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Vortex shedding from bluff bodies in oscillatory flow: A report on Euromech 119

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European Mechanics Colloquium number 119 was held at Imperial College on 16–18 July 1979, when the subject of vortex shedding from bodies in unidirectional flow and oscillatory flow, was discussed. A wide range of experimental work was presented including low-Reynolds-number flows around circular cylinders, the influence of disturbances on bluff body flow, the measurement of fluctuating forces and the influence of oscillations of the stream. About a third of the 33 papers presented concentrated on theoretical aspects and the majority of these were concerned with the 'method of discrete vortices'.

1. Introduction

The last Euromech Colloquium on the subject of vortex shedding from bluff bodies, Euromech 17, was held in Cambridge in 1970 and was reported on by Mair & Maull (1971). It seemed high time, therefore, that this subject be returned to, particularly since there was evidence from the literature of increasing activity in the area of numerical simulation and a growing awareness that vortex shedding plays a dominant role in oscillatory flow. The aim of the Colloquium was to bring together research workers studying bluff body flows in a unidirectional stream with those investigating the flow around bluff bodies in oscillatory free streams such as occur in wave flows past cylinders. Contributions to the meeting were invited from the following areas:

(*a*) Vortex shedding from bluff bodies in unidirectional flow.

(*b*) Fundamental studies of the flow around bluff bodies undergoing vortex-excited oscillations.

(*c*) Bluff bodies forced to oscillate in a unidirectional free stream (in-line or transverse oscillations).

(*d*) Bluff bodies in planar oscillatory flow and in waves (including effects of a mean current).

(*e*) Mathematical models of vortex shedding.

2. Bluff-body wakes in unidirectional flow

Low-Reynolds-number flow around bluff bodies, particularly circular cylinders, has fascinated researchers for many years. It was one of the topics discussed in Euromech 17 and has continued to provide insight into the mechanism of vortex shedding. Gerrard*† (University of Manchester, U.K.) carried out very careful flow visualization

† Asterisks are used to indicate paper presented at the meeting, of which a full list is given at the end of this paper.

studies on a circular cylinder in water using a towing tank and he went to great lengths to minimize any disturbances which he considered might influence the flow. At Reynolds numbers up to a few hundred he found that in magnitude fluid velocities induced in the wake by the passage of a cylinder were comparable to velocities set up by convection in the nominally still water. To avoid these he installed a grid of heating wires in his tank to provide sufficient heat to ensure a uniform temperature. The towing tank has been described in detail by Anagnostopoulos & Gerrard (1976) and the experimental methods used and results obtained can be found in Gerrard (1978).

In the Reynolds-number range up to 350, Gerrard's measurements of Strouhal number are lower, in general, than those of Roshko (1954), Tritton (1959) and Berger (1964*a*, *b*) and he suggests that this quantity may depend upon the disturbance level in the flow. He found that the Reynolds number for the first occurrence of oscillations in the wake of a circular cylinder was 34. At this Reynolds number the length of the recirculation region, containing a pair of contra-rotating standing eddies, is approximately two cylinder diameters long. Coinciding with the onset of oscillations, 'gathers' appear at the boundary of the recirculation region and these are associated with the transfer of fluid across the bubble boundary at its downstream end. At a Reynolds numbers of about 100 Gerrard found that the nature of the vortex motion changed and he suggests that at this Reynolds number diffusion no longer dominates the near-wake vorticity transport process. Above this Reynolds number dye is not seen to accumulate behind the cylinder but is carried immediately into the wake. At low Reynolds numbers fluid taken from the recirculation region is replaced by fluid from downstream returning along the sinuous wake centre-line whereas at higher Reynolds numbers fluid is drawn across from the opposite shear layer into the growing vortex in the manner discussed by Gerrard (1966).

At Reynolds numbers above 140 Gerrard observed dye which had rolled up into a vortex returning towards the cylinder in what he referred to as a 'finger'. The 'fingers' join vortices sometimes of the same sign and sometimes of opposing signs from opposite sides of the wake. He found that the occurrence of fingers drawing dye back towards the cylinder, to the next vortex of opposite sign, was a maximum at a Reynolds number of 250 and that the fingers were present for about 60 % of the time. Gerrard also observed the three-dimensional nature of the wake flow and noted how, as time progresses from the initial start-up of the motion, the influence of the ends begins to spread across the span and gives rise to bowed vortices. He noted disturbances or 'knots' occurring in the spanwise structure and these mark the boundaries of regions of differing instantaneous vortex spacing. Apart from the initial phase of the motion, the vortices were at their most two-dimensional when the 'fingers' were present. In conclusion Gerrard suggested that one of the values of low-Reynolds-number experiments is that the important phenomenon of vortex shedding, which dominates two-dimensional bluff-body wakes, can be studied without the contaminating influence of turbulence. They are also useful, of course, in that they provide data to compare with low-Reynolds-number computer solutions of the Navier–Stokes equations.

Coutanceau & Bouard* (Laboratoire de Mécanique, Poitiers, France) also used flow visualization as their main tool for studying the wakes behind impulsively started circular cylinders at Reynolds numbers up to 10^4. The techniques used have been fully described by the authors in a previous paper (1977). Whereas Gerrard was concerned primarily with vortex-street wake development, Coutanceau & Bouard were interested in the near-wake evolution and the establishment of flow for t^* up to 3·5. The quantity t^* is defined as tU/d, where t is time, U cylinder velocity and d cylinder diameter. In their work they found the near-wake flow to be symmetric. They noted, in addition to the familiar pair of standing eddies, that, depending on the values of t^* and Reynolds number, secondary phenomena appeared in the near-wake region. They observed, just downstream of the separation point, what they call a local 'swelling' of the flow which corresponds to a region of reduced velocity. This feature is visible at Reynolds numbers from 100 to 400 and at higher Reynolds numbers this swelling gives rise to closed streamlines and the formation of a secondary vortex. For Reynolds numbers in the range 800–5000 and at the time $t^* = 2{\cdot}5$, a further 'secondary' vortex appears and the two together constitute a vortex pair situated just downstream of the separation point. These pairs have been observed previously by Honji & Taneda (1969). From their detailed study of the flow field in the recirculation zone, Coutanceau & Bouard have shown that the evolution of these secondary effects can have a strong influence on the early wake development.

