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ABSTRACT

The paper outlines recent development of the Clam wave energy converter and gives details of computer simulation of the turbogenerator power take-off system using data from scale model tests. The results provide information for plant optimization and parameter sensitivity, and indicate the likely character of the electrical output for integration studies.

KEYWORDS

Wave energy, Clam device, power take-off simulation, electrical integration.

INTRODUCTION

The Clam wave energy converter has been under development by a team at Coventry (Lanchester) Polytechnic for the past six years and is now one of the few devices which show enough promise to merit continued Government and industrial support within the now much reduced British wave energy research programme. With the loss of official interest in large scale generating stations, attention is now being focused on smaller devices for power supply to isolated seaboard communities.

The device consists of partially submerged and inflated flexible air bags mounted on a rigid floating spine. Differential wave action along the spine causes the bags to pump air into and out of a common reservoir within the spine in closed system. Each bag is separately connected to the spine by a duct housing a turbogenerator. The turbines are of the Wells design which rotate in the same sense whatever the direction of the air flow, coupled directly to generators.

Current research is concentrated on a device featuring a hollow spine typically 100m long, 9m high, fitted with 8 bags and capable of producing up to 500kw of electricity. The work aims to identify a design for a full scale demonstration prototype whose construction will be the next phase of development (Peatfield and colleagues, 1983).

EXPERIMENTAL TESTS

Previous work on the 2GW scheme Clam device involved 1/50th scale experiments in the Cadnam wave tank to determine performance in 46 defined test seas as well as testing of a 1/10th scale model, some 29m long, at the team's Loch Ness test site. With the change in objective to a smaller device working in much the same high power seas, 1/14th scale was chosen for experiments at Loch Ness, to ease construction, launching and testing.

Tests began in November 1983 to determine device performance in a wide range of sea states and its sensitivity to spine length, height and the number of bags. The models, up to 9m long, were constructed around a steel spine duct with plywood cladding and have corded latex bags of a design similar to that proposed for full scale. The fabricated steel bag-to-spine ducts house purpose built rotating dampers whose flat-bladed rotors may be driven at arbitrary speed and act as very inefficient Wells turbines, providing the linear (pressure drop proportional to flow rate) characteristic of the real thing. By varying the rotor speeds from shore, tests at various damping rates can be easily conducted to optimize this key parameter. The pressure drop across each damper is measured and from known calibrations the flow rate and hence airpower dissipated is deduced. Routinely, 32 channels of data are sampled at 5Hz for 358.4 seconds and stored digitally on disc for subsequent analysis. Fig. 1 shows a model prepared for launch and later on test.

POWER TAKE-OFF SIMULATION

The Clam bag converts wave power to airpower, the turbine airpower to mechanical shaftpower and the generator finally gives electrical output power. To complement the experimental work and complete the picture of Clam performance, digital simulation of the power take-off system has been carried out to determine sensitivity to design parameters, its mean efficiency in given seas and the character of the total output for integration studies.

The computer simulations use airpower data measured at the dampers of the experimental models which have the characteristics of the Wells turbine run at constant speed. The computations are done for all Clams on the spine simultaneously, in order to calculate the variation and statistics of total output. Provided the simulations show rotor speeds not varying greatly from the speed chosen for the turbogenerators, then the assumption that the airpower signals remain invariant is a good approximation and the simulations give a valid picture of full scale performance.

For the most part the work has focused on a system using induction generators coupled directly to the turbines. The characteristic of these machines is a strong restoring torque acting to maintain the rotor at a fixed so-called "synchronous" speed, the torque maximizing at between 5% and 15% overspeed. Any other generator system which keeps turbine speeds near constant could be simulated with constant damping test data in this way. On the other hand, gross variations in speed would affect the damping rate and hence hydrodynamic performance, calling for simulation during model tests with interactive prescription of damping rates determined from the computed performance of real turbogenerators. The rotating dampers in the current Loch Ness models were designed with this work in mind, work which will be undertaken if the power take-off systems which emerge as desirable give wide variation in turbine speed.

