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Vortex shedding from cylinders at low Reynolds numbers

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The presence of discontinuities in the Strouhal-number–Reynolds-number relationship was observed in several flows for cylinders in the Reynolds-number range 50–175. An experimental technique was devised to monitor carefully the shedding frequency and free-stream velocity so that the transitions could be distinctly observed. Quantitative Strouhal-number–Reynolds-number data, for cylinders of length-to-diameter ratio exceeding 150, agree reasonably well with the results of Tritton (1959) and Berger (1964).

1. Introduction

Vortex shedding from cylinders in the Reynolds number range 50–200 is a well known phenomenon in fluid mechanics, and the measurement of the shedding frequency f, is sometimes used to infer the free-stream velocity U. Kovasznay (1949) and Roshko (1954) measured the Strouhal number ($St = Uf/d$; d is cylinder diameter) and reported a continuous variation with Reynolds number ($Re = Ud/\nu$, ν is kinematic viscosity) in the range $50 \lesssim Re \lesssim 200$. (Some irregularities in the shedding motion at the high end of the range were observed by Kovasznay (1949) and Schaefer & Eskanazi (1959).) Since the initial studies, various investigators have observed discontinuities or transitions in the St–Re data at $Re \simeq 70$–100, e.g. Tritton (1959, 1971), Berger (1964), Kohan & Schwarz (1973); while some have not, e.g. Gaster (1969, 1971). These results are reviewed by Berger & Wille (1974) and Gerrard (1978). The precise reasons for the occurrences of the transitions are not known, but reasons of finite free-stream turbulence level, induced vibration of the cylinder and a basic change in the vortex shedding mechanism have been advanced. Tritton (1971) reviewed most of the St–Re data available then, and found considerable differences. (His graph is overlaid here on figures 2a, b for comparison with the present results.)

Thus, our knowledge of the shedding phenomenon from circular cylinders has perhaps lapsed, from the original results of Kovasznay and Roshko which indicated reasonably reproducible and unique shedding, to a state of uncertainty about the presence of transitions and the quantitative St–Re relationship. The purpose of this note is to present results from a series of experiments designed to examine in detail transition and to obtain additional quantitative St–Re data. Three flow facilities and a variety of cylinder diameters and lengths were used to assess the reproducibility of the results.

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2. Experimental arrangement

The present experiments were run in the potential core of a 1·5 cm diameter compressed air jet (TSI Model 1150 Calibrator), the core of a 5 cm diameter fan-powered air jet and the UCSD-AMES 75 × 75 cm low-speed wind tunnel. Vortex-shedding frequencies were measured with a DISA 55F11 hot-wire probe, and the air velocity with a MKS Baratron pressure transducer connected to the plenums of the jets or a Pitot-static tube in the wind tunnel. The hot-wire probe was positioned with supports oblique to the wake axis to minimize flow interference, after Kovasznay (1949). Nichrome wires were used as the shedding cylinders and the diameters were measured with an electron microscope. The wires were tensioned to provide straightness; induced vibrations were not observed. A drill rod was also used for the largest cylinder (0·0348 cm) in the 1·5 cm jet.

To investigate the occurrence of a transition in the experimentally-observed frequency versus velocity relationship,† the flow sources were such that the free-stream velocities could be continuously adjusted, and the velocity monitored continuously with the pressure transducer. A special circuit was developed by T. K. Deaton of UCSD to solve Bernoulli's equation from the measured pressures so that an analog voltage proportional to velocity was obtained. The hot-wire anemometer output was connected to a frequency-to-voltage converter (after some signal conditioning). The two voltages, proportional to shedding frequency and free stream velocity, were connected to a $X-Y$ plotter. By slowly varying the jet air pressure or wind-tunnel motor speed (to keep within the relatively slow response times of the pressure transducer and $X-Y$ plotter), a continuous mapping of the frequency-velocity relationship was plotted. (For the fan-powered 5 cm jet, the flow had low frequency oscillations which prevented use of the $X-Y$ plotter technique.) During a speed traverse, the speed was held constant at selected points to obtain quantitative frequency and velocity data for the St–Re relationship determination. The shedding frequency was measured with an electronic counter, and an integrating digital voltmeter was used to obtain the pressure transducer voltage.