Numerical solutions of the Navier–Stokes equations for two-dimensional circular cylinder flow were presented by Martinez, Boisson & Ha Minh* (Institut de Mécanique des Fluids, Toulouse, France) for Reynolds numbers up to 500. They showed results for the starting and developing flow past a cylinder shedding a vortex-street wake. In the near disturbance-free environment of a numerical calculation cylinder wakes remain stable unless perturbed. Various perturbations were applied and these gave rise to differing transient flows during the establishment of a vortex wake although the final flows appeared to be similar. At a Reynolds number of 100, based on cylinder diameter, they calculated a C_D of 1·35, a Strouhal number of just over 0·15, a fluctuating lift coefficient with a maximum value of 0·2 and a mean separation angle of 115° with fluctuations of about 4° peak to peak. At Reynolds numbers nearer 500 they detected features downstream of separation similar to the 'swellings' described by Coutanceau & Bouard*. Some evidence of secondary vortices can also be found in the numerical solutions of the Navier–Stokes equations by Son & Hanratty (1969). It is problematical, however, whether detailed agreement can be found between two-dimensional computer solutions and experiment for flow past a circular cylinder a long time after the motion has begun. The sensitivity of the flow to disturbances at low Reynolds numbers noted by Gerrard and the influence of three-dimensional effects make low-Reynolds-number comparisons difficult. At higher Reynolds numbers reliable numerical Navier–Stokes solutions are not yet available. However with so much emphasis now being placed on discrete-vortex model development, it is extremely valuable to have Navier–Stokes solutions available and eventually it may be possible to compare them at Reynolds numbers where the applicability of discrete-vortex-model and Navier–Stokes solutions overlap.

Numerous researchers have investigated the hypothesis that all vortex-street wakes possess a similar structure and that a universal Strouhal number can be defined which is independent of the body generating the wake. Griffin* (Naval Research Laboratory, Washington) has extended this idea to encompass the wakes of two-dimensional bluff bodies oscillating transverse to a fluid stream over the reduced velocity range where the vortex-shedding frequency locks on to the body frequency. His Strouhal number St^* is derived from that first introduced by Roshko (1954) where $St^* = f_s d'/U_b$ and

f_s is the shedding frequency, U_b is the velocity just outside the boundary layer at separation and d' is the measured wake width at the end of the vortex formation region. This formulation, which was first used by Calvert (1967) for axisymmetric bluff-body wakes and later by Simmons (1977) for two-dimensional wakes, differs from Roshko's in that d' is a measured quantity rather than being derived from free-streamline arguments; d' is defined as the lateral distance between the maxima of velocity fluctuations at the end of the vortex formation region. The velocity U_b is derived from the base pressure coefficient Cp_b through the relation $U_b = (1-Cp_b)^{\frac{1}{2}}$ and is a characteristic velocity for the near wake. A fuller description of the derivation of St^* is given by Griffin (1978). Under the influence of both flow-excited and forced resonant vibrations the wake width, base pressure and shedding frequency of a bluff body adjust to preserve similarity. Through lock-in the Strouhal number is continuously varying and therefore, as Griffin shows, it is reasonable to expect other wake parameters to change accordingly. Over a broad range of Reynolds number Griffin found St^* to be between about 0·16 and 0·18.

Achenbach* (Institut für Reaktorbauelemente, Jülich, Germany), studying circular-cylinder flows, also used the concept of a universal Strouhal number to help explain the variations of Strouhal number with surface roughness and Reynolds number. He took inspiration from the arguments of Roshko (1961) who had used this idea to link the variations of flow separation point, base pressure and shedding frequency in the subcritical and transitional flow regimes. In the critical regime Bearman (1969) detected weak shedding at a Strouhal number more than double the subcritical value. Achenbach found that the addition of surface roughness not only reduced the critical Reynolds number but also eliminated the high Strouhal number and for example for $k_s/D = 300 \times 10^{-5}$, where k_s is roughness element height, a constant Strouhal number of about 0·24 was measured between Reynolds numbers of 2×10^5 and 5×10^6.

Many of Achenbach's measurements were carried out on a cylinder with a length between walls/diameter ratio of 3·33. An interesting discussion ensued as to the likely influence of aspect ratio on his results and it became clear that participants had widely differing views on this subject. Those working at low Reynolds number found that reducing aspect ratio had the effect of stabilizing the wake and eliminating vortex shedding whereas those working at high Reynolds number observed an opposite effect with vortex shedding becoming stronger at small aspect ratio, presumably due to an increasing spanwise correlation. Even at high Reynolds number, however, it was remarked that an aspect ratio of unity was sufficient to suppress shedding.

Several of the speakers at the Colloquium presented the results of flow visualization studies and the clarity of many of these visualizations was remarkable. In the struggle to understand, model and predict the complex fluid motions developed in the vicinity of a bluff body visualization remains a most effective tool. Whilst most investigators marked the flow with dye or particles Dyment* (Chereng, France) showed results of shadowgraph and schlieren visualization. His technique seemed well suited to showing the fine detail of the flow and in particular the structure of the separating shear layers and the first rolled-up vortices. His photographs of the wake behind a sharp-edged base and a circular cylinder, both in a flow with a free-stream Mach number of 0·6, clearly show structures in the shear layer, similar to those observed by Brown & Roshko (1974) in their mixing-layer studies, developing and rolling into the forming vortices.

Production, concentration, cancellation and diffusion of vorticity are essential features of bluff-body flow. However Zdravkovich* (Salford University, U.K.) reminded us that entrainment of irrotational fluid from outside the wake into the growing vortices also plays an important role. He drew examples from the velocity measurements made behind a circular cylinder by Cantwell (1976), using a flying hot-wire probe, to show that there is a confluence point in the near wake where irrotational fluid which has entered from one side meets fluid entering from the other. This confluence point oscillates in sympathy with the vortex shedding. Cantwell found that a forming vortex entrains fluid which approaches the cylinder along a streamline up to a diameter away from the mean stagnation streamline. Also fluid from the opposite side of the wake crosses the wake axis between the vortices with a transverse velocity component on the order of half the free-stream speed. With the proliferation of discrete-vortex models it is thought that the detailed velocity measurements of Cantwell (1976) and studies such as those of Wlezien & Way (1979) could be used to compare details of the flow field and should prove a more stringent test than the predictions of global properties such as drag coefficient and Strouhal number.

Py* (Institut Universitaire de Technologie, Brest, France) also discussed the flow field around a circular cylinder and attempted to reconstruct the general characteristics of the flow from measurements of surface velocity gradient. The measurement technique is described in Tournier & Py (1978), where electrochemical transducers attached to the cylinder surface are used to record instantaneous surface velocity gradient. The data is analysed in a number of ways including the extraction of the periodic component associated with vortex shedding. Since these signals are strongly coherent around the cylinder the main details of the unsteady flow pattern can be reconstituted. The measurement technique would seem to have potential for giving detailed information on important surface features such as separation point movement.