The Wells Turbine

For these performance calculations, the Wells turbine is adequately characterized by the following parameters:

Design airpower = DAP watts

Design speed = ω_d rads/sec

Design damping characteristic = $\mathcal{E}_d$ $m^3/s/pa$ and

Efficiency = η , a function of instantaneous speed and airpower.

These terms mean that the turbine achieves maximum efficiency in steady flow Q_d with pressure drop Δp_d running at speed ω_d, where DAP=$Q_d . \Delta p_d$ and $\mathcal{E}_d = Q_d/\Delta p_d$. Efficiency at other speeds and power levels is then given in Fig. 2. The design point is not unique, but in conjunction with an induction generator it simplifies matters to take ω_d as the synchronous speed of the generator. The damping characteristic $\mathcal{E}$, which is inversely proportional to the speed, influences hydrodynamic performance of the bag and this relationship is being determined from the model tests.

The value of DAP affects performance of the turbine at all other airpower levels and its optimum value (for a given Clam unit on a given design of spine) is dependent upon the scatter diagram of the resource (as perceived as airpower captured by the bag) and the value to the consumer of the power produced. Fig. 3 shows mean turbine efficiency $\bar{\eta}$ running at design speed in Normally distributed flows, computed readily from η, and at varying speed in experimental data flows computed during the simulations. From performance estimates for the scatter diagram of the site chosen we may then determine the mean annual efficiency $\bar{\bar{\eta}}$ of the turbine. Typically, annual energy captured is a maximum when DAP is approximately 3 times the mean annual airpower; as DAP is reduced output regularity improves but with $\bar{\bar{\eta}}$ decreasing from a peak of around 70%.

Rotor Dynamics

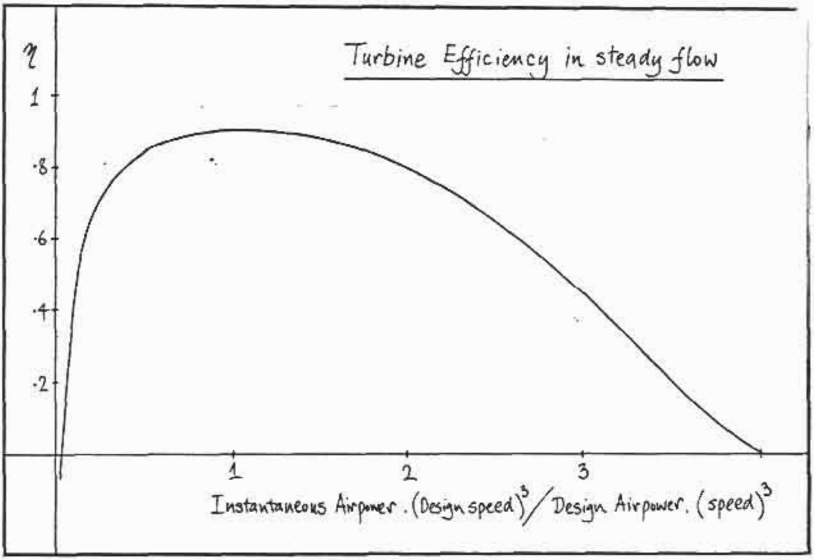
The basis for the simulation is the solution of the equation of motion of the turbogenerator rotors:

$$d/dt(J\omega^2/2) = \text{airpower} \times \text{instantaneous turbine efficiency} - \text{generator mechanical load power}$$

where J is the turbogenerator moment of inertia (kgm^2).