3. Results

$X-Y$ data plots of f versus U are shown in figure 1 for four wires run in the 1·5 cm jet and the wind tunnel. The transitions occurring at $Re = 73$–90 are readily apparent for all cases except the 0·02083 cm wire run in the wind tunnel. For that case, smaller transitions occurred at $Re = 110$ and 132. The onset of highly irregular, turbulent shedding is also seen for those runs where $Re \gtrsim 175$. For all of the runs below $Re \sim 175$, hysteresis was not observed: the trace for increasing velocity was identical to that for decreasing velocity within the width of the plotter pen, including the transition zones. The f versus U data exhibit a linear relationship above and below the transition points. Slight curvature above $Re = 100$, as found by Gerrard (1978), is not indicated.

Discrete Strouhal-number versus Reynolds-number data obtained in the two jet flows are shown in figure 2(a). Below $Re \sim 80$, the data for the smallest wire follow the

† This is equivalent to presenting the results in the form $St.Re$ versus Re. The product $St.Re$ is termed the Roshko number by Kohan & Schwarz, and the Stokes number by Gerrard.

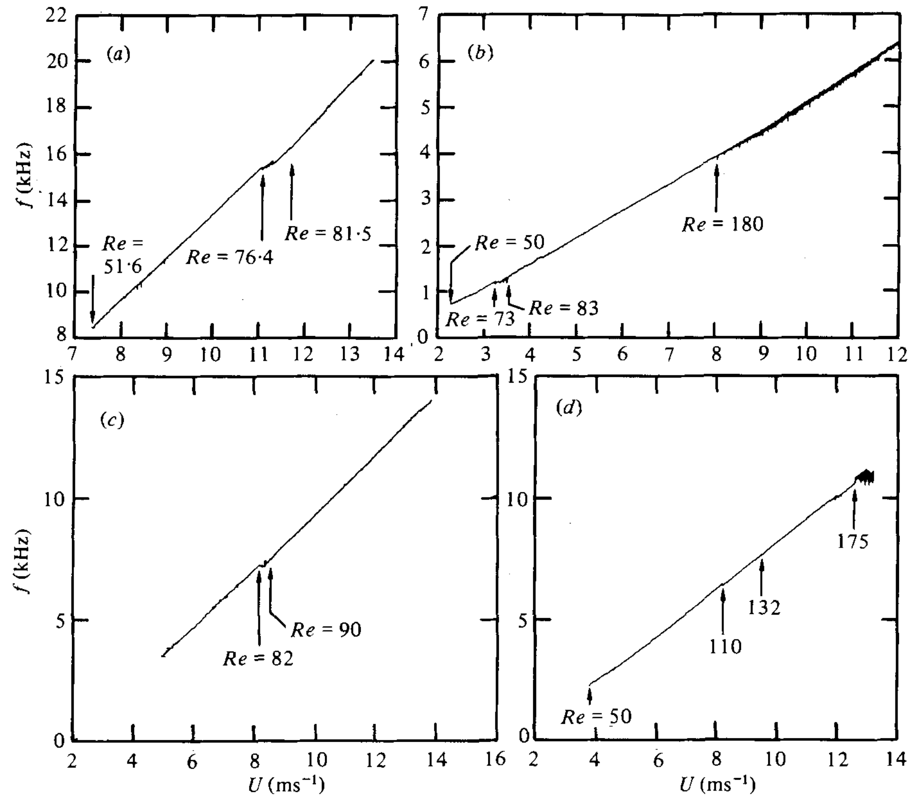

FIGURE 1. X–Y data plots of shedding frequency f *vs.* free-stream velocity U. (*a*) d = 0·0107 cm in 1·5 cm jet flow; (*b*) d = 0·0343 cm in 1·5 cm jet flow; (*c*) d = 0·0160 cm in wind tunnel; (*d*) d = 0·0208 cm in wind tunnel.

curves of Tritton and Berger (low speed modes), and are somewhat lower than Roshko's. There is an apparent l/d (l = wire length) effect: small l/d wires result in low Strouhal numbers. Above $Re \sim 80$, the data tend towards the Tritton and Berger high-speed mode curves. The l/d effect of lower Strouhal numbers remains. Data obtained in the wind tunnel, with wires of l/d 3049–4688, are shown in figure 2(*b*). The results generally follow the Tritton and Berger low-speed and high-speed mode curves.

Although the individual curves of f versus U of figure 1 are very precise, the overall scatter in the final Strouhal-number–Reynolds-number data of figure 2 is not small. Part of this is due to uncertainty in the diameter measurement. The measurement of shedding frequencies by a hot-wire probe placed behind a cylinder is sometimes used for low-speed calibrations of the probe. For precise work, the transitions and scatter about the $St.Re$ or St versus Re curve chosen precludes extremely accurate calibrations, unless separate calibration is made under similar experimental conditions as suggested by Kohan & Schwarz.

