Response of a savonius rotor to unsteady flow[1]

Michael Karweit

Chesapeake Bay Institute
Johns Hopkins University
Baltimore, Maryland 21218

ABSTRACT

A Savonius rotor used as a speed measuring device was subjected to a unidirectional unsteady flow having a mean value U_0. A comparison between the rotor rotation rate in this unsteady flow and its rotation rate in a steady flow U_0 yielded systematic errors in velocities as inferred from steady-state calibrations. Further dependence of the errors on dimensional quantities suggests that present attempts to model the Savonius rotor's dynamics will have to be expanded.

1. Introduction

Since 1958 the Savonius rotor has been incorporated into oceanographic instruments as a current sensing device. For steady flows its average rotational frequency is almost linearly related to the speed of the surrounding fluid; hence it would appear to be useful for measurement purposes.[2] In fact, it is used for such in ocean, shelf, and estuary research. Unfortunately most real flows are at least slightly unsteady and the degree to which steady-state calibrations are applicable is not clear.[3]

To partially answer this question a Savonius rotor was used as a flow measuring device in a known time-dependent unidirectional flow field. Average flow velocities, as inferred from steady-state calibrations of the rotor, were compared to the actual average velocities of the experimental field. Complications arising from flow reversal and below-threshold velocities were avoided by maintaining the flow larger than the threshold of this particular instrument and always in the same direction.

1. Contribution No. 209 of Chesapeake Bay Institute and Department of Earth and Planetary Sciences, Johns Hopkins University.

Received: *4 April 1973*; revised: *9 April 1974*.

2. See Kalvaitis (1972) for a short survey of Savonius rotor characteristics.

3. Response to longitudinal fluctuations (parallel to the axis of the rotor) and step changes in velocity have been measured by Gaul (1963) and Fofonoff and Ercan (1967), respectively.

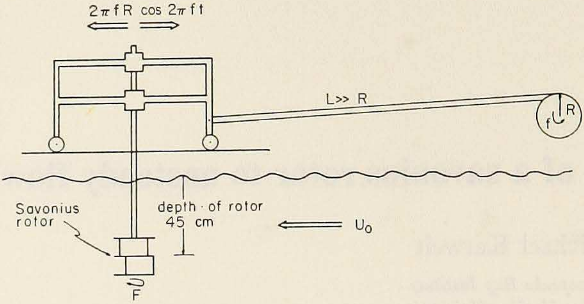

Figure 1. The experimental apparatus. The carriage holding the Savonius rotor oscillates with velocity $2\pi fR \cos 2\pi ft$ over a flume having a speed U_0.

2. Description of experiments

Measurements were made in the Chesapeake Bay Institute's flume. Its cross section is square, 1 meter on a side; and its speed is continuously variable from 0.5–100 cm/sec with a setting of a calibrated speed control. To produce a flow field $u(t) = U_0 + 2\pi fR \cos 2\pi ft$ as seen by the rotor, a rotor was vertically mounted on a movable carriage straddling the flume. By oscillating this carriage along the axis of the flume at velocity $2\pi fR \cos 2\pi ft$ and setting the flume at speed U_0 the desired unidirectional $u(t)$ was obtained.[4] The rotor (17 cm × 16 cm dia.), supplied by Braincon Corporation for use in their current meters, was held by a thin frame with no end plates and submerged 45 cm into the flume to limit surface disturbances. Oscillation of the carriage at velocity $2\pi fR \cos 2\pi ft$ was accomplished by connecting it to a motor crankshaft with stroke R and adjusting the motor to speed f (Hz). (See Figure 1). Thus the oscillating carriage provided an unsteady zero-average component of $u(t)$. By fixing the flume at U_0 and varying R and f for the carriage oscillation, the rotor would see a constant average velocity and its response to unsteadiness could be measured. For a range of steady flows $2.0\ \text{cm/sec} \leq (u(t) = U_0) \leq 50.\ \text{cm/sec}$ the average rotor frequency F (Hz) was measured and found to fit the linear curve $U = a + bF$ where $a = 1.5$ cm/sec and $b = 34.55$ cm are the calibration constants of the instrument. For small U (≤ 2 cm/sec) the calibration curve is not linear and this region was avoided in the experiment.