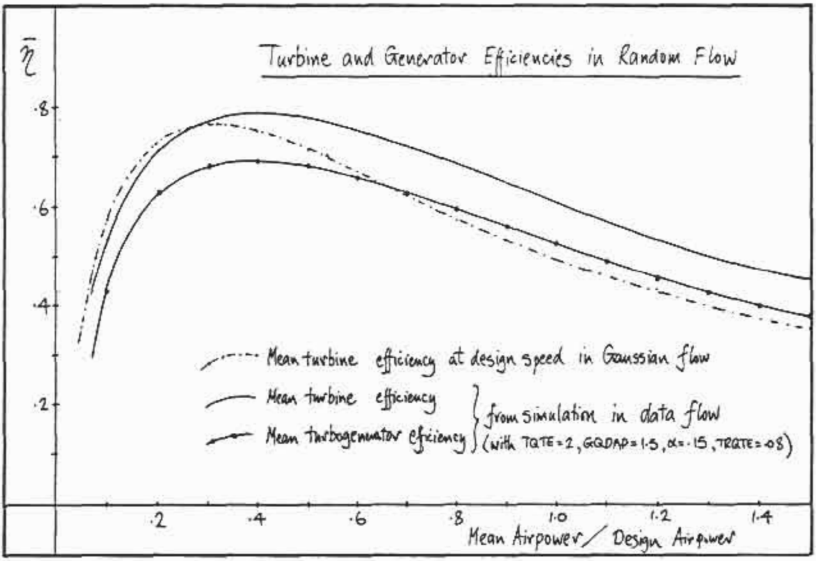
To model the continually transient magnetic conditions within the generator, the mechanical load it provides is here assumed to satisfy a first order lag equation with time constant τ, following the steady state load which, for an induction generator, is a function of its speed and design parameters.

In order to provide comprehensive information applicable to Clam (or generically similar) systems of any size and rating in any wave climate, the defining equations and results have all been expressed in terms of various dimensionless parameters which describe the power take-off plant and airpower resource. The most significant among these are:



Turbine Efficiency in steady flow
η
1
·8
·6
·4
·2
1
2
3
Instantaneous Airpower . (Design speed)³ / Design Airpower . (speed)³

Fig. 2



Turbine and Generator Efficiencies in Random Flow
η̄
·8
·6
·4
·2
Mean turbine efficiency at design speed in Gaussian flow
Mean turbine efficiency
Mean turbogenerator efficiency
from simulation in data flow
(with TQTE = 2, GQDAP = 1·5, α = ·15, TRQTE = ·08)
·2
·4
·6
·8
1·0
1·2
1·4
Mean Airpower / Design Airpower

Fig. 3

$$TQTE = \frac{\text{Rotor inertia time constant}}{\text{Energy Period of Airpower signal}} = \frac{J.\omega_A^2}{DAP.T_E}$$

$$GQDAP = \frac{\text{Generator maximum power}}{DAP} = (\text{approx.}) \frac{2.5 \times \text{Generator rating}}{DAP}$$

α = Generator slip (=fractional overspeed) at maximum torque

$$TRQTE = \frac{\text{Generator magnetization time constant } \tau}{T_E}$$

$$MQDAP = \frac{\text{Mean airpower of test data}}{DAP}$$

Other generator parameters enter the output calculations (and hence affect its efficiency) but dynamic response is insensitive to these and is adequately described by α, τ and the machine rating. The spectral distribution of the airpower signal, for given energy period T_E, also has little affect on the results for the variations observed. The model test signals show spectra well fitted by a Pierson-Moskowitz type of distribution with index 6 rather than index 4, usually assumed for wave height in fully developed seas.