Although many investigators have studied the flow around isolated, two-dimensional bluff cylinders in a uniform smooth flow it is seldom that such conditions are met in practice. Several authors at the Colloquium presented work on the influence of factors such as free-stream turbulence, body roughness, proximity of tunnel walls, proximity of neighbouring bodies and the effect of a superimposed acoustic field. Buresti & Lanciotti* (Facoltà di Ingegneria, Pisa, Italy) described their investigation into the flow field around a circular cylinder in cross-flow placed at various distances from a plane, parallel both to the flow and to the cylinder axis. Details of their experimental arrangement are given in Buresti & Lanciotti (1979). They found that for a smooth cylinder, within the subcritical Reynolds number regime, the main features of the vortex-shedding mechanism remained unaltered for distances from the plane greater than approximately 0·4 cylinder diameters. In particular the Strouhal number did not show any significant variation from its isolated cylinder value, and this is in agreement with the measurements of Bearman & Zdravkovich (1978), although they found that shedding was suppressed for gaps less than 0·3 cylinder diameters rather than 0·4. In the absence of the cylinder the boundary-layer thickness on the plane boundary was equal to 0·1 cylinder diameters in Buresti & Lanciotti's experiment, whereas in Bearman & Zdravkovich's it was 0·8, and it is interesting to find the two sets of results so similar. Buresti & Lanciotti also investigated the case of artificially roughened cylinders which simulated flow in the supercritical regime. In their terminology the supercritical regime corresponds to what Roshko (1961) called the transitional flow regime. In general their results with the cylinder in the free stream agree with those of Szechenyi (1974) on roughened cylinders and as the boundary was approached the Strouhal number remained constant in the same way as it did for the subcritical case.

The flow past a cylinder near a boundary has many similarities with the flow past two cylinders in a side-by-side arrangement. Auger & Coutanceau* (E.N.S.M.A., Poitiers, France) considered the complex problem of a number of cylinders in a side-by-side arrangement and described measurements of the flow through a grid of regularly spaced circular cylinders set normal to a stream in a duct. They visualized the air flow by seeding it with fine aluminium particles and illuminating with a short-duration flash. As had previously been observed by several other workers, there are two distinct flow patterns in the wake of the cylinders dependent on the ratio X_T of the spacing between the cylinder centres to the cylinder diameter. Auger & Coutanceau found that when the reduced pitch X_T was greater than 2 no amalgamation of the wakes occurred downstream of the grid and that neighbouring shear layers from adjacent cylinders shed vortices in phase. This observation is similar to that made by Bearman & Wadcock (1973) who found that two cylinders side by side shed vortices in this manner when the gap between them was greater than a cylinder diameter. With X_T less than 2 Auger & Coutanceau found that individual cylinder wakes joined together to form composite groups. These groups did not contain a set number of individual wakes at any fixed location behind the grid; the wake groupings could change with time. From an analysis of 17 different grids, however, they concluded that the most probable structure of the flow was the one on which all the groups contained, as near as possible, the same number of individual wakes. Measurements of shedding frequency were made in addition to the visualization work and these confirmed the existence of the two types of flow. When X_T was greater than 2 only one dominant vortex-shedding frequency appeared whereas when X_T was less than 2 up to four could be found depending on time and location in the grid wake.

The presence of free-stream turbulence can modify vortex-shedding behaviour and Petty* (Queen Mary College, London) discussed this problem, which is of fundamental and practical importance. He described how turbulence can influence shedding directly, by increasing diffusion and cancellation of vorticity and by reducing spanwise correlation lengths, and also indirectly by affecting the mean flow. Engaging the concept of a universal Strouhal number, it is clear that if turbulence changes a flow separation or reattachment point, by initiating transition or by enhancing free shear-layer growth by more vigorous mixing, then the shedding frequency must change. Petty illustrated this with measurements made on rectangular cylinders of various length-to-breadth ratios. His results supplement those of Laneville & Williams (1979) and show that two-dimensional bluff-body flow is sensitive to turbulence intensity but almost immune to changes in turbulence scale. Petty also explored the notion that acoustic excitation can produce a similar effect to free-stream turbulence on bodies with sharp-edged separation. He excited the flow at the shear-layer transition wave frequency and found that, to a limited extent, it reproduced some of the effects caused by free-stream turbulence. However it may be that the random excitation offered by free-stream turbulence is much more efficient at increasing the growth scale of already turbulent shear layers than a pure acoustic tone.

An experimental finding of Petty's that one of the reporters found particularly intriguing was that the addition of free-stream turbulence increased the base pressure and *lowered* the drag of a two-dimensional blunt-based body with a slender streamlined nose. From measurements on axisymmetric bluff bodies where the shear layer leaves the body at a sharp edge it is known that the addition of turbulence increases the entrainment into the free shear layer and *increases* base drag. In Petty's analogous two-dimensional experiment, however, regular vortex shedding makes the major contribution to body drag and it must be concluded that drag is reduced by a weakening of the shed vortices through perhaps a greater diffusion of the shear layers and a larger vorticity cancellation.

Acoustic excitation was the main theme of the paper by Welsh, Parker & Stoneman* (University College, Swansea, U.K.) and a novel feature of this presentation was that it had been previously recorded on a video tape. Thus we were able to see flow visualization, using smoke in a wind tunnel, and to experience the intensity of the sound generated by vortex shedding under conditions of acoustic resonance. They studied a range of flat plates, mounted in the centre of a closed duct and parallel to the main flow, and the trailing and leading edges of the plates were either square or semicircular. A resonance was set up when an acoustic wave standing between the tunnel walls corresponded in frequency to vortex shedding from a plate. This phenomenon has been described in detail by Parker (1967, 1968) and the acoustic mode set up in these experiments is known as the Parker β-mode. In this mode the pressure amplitude variation across the duct is such that nodes are established upstream and downstream of the plate along the centre-line of the duct. Transverse acoustic particle velocities are at a maximum near the centre of the duct in the vicinity of the plate and velocities along the plate surface are at a maximum near the leading and trailing edges.

The effects of acoustic resonance on vortex shedding appear to be very similar to those found on oscillating bluff bodies in 'quiet' flows, in that the shedding frequency locks to the external frequency over a narrow range of wind speed. When resonance occurs flow visualization shows the vortices to be extremely regular and well defined. For plates with square leading and trailing edges and with a chord-to-thickness ratio of 5 the separation bubbles starting at the leading edge stretch almost to the trailing edge and the shedding frequency is about half that for a plate with semicircular leading and trailing edges. At a particular wind speed an interaction takes place between natural vortex shedding and the duct acoustics and the familiar locked vortex-shedding state is achieved. If the flow velocity about a square-edged plate is reduced such that the natural vortex-shedding frequency would be about half the acoustic resonant frequency a loud sound is emitted and the vortices are found to be shedding at twice their natural rate. This sudden change in the Strouhal number is associated with a change in the time mean flow pattern and the leading-edge separation bubbles are drastically reduced in length. Presumably these changes are consistent with the concept of a 'universal Strouhal number' for vortex shedding. In this excited state Welsh *et al.* found that the separation bubbles were oscillating in sympathy with vortex shedding and that the shed vortices appeared to have their origin in the bubbles.

Among the interesting results presented by Welsh *et al.* was the finding that a circular cylinder can also experience lock-in owing to acoustic resonance, although the phenomenon is not so pronounced as for the flat plates. Using a 6·3 mm diameter cylinder in a 120 mm duct, they found lock-in occurred at a speed of about 46 m s^{-1}. This result suggests that experiments on circular cylinders spanning rectangular ducts can be influenced by acoustic resonance of this type if the Mach number of the free stream approaches a value equal to about $2\frac{1}{2}$ times the geometric blockage ratio.