The procedure for taking data was as follows: U_0, R, and f were selected and the rotor rotation rate F was recorded in the resulting flow; then for the same U_0, f was set to zero (i.e. the oscillation motor was turned off) and a rotor rotation rate F_0 was recorded. In the present experiments the F's were estimated from the average rotational period of the rotor over 128 periods using

4. Although the present experimental flow is not identical to the desired flow field in which the rotor remains fixed and the flow fluctuates about it, one can show that the torque produced on such a symmetric body is the same; and, hence, the results produced here are equivalent.

Table I. The experimental data.

f (Hz)	R(cm)	U_0(cm/sec)	E
0.1	2.54	5.0	0.03
		10.0	0.01
		15.0	0.00
		20.0	0.00
		25.0	0.01
		30.0	0.00
	4.73	5.0	0.13
		10.0	0.01
		15.0	0.02
		20.0	0.00
		25.0	0.02
		30.0	0.00
	7.39	10.0	0.05
		15.0	0.01
		20.0	0.01
		25.0	0.02
		30.0	0.01
	9.91	10.0	0.15
		15.0	0.10
		20.0	0.02
		25.0	0.03
		30.0	0.00
0.3	2.54	10.0	0.16
		15.0	0.03
		20.0	0.01
		25.0	0.00
		30.0	0.00
	3.41	9.0	0.29
	4.73	15.0	0.25
		20.0	0.09
		25.0	0.02
		30.0	0.00
	7.39	20.0	0.31
		25.0	0.12
		30.0	0.05
	9.91	25.0	0.27
		30.0	0.15
0.5	2.54	10.0	0.51
		15.0	0.22
		20.0	0.12
		25.0	0.06
		30.0	0.01
	4.73	20.0	0.42
		25.0	0.27
		30.0	0.14
	7.39	30.0	0.38
0.6	3.41	19.0	0.40
0.7	2.54	15.0	0.49
		20.0	0.30
		25.0	0.16
		30.0	0.09
	3.41	21.0	0.46
	4.73	25.0	0.54
		30.0	0.35
0.8	3.41	28.0	0.36
		33.0	0.23
		31.0	0.29
		26.0	0.37
		23.0	0.49
		20.0	0.61
0.9	2.54	20.0	0.47
		25.0	0.28
		30.0	0.18
	3.41	26.0	0.50
	4.73	30.0	0.54
1.1	2.54	20.0	0.69
		25.0	0.42
		30.0	0.30

a proximity sensor to detect revolutions. For the range $2.54\ \text{cm} \leq R \leq 9.91\ \text{cm}$, $0.1\ \text{Hz} \leq f \leq 1.1\ \text{Hz}$, and $5\ \text{cm/sec} \leq U_0 \leq 30\ \text{cm/sec}$, data were taken.

3. Results

Using the steady-state calibration constants to infer U from the recorded F's, the data are transformed into dimensionless errors as:

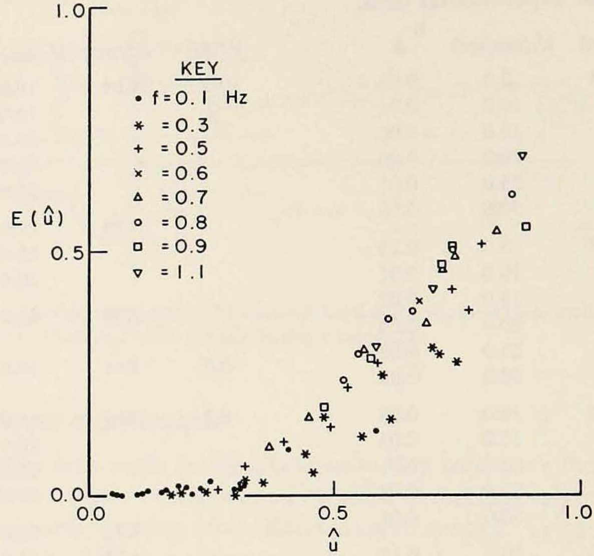

Figure 2. Relative error $E(\hat{u})$ vs. velocity fluctuation $\hat{u}$ for a range of oscillation frequencies f.

$$E(R,f,U_0) = \frac{b(F-F_0)}{a+bF_0} = \frac{U-U_0}{U_0}.$$

E, then, is the relative difference in inferred speed in an oscillating flow assuming a steady-state calibration. Table I lists the experimental data.