Simulation Results

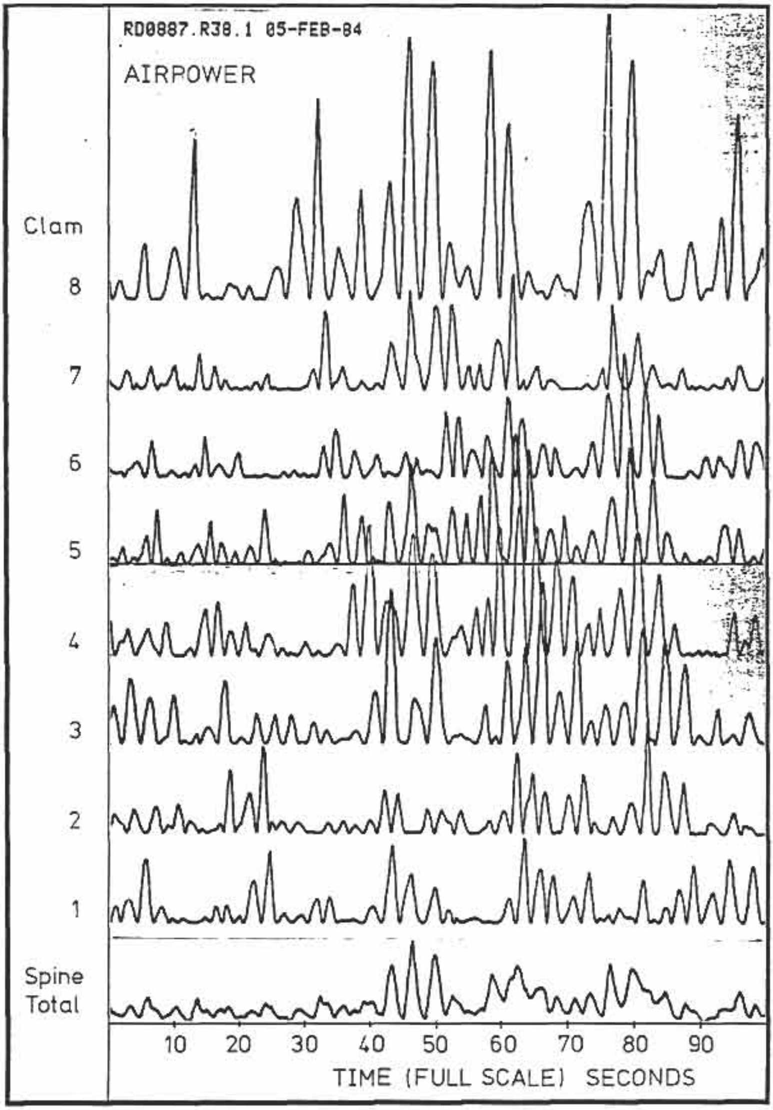
The airpower data used for the results presented here were recorded at Loch Ness in February 1984 during a test of a 1/14th scale model of an 8 bag, 80m long, 7m high device. The time traces shown cover a representative section equivalent to 100 seconds at full scale, the whole test, equivalent to 1341 seconds, was used for all statistical calculations. Fig. 4. shows the airpower signals used to "drive" the simulations. Full scale equivalent mean values for the whole test were:

Clam	1	2	3	4	5	6	7	8	average
kw	19.0	20.4	36.2	39.8	30.0	24.9	22.5	63.1	32.0

which represents roughly average annual performance for the model tested. The power distribution and spectral spread of the data were very similar in other sea states, so for the simulations other airpower levels were generated from the same data by multiplying throughout by the same factor. A feature worth pointing out is an interval of wave activity running down the spine (which was moored at an angle of about 40 degrees to the principal wave direction) starting at time 27 sec. at Clam 8 and reaching Clam 1 at time 42 sec., followed immediately by a period of about 10 seconds (1.5 waves) during which spine breathing was particularly monochromatic, displayed clearly in the spine total trace.

The format of the rest of the diagrams is the same. Each shows results computed from the airpower data for various parameter choices, Clam 5 was chosen as it usually displays average response. The time traces are:

(i) Clam 5 Rotor speed (normalized by the induction generator synchronous speed)



RD0887.R38.1 05-FEB-84
AIRPOWER
Clam
8
7
6
5
4
3
2
1
Spine
Total
10
20
30
40
50
60
70
80
90
TIME (FULL SCALE) SECONDS

Fig. 4

(ii) Clam 5 Airpower (data)

(iii) Clam 5 Shaftpower (the turbine output power)

(iv) Clam 5 Output power (the electrical output from the generator)

(v) Spine total Output power.

