BRIEF COMMUNICATIONS

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Kármán vortex formation from a cylinder: Role of phase-locked Kelvin–Helmholtz vortices

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The formation length of Kármán vortices can be drastically reduced by small-amplitude excitation at a frequency much higher than the natural frequency of Kármán vortex formation, namely the Kelvin–Helmholtz (KH) frequency of the separating shear layer. Phase-locked patterns of KH vortices are attainable. These spatially stationary patterns coexist, however, with the spatial and temporal development of the Kármán vortices.

Schiller and Linke[1] first observed the large variation in the formation length of Kármán vortices over the range of Reynolds number from 10^3 to 10^4. Since then, a number of insightful investigations have demonstrated substantial variations of the fluctuating lift coefficient $\tilde{C}_L$ and the mean base pressure coefficient C_{pb} when the Reynolds number is varied over this range. On the other hand, relatively insignificant changes in Strouhal number S occur. Gerrard,[2] Roshko and Fiszdon,[3] McCroskey,[4] Unal and Rockwell,[5] Zdravkovich,[6] and Szepessy and Bearman[7] have assessed these features from various perspectives. Lin, Towfighi, and Rockwell[8] have quantitatively characterized the instantaneous and averaged structure of the near-wake, which involves a substantial decrease in the vortex formation length, as the Reynolds number is increased from 10^3 to 10^4.

A crucial feature of the flow structure over this range of Re is the onset of the Kelvin–Helmholtz (KH) instability in the free shear layer formed from the surface of the cylinder. This instability eventually leads to small-scale vortices, often called Bloor–Gerrard vortices, after Bloor[9] and Gerrard.[2] Gerrard,[10] Wei and Smith,[11] Kourta *et al.*,[12] Unal and Rockwell,[5] Filler, Marston, and Mih,[13] Ahmed, Khan and Bays-Muchmore,[14] and Sheridan *et al.*[15] have employed qualitative flow visualization and pointwise velocity measurements to characterize various aspects of these small-scale vortices, which eventually become part of the large-scale Kármán vortices. Since the origin of the small-scale KH vortices is a convective instability, it should be possible to control their development with small-amplitude perturbations at an appropriate frequency. Indeed, Filler *et al.*[13] and Sheridan *et al.*[15] have demonstrated the sensitivity of the KH instability to imposed excitation and visualized the consequent influence on the Kármán vortices.

The overall objective of the present investigation is to determine whether phase-locked patterns of KH vortices are attainable at very low amplitudes of excitation. Emphasis is on the interrelationship between possible phase-locking of the KH patterns and the manner in which the non-phase-locked Kármán vortices develop in space and time. All these features are quantitatively interpreted with the aid of instantaneous distributions of vorticity and streamline patterns, allowing definition of the instantaneous topology of the near wake.

A cylinder of diameter $D=51$ mm was mounted horizontally in a water channel having a height of 597 mm, a width of 914 mm, and free-stream velocities of 91 and 183 mm/s. The corresponding values of Reynolds number were Re=5000 and 10 000. The effective length of the cylinder, 10.3D, was determined after considering the results of Szepessy and Bearman.[7] The cylinder was subjected to perturbations in the cross-flow direction at a desired amplitude and frequency by a computer-controlled motor system located above the free surface.

High-image-density particle image velocimetry was employed in order to determine the instantaneous structure of the flow over a plane orthogonal to the axis of the cylinder. This technique is described by Rockwell *et al.*,[16] Rockwell *et al.*,[17] and Rockwell and Lin.[18] In essence, an argon–ion laser beam (four watts) was conditioned by focusing optics, then deflected from a mirror having 72 facets, in order to provide high-speed scanning at frequency of 626 Hz over the plane of interest.

The flow was seeded with 12 μm diameter metallic-coated particles. Multiply exposed images of these particles were recorded at a lens magnification $M=0.34$ on high resolution Kodak Tmax 35 mm film. Subsequently, the images were digitized at a resolution of 125 pixels/mm. Then, the velocity vector was determined at successive locations using an interrogation window size of 0.8 mm×0.8 mm with 50% overlap. A single value of velocity was obtained at each location of the interrogation window using the single-frame, cross-correlation approach of Meinhart, Prasad, and Adrian.[19]

Figure 1 shows contours of constant positive (white) and negative (gray) instantaneous vorticity formed from the stationary cylinder. At Re=5000, the shear layers do not exhibit small-scale concentrations of vorticity, as typically observed at Re=5000 in previous investigations. Since these concen-

