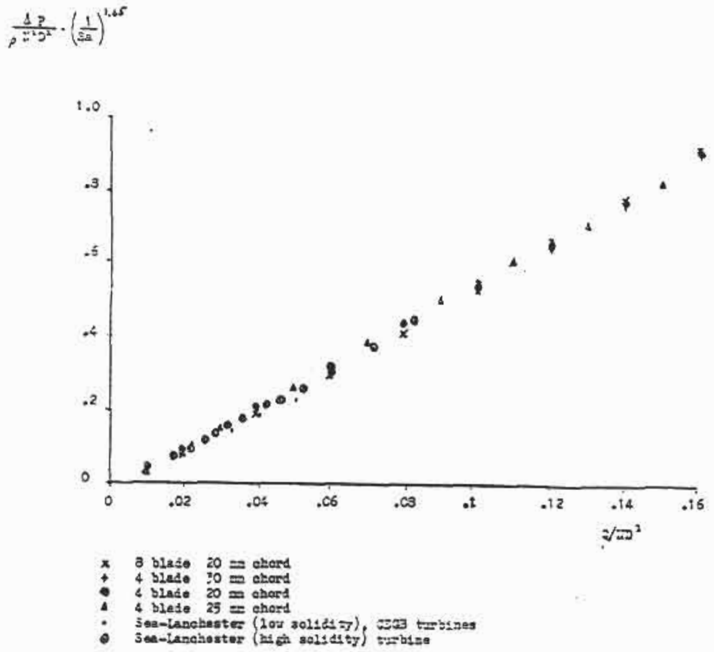
Rotating damper specimen results

Figure 5



Rotating damper non dimensional results

Figure 6



Rotating damper and Wells turbine comparison

Figure 7

ACKNOWLEDGEMENT

The authors are grateful to the Department of Energy and Sea Energy Associates Ltd. for their support, and to Coventry (Lanchester) Polytecnic for providing additional facilities.