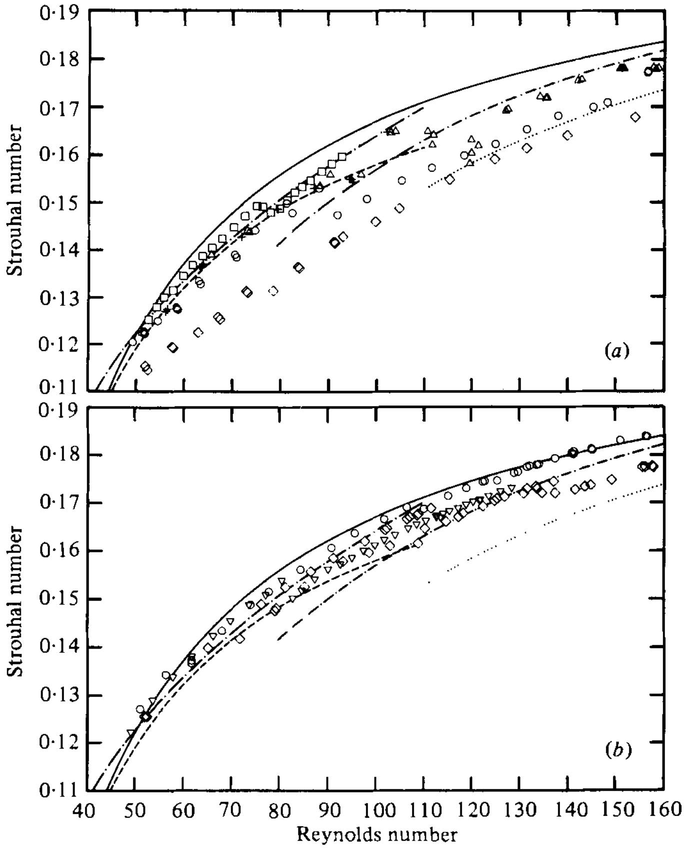

FIGURE 2. Experimental St–Re data. (*a*) Data in 1·5 cm and 5 cm jet flows: □, d = 0·0107 cm, l/d = 150; +, △, d = 0·0107 cm, l/d = 467; ○, d = 0·0208 cm, l/d = 77; ◇, d = 0·0348 cm, l/d = 46. (*b*) Data in wind tunnel: ○, d = 0·0208 cm, l/d = 3605; ▽, d = 0·0160 cm, l/d = 4688; ◇, d = 0·0246 cm, l/d = 3049. Reference data from Tritton (1959): ——, Roshko (1954); –·–, Tritton (1959), low-speed mode; – – – – –, Berger (1964), low-speed mode; –··–·, Tritton and Berger high-speed mode; ······, Berger basic mode.

4. Discussion and conclusions

The present results have indicated, under a variety of conditions, the presence of transitions in vortex shedding from cylinders at low Reynolds numbers. The experimental technique provided a sensitive method for indicating transitions in the frequency–velocity data. Quantitative St–Re data agreed reasonably well with that of Tritton and Berger (low- and high-speed modes) for cylinders of $l/d \gtrsim 150$. For lower l/d ratio cylinders, lower Strouhal numbers were obtained. The Berger 'basic' mode of shedding, which requires an extremely low turbulence level in the free stream, was apparently not obtained in the present experiments.

The values of Re = 70 to 110 for the transition agree with the previous studies of Tritton, Berger, Kohan & Schwarz and Gerrard. Gerrard has proposed that a basic change in the structure of the vortex wake occurs at $Re \approx 100$, which may be associated with the observed transitions. Also, Phillips (1956) observed that the vortex wake is two-dimensional along the spanwise direction for $Re > 80$, can be three-dimensional for $80 \lesssim Re \lesssim 100$ depending on free-stream disturbances, and is three-dimensional for $Re > 100$ with a periodicity of 15–20 d. This may also be reflected in a change in the St–Re data at $80 \lesssim Re \lesssim 100$.

The reason for the non-observance of transitions, as by Gaster, remains to be explained. A possibility is that the transitions are sometimes small, as in the case of the 0·0208 cm wire in the wind tunnel in the present experiments, and may not be readily observed if only discrete frequency and velocity data are obtained.

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