3. Vortex-induced oscillations: free and forced

An area where significant advances have been made since Euromech 17 is in the mathematical representation of vortex-excited oscillations. Inspired by the observation of Bishop & Hassan (1964) that an oscillating cylinder/wake combination possessed the characteristics of a nonlinear oscillator, Hartlen & Currie (1970) explored the use of a van der Pol oscillator-type equation to represent this phenomenon. They chose their equation on the basis of comparison with experimental results rather than by an appeal to the fundamental equations of fluid flow. In bluff-body aerodynamics it seems likely that many advances must take this path. At the previous Euromech, Feng & Parkinson (see Feng 1968) presented experimental results on a lightly damped two-dimensional circular cylinder undergoing vortex-induced oscillation. They observed, in addition to the normal resonant lock-in behaviour, a jump in the oscillation amplitude at a particular reduced velocity and a hysteresis effect when the velocity was increased through resonance and then reduced again. These effects were not predicted in the original work of Hartlen & Currie (1970) and in a review paper Parkinson (1974) drew attention to this apparent inadequacy of the van der Pol oscillator equation. Since then a whole family of nonlinear oscillator-model equations have been proposed, mostly with higher-order damping terms, to try and explain experimental results in more detail.

Berger, Breitschwerdt & Kobayashi* (Technische Universität Berlin, Germany) presented an improved oscillator model and applied it to the Feng–Parkinson data as well as to some of their own results. Their coupled equations are of the form

$$\ddot{x} + 2\beta\dot{x} + x = \alpha\Omega^2 C_L,$$

$$\ddot{C}_L + f^*\dot{C}_L + \Omega^2 C_L = b\dot{x},$$

where x is the cylinder displacement, β the damping ratio, a the modified mass ratio, Ω the ratio of Strouhal frequency to cylinder frequency, C_L the lift coefficient and b is a constant. The oscillator damping function f^* chosen by Berger *et al.* is

$$\sum_{n=0}^{2m} \alpha_{2n} C_L^{2n},$$

and in order to describe both the 'soft' and 'hard' excitation observed in experiments a minimum order of $m = 5$ is necessary. A high order is required in order to allow for such features as the sudden increase in correlation length with cylinder amplitude. It appears (Parkinson 1974), however, that the structural damping of Feng's cylinder changed depending on the aerodynamic loads applied and Wood & Parkinson (1977) suggest that some of the experimental results can be explained on the basis of a nonlinear structural damping term. We are left, therefore, not being certain whether to blame the structure or the fluid, although the work of Berger *et al.* and the lift measurements of Feng would suggest the fluid. This point has been brought out in some detail in a recent 'selective' review of fluid-induced vibrations by Sarpkaya (1979).

A successful oscillator model should also be able to predict the fluctuating lift characteristics of a cylinder forced to oscillate. In this case the right-hand side of the oscillator equation is known *a priori*. Such results were presented by Staubli* (ETH, Zürich, Switzerland) who measured forces on a circular cylinder forced to oscillate, at amplitudes up to nearly a cylinder diameter, in a towing tank. He worked over the Reynolds number range $2{\cdot}5 \times 10^4$ to 3×10^5. Under the strictly controlled conditions existing in a forced oscillation experiment the influence of oscillation amplitude and reduced velocity can be examined separately. At a given oscillation amplitude Staubli found that as reduced velocity was increased towards the lock-in value a sudden jump in the lift force from the Strouhal frequency to the body frequency did not occur. Both frequencies are found in a spectrum of the fluctuating lift force and as lock-in is approached power drains from the Strouhal frequency into the body frequency. Similar observations have been made by Bearman & Davies (1977) on other shapes of bluff body. Staubli also found that the maximum excitation on an oscillating cylinder occurred at a lower non-dimensional frequency (higher reduced velocity) than the stationary cylinder Strouhal frequency. In fact at the stationary cylinder Strouhal frequency the lift force out of phase with the cylinder velocity, generating damping, was at its highest. Careful measurements of the lift characteristics of forced cylinders will throw much-needed light on the problem of vortex-induced vibrations and should resolve the problem of what caused the amplitude jump in Feng's experiment.

Complementary data on unsteady pressures on a forced oscillating circular cylinder were presented by Bublitz* (DFVLR, Göttingen, Germany) for the Reynolds-number range $8{\cdot}3 \times 10^4$ to $6{\cdot}6 \times 10^5$. His pressure spectra, which were measured with oscillation amplitudes up to 0·10, also show the separate existence of pressure fluctuations at the body and vortex frequencies except at lock-in, where they merge. At Reynolds numbers greater than about 6×10^5 no distinct vortex-shedding peak could be seen on the spectra and the body movement produced the only dominant frequency.

Measurements of vortex-induced vibrations of freely oscillating rectangular cross-section cylinders of various height-to-width ratios were presented by Gerhardt, Kramer & Kuhnert* (Department of Aeronautical Engineering, Aachen, Germany). In addition to measurements of oscillation amplitudes they investigated the response of the wake to vortex-induced vibration using hot-wire anemometers. Researchers who are employing nonlinear oscillator models seem, without exception, to have attempted to predict circular cylinder amplitudes. It seems that some attention should be paid to rectangular cylinders since these have the interesting possibility of an interaction between vortex shedding and galloping as discussed by Wawzonek & Parkinson (1979).

4. Numerical methods

Various numerical schemes exist for predicting the forces and details of the flow round bluff cylindrical bodies, both in uniform and oscillatory flow. Some of these, such as Morison's equation, which will be discussed later, are really methods of correlating data relying on empirical coefficients. Others such as the wake oscillator model, already discussed, make use of a mathematical model which appears to describe certain features of the phenomenon but has no strong physical basis. There are also two methods of representing the flow past bluff bodies which attempt to model the separating shear layers physically. These are the free streamline and wake-source models on the one hand which generally only model the mean flow details, although some limited applications have been made to unsteady flows. On the other hand there are the vortex wake models of differing degrees of sophistication which attempt to represent the behaviour and influence of the wake vorticity shed in the separating shear layers, and which provide an instant-by-instant picture of the flow as it develops.

A number of papers in the Colloquium dealt with the latter methods of modelling the vorticity in the wake. Most of these used what we have termed the discrete-vortex method in which large numbers of vortices are inserted into the flow field to represent the vortex sheets and their subsequent roll-up in a fairly detailed way. However two papers discussed the results of using simplified vortex wake models, from which important conclusions could be drawn without the need for such extensive computation.