The experiment contains two time scales $1/f$ and $1/F$, and two length scales R and b from which the error E could be parameterized. Attempts to explain E in terms of different dimensionless combinations of these scales were not wholly successful; that is, that portion of E not explained by the various parameterizations always depends on a dimensional quantity. One possible explanation for this insufficiency is that the rotor responds differently at, say, different oscillation frequencies. Consequently a uniform parameterization of its response error would not be successful.

In spite of these difficulties it is useful to parameterize E as a function of the velocity fluctuation

$$\hat{u} = \frac{2\pi fR}{a+bF} = \frac{u(t)_{\max} - U_0}{U_0}.$$

We plot $E(\hat{u})$ vs. $\hat{u}$ in Figure 2. Clearly for $\hat{u} > 0.5$ errors in excess of 20% are to be expected—and always in the positive direction. If one extended the results of this unidirectional laboratory experiment to an example in the field, a Savonius rotor current meter moored 30 m deep would read approximately

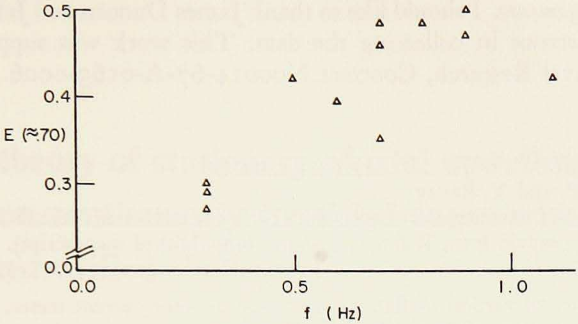

Figure 3. Relative error $E(\hat{u})$ for a velocity fluctuation $\hat{u} \approx 0.70$ vs. oscillation frequency f.

20% high if the average current were 12 cm/sec and a surface swell of period 5 sec and amplitude 80 cm were present.

The spread of the data in Figure 2 is not all experimental scatter. Three parameters R, f, U_0 were adjustable in the experiment and it was possible to obtain a series of measurements for different f having the same dimensionless $\hat{u}$. For $\hat{u} \approx 0.70$ data were collected over a range of f. Figure 3 shows the results. As pointed out above E is not fully described as a function of $\hat{u}$, but in addition depends on f.

(For these data, a simple correction formula was estimated as $E^* = 0.663\hat{u}^2 + .163\,(f - f_0)$, where $f_0 = 0.369$. Using this correction, $|E - E^*|$ was less than .07 in over 90 percent of the cases.)

4. Conclusions

Several inferences can be drawn from these results. First, since the error E is apparently positive everywhere, any unsteadiness in the flow will produce a systematic bias in readings—high; and depending on length and time scales, this bias may be very large. The data suggest, for example, that if a Savonius rotor were used to measure a flow where $\hat{u} > 0.5$, errors in inferred velocity could exceed twenty percent—other models of unsteadiness and nonlinear interactions notwithstanding. Second, attempts to model the dynamics of the Savonius rotor must be at least expanded to include non-linear terms. Linear models have the property that errors average to zero—clearly inappropriate in view of the presented data. Second order models such as Fofonoff and Ercan (1967) or Wyngaard, Bauman and Lynch (1971) (a model for cup anemometer dynamics), although providing for non-zero average errors, are parameterized to a nondimensional form. Again the Savonius rotor cannot comply, because in terms of the presented nondimensional parameters its response is still related to f. It appears that the response of the Savonius rotor to unsteady flow will not be modeled easily.

Acknowledgements. I should like to thank James Duncan and Jeffrey Michael for their assistance in collecting the data. This work was supported by the Office of Naval Research, Contract N00014-67-A-0163-0006.

REFERENCES

FOFONOFF, N. P. and Y. ERCAN

1967. Response Characteristics of a Savonius rotor current meter. Tech. Rep. Woods Hole Oceanographic Inst., Ref. 67-33, 36 pp. (unpublished manuscript).

GAUL, ROY D.

1963. Influence of vertical motion on the Savonius rotor current meter. Tech. Rep. A. and M. College of Texas, Ref. 63-4T, 29 pp.

KALVAITIS, A. N.

1972. Survey of the Savonius rotor performance characteristics. MTS Journal v. 6 n. 4, July–August 1972, pp. 17–20.

WYNGAARD, J. C., J. T. BAUMAN, and R. A. LYNCH

1971. Cup Anemometer Dynamics. Presented at Symposium on Flow – Its Measurement and Control in Science and Industry, Pittsburgh, Pennsylvania 9–14 May, 1971, 18 pp.