All power values are expressed as multiples of DAP, the design airpower of the turbine.

Figs. 5-10 show the effects of varying mean airpower, rotor inertia and generator "stiffness". Each diagram was obtained by changing just one of the parameters MQDAP, TQTE and α from the base case of Fig. 5 which has TQTE=2.0, MQDAP=0.5, GQDAP=1.5, α=.15 and TRQTE=.08.

The maximum mean airpower encountered through the year is approximately 3 times the annual mean, so choosing the turbine DAP to be 3 or 4 times the annual mean, the working range for MQDAP is from 0 to 1 (possibly more if Clam 8, more energetic than average, has plant identical to the rest). At the higher airpower levels energy is cast off by the turbine as flowrate increases beyond stall at the rotor blades. Fig. 6 shows a succession of double peaks on the shaftpower trace at around 60 seconds corresponding to the high single peaks of the airpower trace. In these circumstances the entire efficiency curve of Fig. 2 is traversed back and forth twice per wave.

Figs. 7, 5 and 8 show the benefits of increasing rotor inertia. Indeed the lightest case (TQTE=0.5) shows unacceptable periods of overspeed, even at moderate airpower levels, running up to 1.76 during the whole test with correspondingly low generator efficiency. Deficiency in inertia and consequent overspeed can be offset to some extent by using a more powerful generator but this increases the effective stiffness and hence the variability of the output.

The fluctuations in turbine speed in sympathy with airpower pulses, more marked at low inertias, increase mean turbine efficiency but at the expense of generator efficiency. Calculations for the whole test show a net benefit as inertia increases, mean turbine efficiency tending to approximately 74% as inertia tends to infinity, in close agreement with the efficiencies computed for Gaussian flows at constant speed shown in Fig. 3.

For low values of slip (the fractional overspeed), the torque from an induction generator is approximately proportional to the slip. Fig. 9 illustrates a "stiff" generator with α=.05, the torque and output varying sharply as the rotor speed fluctuates. Fig. 5 corresponds to α=.15, most commercial machines falling within this range. Fig. 10 indicates what can be expected from an alternator-DC system with a "ramp" control strategy as proposed for the 2GW Clam scheme (Lockett and Raabe, 1982), in which output increases linearly with speed from zero to maximum as normalized speed rises from 1 to 1+α, staying constant thereafter. Low stiffness thus gives a meandering speed trace, roughly following the envelope of the airpower signal, with oscillations at double the wave frequency superimposed. Output is smoother but net efficiency is lower.

An Example

To put these dimensionless results in perspective, consider a device with, say, 8 bags which captures an annual mean of 40kw of airpower per bag. For