Von Kármán was one of the first to use discrete point vortices to model bluff-body wakes and his stability criterion and drag formula are significant milestones in the study of vortex shedding from bluff bodies. Greenway* (University of Oxford) adapted von Kármán's original drag formula to take some account of the viscous nature of real vortices. He superimposed Hamel–Oseen vortices with finite core radii and derived a modified vortex-street drag formula. Although the drag predictions, in Greenway's words, are disappointing the method does demonstrate that the spacing ratio must change down the wake to maintain a constant C_D as the vortices diffuse. An interesting variation on the problem of predicting vortex-shedding frequency behind a bluff body was presented by Maull* (University of Cambridge). His linearized model of the wake replaces the vortex street by a distribution of vorticity strength moving with a constant velocity along the wake centre-line, similar to that used in linearized unsteady aerofoil theory. To ease mathematical complexities he took as his example a circular cylinder shedding vorticity at the 90° points. The net vorticity shed is introduced into the wake at the rear of the cylinder and an equation is set up relating this vorticity to the vorticity previously shed and its image in the cylinder. Substituting into this equation a solution for the wake vorticity in the form of a sinusoidal oscillation he obtained values for the convection speed of the wake vorticity and the Strouhal number. He found a Strouhal number of 0·27, which is close to the value expected in the transcritical regime, and a convection speed for the vorticity of 75 % of the free-stream velocity and again this seems a reasonable figure. What can be learnt from these results? Is it that only a crude representation of the vorticity field is needed to predict the shedding frequency and is this why some discrete-vortex-based calculation methods seem to give good Strouhal-number predictions but poor representations of the rest of the flow?

The remaining numerical papers described discrete-vortex-model calculations in which the vortex sheets were represented by arrays of isolated point vortices. The subsequent behaviour of these sheets of vorticity, representing separating shear layers at high Reynolds number, was obtained by tracking the point vortices numerically (see for example Clements & Maull 1975 for a review). A number of difficulties arise in the application of this method to bluff-body flows. Particular problems are the specification of the positions of the separation points and the way in which vortices are introduced into the flow at these points, the stability of the subsequent vortex motions and the difficulty of reconciling the need for large numbers of vortices to obtain a satisfactory representation of high-Reynolds-number flow with restrictions imposed by computation time and storage.

In order to bypass the difficulty of specifying the separation points on a continuously curved surface such as a circular cylinder, without the need for a separate and doubtful boundary-layer separation calculation, most of the papers looked at flow past bodies with separation fixed at sharp edges. However Stansby* (Salford University, U.K.) in his study of flow past a pair of circular cylinders made use of a simple criterion that separation should occur at points where the surface velocity had fallen by 5 % from its maximum value. This suggestion attracted considerable criticism because of the lack of evidence for such a general assertion, but was defended on the grounds of giving realistic results. If the movement of the separation points is relatively unimportant for the flow in question, their fixed empirical values might as well have been chosen. On the other hand if this movement is important it would seem more appropriate to predict the separation points from a quasi-steady boundary-layer calculation such as, for example, Polhausen's method as used by Deffenbaugh & Marshall (1976).

In the case of separation from a sharp edge, vortices representing the separating shear layer are usually fed into the flow with the correct strength to satisfy a Kutta–Joukowski condition at the edge. However the point at which they first appear in the flow, and are made to satisfy this condition, has a considerable influence on the shedding process and has to be specified in some way. Bearman & Kamemoto* (Imperial College, London) presented a systematic study of the effects of varying the position of these points, in their paper on the impulsively started flow past a pair of flat plates normal to the stream. The results of their computations suggested that in the case of a flat plate there was a suitable range of points along the extensions of the plate at a distance in plate diameters which depended on the non-dimensionalized time step used. If the vortices were shed from any point in this range the resulting vortex sheets developed in a reasonably consistent manner. But outside the range their behaviour was increasingly unrealistic.

Graham* (Imperial College, London) and de Bernardinis & Parker* (Imperial College, London) also presented calculations with vortex shedding from sharp edges. In both these papers the initial vortex position was fixed on the extension of the wetted surface by relating its distance from the edge to the length of continuous vortex sheet which would have been shed from the edge during the time step Δt. This generally gave a position within the range suggested by Bearman & Kamemoto's results, although varying with the instantaneous rate of vortex shedding. In calculating this length the vortex sheet was assumed to be convected at the mean of its upper and lower surface velocities. More recently Maull (1979) has questioned the validity of this assumption close to the separation point and has proposed a different formula for the convection velocity derived from the integral of the vorticity flux at separation.

Nagano, Naito & Takata* (University of Tokyo, Japan) and Ashurst* (Sandia Laboratories, Livermore, U.S.A.) both presented calculations for finite Reynolds number. The introduction of viscosity avoids the problem of shedding vortices from a sharp edge, since a finite length or velocity seale is now introduced by the assumed presence of an upstream boundary layer. In Nagano's calculation of flow past a square prism, the strength $\Delta\Gamma$ of the shed vortices was related to the velocity U_e, calculated from the inviscid flow at the outer edge $y = \delta$ of the separating boundary layer. Thus:

$$\Delta\Gamma = \tfrac{1}{2}U_e^2(\delta)\,\Delta t.$$

The initial vortex position was fixed by this value of $\Delta\Gamma$ and the Kutta–Joukowski condition at the edge. This method, although leading to realistic results, is equally incorrect at high Reynolds number since, according to boundary-layer theory, the outer velocity U_e of the boundary layer is given to first order by the inner velocity $U(y \rightarrow 0$, not $\delta)$ of the inviscid flow, the difference being quite significant at an inviscid flow singularity such as a corner. Ashurst, on the other hand, using a much larger number of vortices in his calculation, distributed them over the thickness of the upstream boundary layer so that they approximately represented the vorticity distribution in the boundary layer. The vortices were then convected without difficulty into the separating shear layer. Stansby selected his vortex release points such that the subsequent convection velocity of the vortices at these points was correctly related to their strength, on the assumption that the sheet moved at the mean of the velocities on either side of it.

All the calculations presented, except Ashurst's, used a direct calculation, through the Biot–Savart law of the convection velocity at each vortex in the field. The computation time required to do this increases as n^2 per time step, which limits the number n of vortices which can be reasonably computed to the order of 300. This limitation, as for example in Bearman & Kamemoto's calculation, means that only the initial development of a given flow can be computed. Others (Stansby; Nagano *et al.*; Graham; de Bernardinis & Parker) following the original suggestion of Clements (1973), amalgamated clusters of vortices into a single point vortex, thus permitting longer calculations. This procedure was however felt to be questionable, from the point of view of the effect on the flow of a sudden amalgamation. For example, the vortex invariants (see Birkhoff & Fisher 1959) cannot all be satisfied, even in planar flow, and there is also a major computational difficulty of systematically identifying the boundaries of vortex clusters.