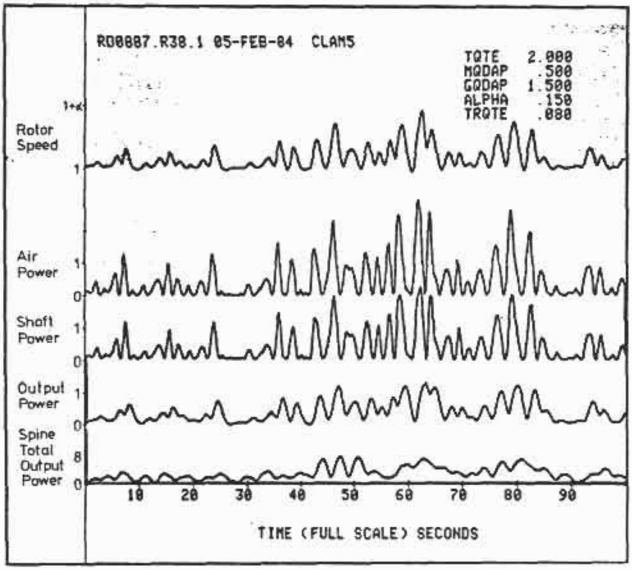

RD0887.R38.1 05-FEB-84 CLAM5
TQTE 2.000
MQDAP .500
GQDAP 1.500
ALPHA .150
TRQTE .080
Rotor Speed
Air Power
Shaft Power
Output Power
Spine Total Output Power
10 20 30 40 50 60 70 80 90
TIME (FULL SCALE) SECONDS

Fig. 5

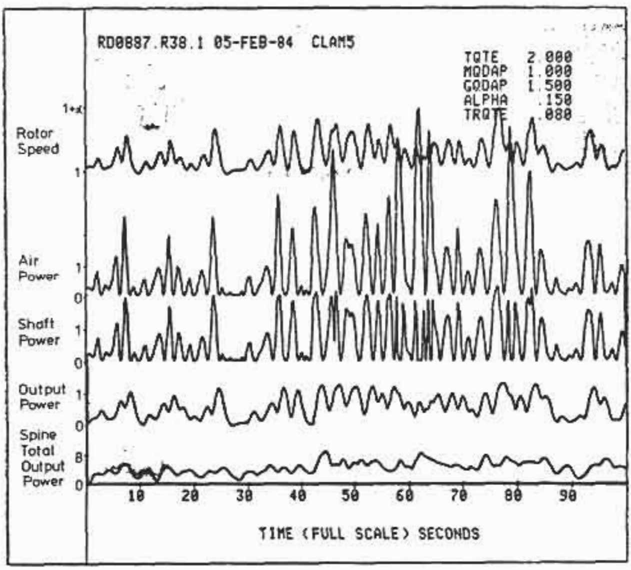

RD0887.R38.1 05-FEB-84 CLAM5
TQTE 2.000
MQDAP 1.000
GQDAP 1.500
ALPHA .150
TRQTE .080
Rotor Speed
Air Power
Shaft Power
Output Power
Spine Total Output Power
10 20 30 40 50 60 70 80 90
TIME (FULL SCALE) SECONDS

Fig. 6

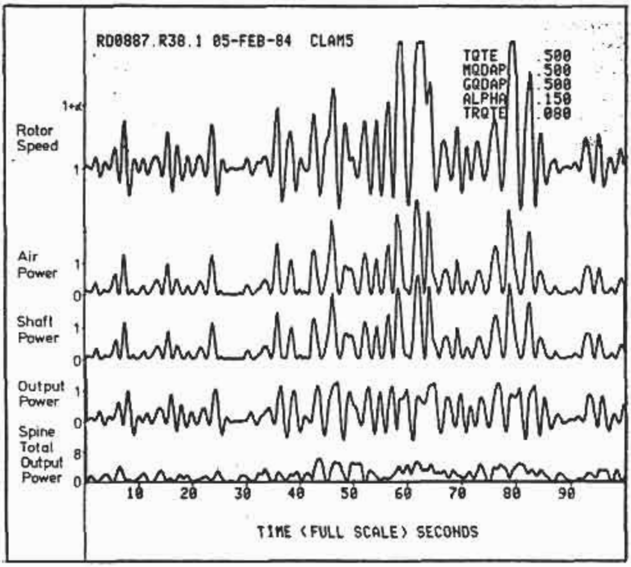

RD0887.R38.1 05-FEB-84 CLAM5
TQTE .500
MQDAP .500
GQDAP .500
ALPHA .150
TRQTE .080
1+α
Rotor Speed
1
Air Power
1
0
Shaft Power
1
0
Output Power
1
0
Spine Total Output Power
8
0
10
20
30
40
50
60
70
80
90
TIME (FULL SCALE) SECONDS

Fig. 7

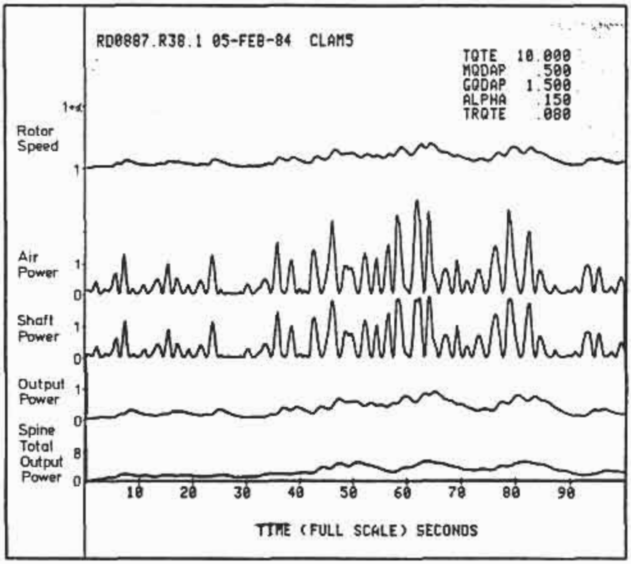

RD0887.R38.1 05-FEB-84 CLAM5
TQTE 10.000
MQDAP .500
GQDAP 1.500
ALPHA .150
TRQTE .080
1+α
Rotor Speed
1
Air Power
1
0
Shaft Power
1
0
Output Power
1
0
Spine Total Output Power
8
0
10
20
30
40
50
60
70
80
90
TIME (FULL SCALE) SECONDS

Fig. 8

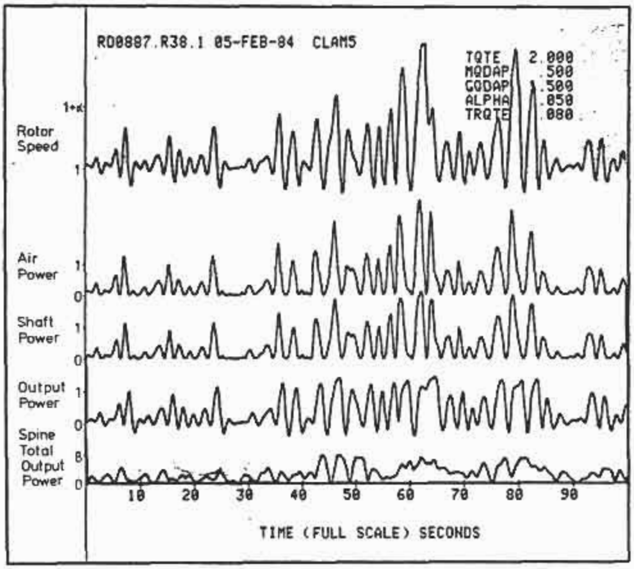

RD0887.R38.1 05-FEB-84 CLAM5
TQTE 2.000
MQDAP .500
GQDAP .500
ALPHA .050
TRQTE .080
Rotor Speed
Air Power
Shaft Power
Output Power
Spine Total Output Power
10 20 30 40 50 60 70 80 90
TIME (FULL SCALE) SECONDS