For longer flow times, most of the inviscid vortex calculations showed an increasing randomization, which as Moore (1974) has pointed out stems from the inherent instability of arrays of point vortices. This increasing randomization was felt to be a major factor in the difficulty of modelling oscillatory flows past bluff bodies. In unidirectional flows randomization occurs in comparatively isolated vortex clusters forming the vortex street and being swept away from the body. But in oscillatory flow these clusters return, passing close to the body, and feed a strongly chaotic element into the initial formation process. Nagano *et al.* used vortices with growing viscous cores as suggested by Chorin & Bernard (1973) to represent a finite-Reynolds-number shear layer and this technique does dampen the instability. An alternative method of representing viscosity (Chorin 1973) is by the addition of a random walk to the motion of the vortices, which Ashurst incorporated in his calculation of flow down a step. Milinazzo & Saffman (1977) have pointed out that this method requires the use of a very large number of vortices to give an adequate representation of high-Reynolds-number flow. Ashurst was able to represent the flow in this case with a fairly large number of vortices (~ 1000) by using the grid method originally proposed by Hockney (1970) for plasma calculations. In this method the vortices are averaged over a mesh and the velocity field is calculated on the mesh by a rapid method of solution of the Poisson equation such as the fast Fourier transform method. The grid method introduces errors due to grid-induced anisotropy of the vortex interactions (Eastwood & Hockney 1974) and a numerical viscosity related to the mesh size for which some corrections were made in the calculation of the velocity field at each time step. The effects of viscous diffusion were represented by a combination of growing viscous cores and a random walk in this computation. Ashurst found that the subsequent flow development was fairly insensitive to the initial core size (at separation), but very sensitive to the distribution of inlet vorticity. The existence of a recirculating region downstream of the step was dependent on the introduction of (cancelling) vorticity of opposite sign generated by a no-slip condition applied to the walls beneath the separation. Without this, as Clements (1973) found, a recirculating region failed to appear. With these adjustments the calculation predicted a very realistic flow pattern and some quantitative agreement with experimental measurements of turbulent shear stress indicated the probable importance of two-dimensional structures in determining the latter in this situation.

Nagano similarly found that it was necessary to reduce the total vorticity in the separating shear layers of a square prism, in order to obtain realistic results. In this case the reduction was effected by removing vortices, justified as accounting for three-dimensional effects which would occur in a real flow. In the calculations of Bearman & Kamemoto, where systematic vortex removal was not employed, the initial roll-up and development of the separating shear layers were very well predicted, but after longer times the shear layers appeared to roll up closer to the body surface than experimentally observed. When vortex shedding is forced to become two-dimensional, as for example on a vibrating body (Bearman & Davies 1977), the shear layers are observed to roll up closer to the body than otherwise, but the proportion of vorticity cancelled by mixing of opposite sides of the wake remains approximately unaltered. This may therefore partially justify the removal of vorticity in the representation of those flows which are only two-dimensional in the mean, but exhibit the usual lack of spanwise correlation in vortex shedding. But it should be emphasized that irrespective of this the numerical computations do not predict significant mixing of vortices from the two sides of the wake, in contrast with experimental observations. Hence vortex removal may well be an artificial device to overcome this defect.

In most of the numerical schemes the solid boundaires were dealt with by means of conformal transformation, where necessary, and image vortices. However both de Bernardinis & Parker and Ashurst used essentially the boundary integral-equation technique, representing the boundaries by surface vortex distributions.

The papers by Stansby and Bearman & Kamemoto both dealt with unidirectional flow past a pair of two-dimensional bodies, side by side. For decreasing separation-to-diameter ratio $s/d < 2$ a symmetric flow pattern developed with the flow about either body substantially affected by the presence of the other. In this regime it was also possible by applying a small perturbation at the start to generate a strongly biased flow, resulting in (Bearman & Kamemoto) a drag coefficient approximately 100% higher on one body compared with the other. The body with the higher drag coefficient shed a regular vortex street but the other shed a much more diffuse and irregular wake. These results are qualitatively in agreement with experimental observation (Zdravkovich 1977). The asymmetry causes a considerable movement of the separation points in the case of circular cylinders, away from the normal mean positions for an isolated cylinder. Although Stansby's method of predicting separation had very little basis in boundary-layer theory, the results were not too unrealistic. But no direct comparisons with for example instantaneous pressure distributions were presented.

Nagano's calculations for a square prism oscillating laterally were carried out for a range of non-dimensional frequency (relative to the Strouhal frequency) and amplitude, The results clearly demonstrated what is usually described as the lock-in phenomenon, in which the energy at the natural Strouhal frequency is reduced and that at the frequency of oscillation increased, as the two frequencies are made to approach one another from either side. The predicted lift amplitudes and phases with respect to the oscillation were found to be in qualitative agreement with experimental results.

Ashurst presented a computer-generated film of two types of internal flow. The first dealt with the flow down a two-dimensional step in a channel already mentioned. The second modelled the intake and exhaust flow through an axisymmetric valve/cylinder/piston arrangement. In both cases the flow predictions were qualitatively realistic when compared with flow visualization experiments, but no detailed quantitative comparisons were presented. However one experimental paper was presented dealing with flow down a step. Dumaine, Lebouche & Martin* (L.E.M.T.A., Nancy, France) presented the results of some experimental measurements of a pulsatile flow, $U = U_0 + U_1 \sin \omega t$, through a sudden enlargement of a two-dimensional channel. They found that the recirculating region behind the step on either wall gave rise to periodic vortex shedding. Large accumulations of vorticity associated with gross fluctuations in the bubble length were observed to be shed at the frequency of pulsation with subharmonic variations in intensity. The vortex shedding was inferred from measurements of negative wall shear stress using a pair of electrochemical surface probes (see also Py*). At large values of ω or small values of U_1/U_0 vortex shedding did not occur. In this case only very small fluctuations in the bubble length were observed and the region of negative shear stress was not convected downstream. This does not necessarily mean that no vorticity was shed, only that it was relatively weak.

Two numerical calculations of oscillatory flows with zero mean velocity were presented. Graham* discussed the calculation of oscillatory cross-flow round a single sharp edge on an infinite wedge. Dimensional analysis was used to establish the form of the vortex-induced force, which was then applied to the case of oscillatory flow past finite sharp-edged bodies such as plates and square prisms. The point vortex method was used to calculate the development of the flow structure. Although the method predicted qualitatively the shedding of vortex pairs, one per cycle, at about 60° to the free-stream direction observed from flow visualization, the quantitative results for the predicted force were too large when compared with experiment, considerably so for the square prism. De Bernardinis & Parker, who had calculated the oscillatory flow past an axisymmetric disk and through an orifice plate in a pipe, found the same type of flow development close to the edge from which the axisymmetric vortex sheet was shed. However, detailed flow visualization experiments using a normally oscillating disk in a tank of water showed that the flow consisted of interacting vortex rings, usually convecting away from the plate on one side only, according to the starting conditions. However this phenomenon, although surprisingly axisymmetric, could not be reproduced numerically for large computation times. The internal orifice flow was also compared with experiments, but after the first flow cycle it was difficult to make comparisons with the motion of the shed vortices observed in the experiments, since they rapidly became three-dimensional and confused.