Fig. 9

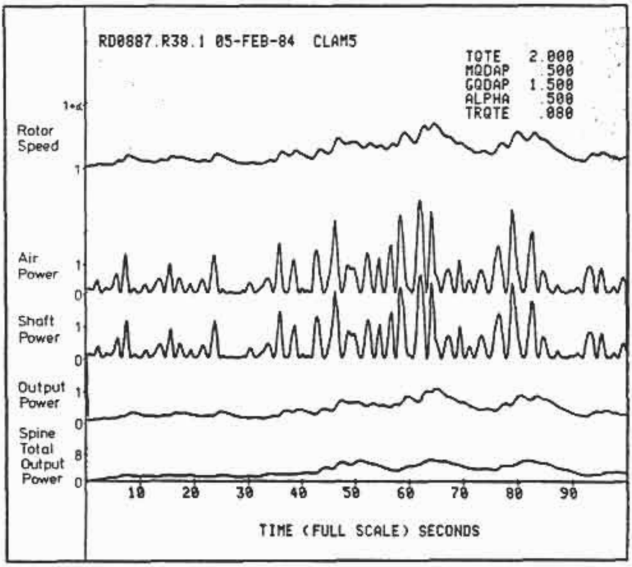

RD0887.R38.1 05-FEB-84 CLAM5
TQTE 2.000
MQDAP .500
GQDAP 1.500
ALPHA .500
TRQTE .080
Rotor Speed
Air Power
Shaft Power
Output Power
Spine Total Output Power
10 20 30 40 50 60 70 80 90
TIME (FULL SCALE) SECONDS

Fig. 10

typical resource scatter diagrams this implies an optimum design airpower DAP for the turbines of around 140kw. The design damping rate $\mathcal{E}_d$ is the optimum rate determinable from model tests and is not very sensitive to power level. The design speed ω_d is the synchronous speed of a suitable induction generator (or equivalent) rated at around 85kw, for example 1500 rpm for a 4-pole machine, with a magnetization time constant of about 0.5 sec. Values for DAP, $\mathcal{E}_d$ and ω_d then effectively fix a best design of Wells turbine, here a single stage 6-bladed machine of diameter 1.5m and hub to tip ratio 0.6 (White, 1981). The working parts of such a turbogenerator could have comparatively low moment of inertia, perhaps 20 kgm^2, so to make TQTE=10, the highest inertia example shown in Fig. 8, would require J=340 kgm^2 for airpower energy periods of about 6 seconds, which could be achieved with a shroud ring around the rotor blade tips with a mass of about 600 kg.

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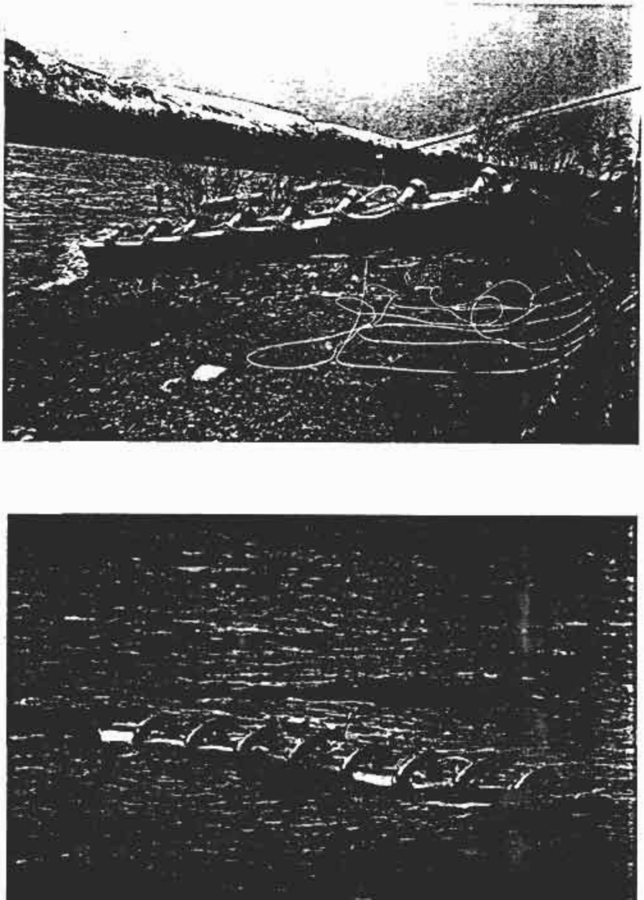

Fig.1