5. Oscillatory flows

The need to predict the forces induced on offshore structures in waves has given a great impetus to the study of oscillatory flows past bluff bodies. These may be taken as consisting of all those flows in which the oscillatory motion is comparable to or greater than the mean. The most generally used equation for predicting the force on bodies (of diameter d) in two-dimensional oscillatory flow ($\mathbf{U}$) is that due to Morison *et al.* (1950):

$$\mathbf{F}(\text{per unit length}) = \tfrac{1}{2}\rho\mathbf{U}|U|\,dC_D + \frac{\pi}{4}d^2\frac{d\mathbf{U}}{dt}C_M.$$

The drag and inertia coefficients C_D and C_M are given empirical values depending on the Keulegan–Carpenter number (ratio of flow orbit to body diameter), Reynolds number and the relative mean current (ratio of mean to oscillatory velocity). This equation predicts that the drag part of the force will lie along the instantaneous relative-velocity vector $\mathbf{U}$ and the inertia part along the acceleration vector. However, although simple and convenient to use, this equation is severely limited. It does not, for example, predict the significant transverse forces which arise in planar oscillatory flow nor indicate the way in which the coefficients might be expected to vary. Singh* (National Maritime Institute, Feltham, U.K.), Grass* (University College London) and Chaplin* (University of Liverpool, U.K.) discussed the dependence of these coefficients on Keulegan–Carpenter number and Reynolds number, and Verley & Moe* (VHL, Trondheim, Norway) the dependence on velocity ratio as well. In each case the dependence was attributed to changes in the vortex wake structure influencing the amplitude and also the phase of the forces. The significance of phase, for example, is demonstrated by computing the r.m.s. total-force coefficient, which varies smoothly and monotonically with Keulegan–Carpenter number unlike either the inertia or drag coefficients (Maull & Milliner 1978; Singh 1979). Most of the papers presented in this section therefore included flow visualization in order to provide at least qualitative information on the various modes of vortex shedding which were taking place.

Barnouin & Olagnon* (CNEXO/COB, Brest, France) presented the results of measurements of lateral displacement of a circular pile flexibly mounted vertically in a tidal stream. In this case the oscillatory velocity due to the transverse motion of the pile was comparable with the stream velocity. Vortices tended to be shed from the pile at the extremes of the pile's movement and were thus locked to the oscillatory motion. The amplitude of the pile motion was a function of depth and the authors assumed incoherent vortex shedding for the purposes of calculating forces. At the relatively large amplitudes of motion near the surface the vortex shedding was generally found to be controlled by the oscillatory part of the flow. Verley & Moe* observed the same phenomenon when studying a circular cylinder forced to oscillate in the streamwise direction. When the amplitude of the oscillatory motion was comparable with the stream velocity, vortices were shed in pairs at the end of the high relative velocity (upstream-going) half of the cycle. During the other half of the cycle these vortices were convected back past the cylinder by their own mutually-induced velocity.

In Verley & Moe's experiment the cylinder was oscillated on a pendulum in line with a uniform stream of velocity $\bar{V}$. Their measurements showed that for small values of $\bar{V}/U_0 < 3$ (U_0 being the amplitude of the oscillatory velocity of the pendulum), Morison's equation with a single drag coefficient did not give satisfactory results. For $\bar{V}/U_0 < 0{\cdot}25$ an equation with two independent drag coefficients, one for the steady drag and a second for the oscillatory drag, was required. Thus

$$F_D = \tfrac{1}{2}\rho C_{D_1} d\bar{V}^2 + \tfrac{1}{2}\rho C_{D_2} dU|U|,$$

where C_{D_2} took approximately the same value as in planar oscillatory flow at the same Keulegan–Carpenter number but without a current. For $\bar{V}/U_0 > 3$, Morison's equation gave good results with a single drag coefficient which approached the corresponding steady flow value for large Keulegan–Carpenter numbers.

The formation and growth of a separation region in a flow with streamwise oscillations was illustrated by Favier, Rebont & Maresca* (Institute de Mécanique des Fluides, Marseille, France) who presented a study of oscillatory separated flow past an aerofoil at high incidence. In this case the separation always grew from the leading edge during the decelerating half of the cycle. Then as the stream accelerated the separation point and vortex thus formed were convected downstream, leaving a growing length of attached flow on the upper surface.

In the absence of mean flow, the vortex-shedding process responds entirely to the oscillatory flow, leading to a variety of different vortex-shedding regimes. Both Singh* and Grass* showed examples of these flows over a range of Keulegan–Carpenter numbers. At high values of Keulegan–Carpenter number a large number of vortices were shed each half-cycle in a quasi-Kármán vortex street, with some random variation in the number of vortices shed. At low Keulegan–Carpenter number two vortices were shed per half-cycle. Each vortex tended to form a pair with a vortex of opposite sign swept back past the cylinder from the previous half-cycle. These vortex pairs then convected away from the cylinder at large angles to the direction of oscillation. Singh also found that this process was substantially the same for sharp-edged bodies such as flat plates and square prisms where the separation points were fixed. The presence of large intense vortices close to the body particularly during the phase when they were swept back past the body gave rise to much higher velocities than predicted by attached-flow theory. Grass* presented measurements of maximum velocities detected in the fluid during a flow cycle obtained by photographing particle streak lines. These indicated velocities in the region of returning vortices as high as double the overall maximum predicted by attached-flow theory.

These well-defined vortex structures, observed both by Singh* and Grass*, are not so far predicted by the numerical point vortex computations such as Stansby's (1977). It is significant in this context that, although these computations are felt to give fair predictions of the in-line forces in planar oscillatory flow, at least when compared with standard predictions using Morison's equation, they are not successful in predicting transverse forces. They should also be assessed for their ability to predict peak velocities in the flow field in view of the importance of these velocities in determining the forces on oil riser pipes adjacent to larger cylindrical members.

Planar oscillatory flow omits the important vertical velocity component usually present in waves. For example, the particle orbits in deep water waves are approximately vertical circles so that the wake of a horizontal cylinder does not return periodically past it as in planar oscillatory flow. Chaplin* presented the results of simulating such an interaction, by rotating a circular cylinder orbitally in a tank of otherwise still water. The cylinder was rotated so that its orientation remained fixed with respect to the tank. The latter was sufficiently large that after an initial starting-up flow a period of steady flow, representative of a horizontal cylinder in waves, ensued before the effects of the finite size of the tank interacted with the stirring process. Chaplin* presented results for the variation of the drag and inertia coefficients, which were obtained from the mutually orthogonal force components in this case, against Keulegan–Carpenter and Reynolds numbers. He also gave a flow visualization demonstration with a small bench-top model. The vortex wake generated by the cylinder in the range of Keulegan–Carpenter number studied (12–36) was seen to be always slightly inclined inwards relative to the tangent of the cylinder's orbit. He related this inwards inclination to the negative apparent mass measured on the cylinder.

Vortex shedding from isolated edges in oscillatory flow was also discussed. Patel* (University College London) showed that vortices shed from the sharp right-angle bilge of a rolling barge contributed significantly to the damping of the motion. The vortex-shedding process was shown in a flow visualization of the motion. However the vortices were not obviously seen to be shed in the contra-rotating pairs observed by Graham* in visualizations of oscillatory flow past a single sharp 30° edge. This may have been due to the fairly rapid diffusion of the dye used to mark the vortices in the rolling-barge case.

Knott & Mackley* (University of Sussex, U.K.) presented measurements and visualization of the flow in and out of a sharp-lipped tubular wave-energy device. These also showed that the formation of ring vortices at the lip of the intake were important in determining energy losses in the device. A vortex ring structure somewhat similar to that predicted by de Bernardinis & Parker* in oscillatory flow through an orifice plate was observed but no quantitative measurements of the vortices were available.

As an alternative to the use of Morison's equation the forces induced on bluff bodies by vortex shedding are generally calculated by application of Blasius equation in either the physical or a transformed plane in the numerical discrete-vortex calculations. This requires a knowledge of the strengths and paths of the point vortices at each instant of the flow. Maull & Milliner (1978) have suggested that this equation might also be used as a basis for predicting forces from observations of the motion and strength of the large-scale vortex structures in experiments. To do this properly requires much more detailed measurements of the instantaneous velocity fields than have been obtained so far. However the studies of vortex shedding presented at this Colloquium represent an important step forward.

6. Conclusions

This meeting was initiated by a feeling that many of the new phenomena now being discovered in oscillatory and wave flows past bluff bodies could be more readily understood by reference to studies in the more thoroughly researched field of vortex shedding in unidirectional streams. While confirming that this was true the meeting also concluded that there are still a number of interesting unresolved problems in unidirectional flows.

One of the most important aspects which emerged from the Colloquium was the development, since the holding of the last Euromech on the subject, of numerical methods to predict two-dimensional flows with vortex shedding and the application of these methods to both new and classical flows. However it is clear that, although these methods have become fairly sophisticated and qualitatively the predictions of gross features of the flow such as Strouhal number and drag are often good, many important flow details are inaccurately predicted and empirical 'fixes' are frequently required to obtain realistic results. Significant questions were raised in this context over the applicability of two-dimensional calculations to flows in which three-dimensional effects are known to play an important role, and the degree to which this discrepancy can be allowed for by other techniques. Several methods also included viscous effects, but again it is not clear how well these are being modelled in the case of flow simulations using only relatively small numbers of vortices. Direct solutions of the Navier–Stokes equations (as shown at the meeting) are still only reliable at fairly modest Reynolds numbers. However it is to be hoped that a direct comparison between the two numerical methods (high-Reynolds-number discrete-vortex model with viscosity and low-Reynolds-number Navier–Stokes solution) may soon be made at an intermediate Reynolds number. This would remove some of the uncertainties introduced by adjusting two-dimensional discrete-vortex-model solutions to agree with experimental results influenced by three-dimensional effects.

In the area of two-dimensional bodies oscillating in a uniform stream it is now apparent that lock-in is rather better understood and modelled than it was in 1970. The nonlinear oscillator model has emerged as an important prediction method for vortex-induced oscillations. Questions still remain, however, as to whether all the observed experimental results can be explained in terms of a nonlinear lift term. Also researchers should attempt to model vortex-induced oscillations of bodies other than circular cylinders and in particular bodies with sharp edges should be considered.

Many papers at the Colloquium demonstrated what a very important role good flow visualization still has to play in our understanding of vortex shedding. As more and more ingenious attempts are made to model the details of the flow structures in numerical calculations, flow visualizations can offer valuable inspiration.

Papers presented at the meeting

E. Achenbach. Vortex shedding from rough cylinders in cross flow.

W. T. Ashurst. Piston-cylinder fluid motion via vortex dynamics.

J. L. Auger & J. Coutanceau. Characteristics of the air-flow through a tube-grid at relatively high Reynolds number.

B. G. Barnouin & M. M. Olagnon. Analysis of the dynamic response of a full-scale pile to the impulse forces caused by vortex shedding during hydroelastic oscillations.

P. W. Bearman & K. Kamemoto. Vortex shedding from two cylinders in a side-by-side arrangement: experiment and numerical simulation.

E. Berger, K. Breitschwerdt & T. Kobayashi. Comparison of oscillator-model theory with experiments on vortex-excited vibrations.

B. de Bernardinis & K. H. Parker. Unsteady flows for disks and orifices.

P. Bublitz. Unsteady pressure measurements on an oscillating circular cylinder.

G. Buresti & A. Lanciotti. Experiments on the flow field around a circular cylinder near a plane surface.

J. R. Chaplin. Circular orbital flow around a cylinder.

M. Coutanceau & R. Bouard. Some new aspects of the wake evolution behind an impulsively started cylinder.

J. Y. Dumaine, M. Lebouche & M. Martin. Response of a sudden-enlargement's wake to a pulsating flow: conditions of vortex shedding.

A. Dyment. The structure of the near wake of a bluff body in two-dimensional flow at large Reynolds numbers.

D. Favier, J. Rebont & C. Maresca. Vortex shedding from a body oscillating in-line in a uni-directional free stream and from a fixed body in plane oscillatory flow.

H. J. Gerhardt, C. Kramer & B. Kuhnert. Vortex shedding from stationary and oscillating rectangular prisms.

J. H. Gerrard. The wake of a stationary bluff body in a uniform stream and the effect of disturbances.

J. M. R. Graham. Vortex shedding from a single edge in oscillating flow.

A. J. Grass. Vortex-induced velocity magnification effects in oscillatory flow past circular cylinders.

M. E. Greenway. A modified vortex-street drag equation.

O. M. Griffin. Universal similarity in the wakes of stationary and vibrating bluff bodies.

G. F. Knott & M. R. Mackley. Eddy motions near plates and ducts induced by water waves and periodic flows.

G. Martinez, H. Boisson & H. Ha Minh. Vortex shedding from circular cylinders – a numerical simulation.

D. J. Maull. A linearized model of vortex shedding.

S. Nagano, M. Naito & H. Takata. A numerical analysis of two-dimensional flow past a rectangular cylinder by a discrete-vortex method.

M. H. Patel. The influence of vortex shedding on the roll motions of a flat-bottomed barge.

D. G. Petty. The effects of turbulence on the flow past bluff bodies: a classification and a challenge.

B. Py. Some comments on the instrumental reconstruction of the flow field around a cylinder in uniform flow.

S. Singh. Flow visualization of vortex shedding from a bluff body in oscillatory flow.

P. K. Stansby. Numerical study of vortex shedding from two circular cylinders.

T. Staubli. An investigation of the fluctuating forces on a transverse-oscillating circular cylinder in a unidirectional flow.

R. L. P. Verley & G. Moe. Steady and oscillating forces on a cylinder oscillating in-line with a steady current.

M. Welsh, R. Parker & S. Stoneman. Interaction between vortex shedding and acoustic resonance.

M. M. Zdravkovich. Variation on the theme of mechanics of vortex shedding.

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