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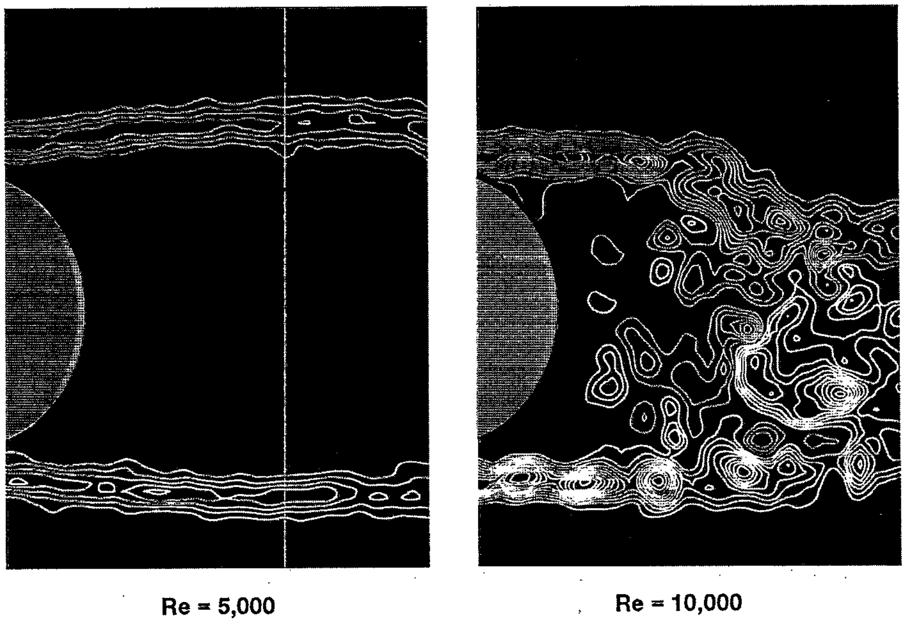


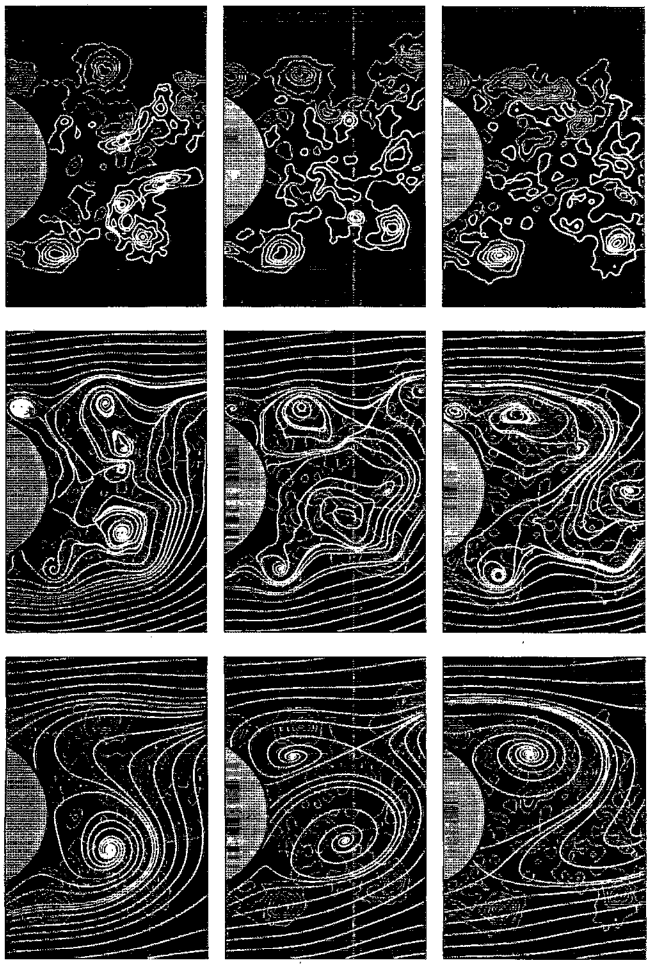
FIG. 1. Contours of constant positive (white) and negative (gray) vorticity in the near-wake of a stationary circular cylinder at Re=5000 and 10 000.

trations arise from a convective instability of the KH type, their onset is extremely sensitive to the disturbance level of the free stream, which was very low in the present investigation (Chyu[20]). Moreover, Kármán vortices form well downstream of the base of the cylinder; in fact, they are not visible within the field of view of Fig. 1. On the other hand, at Re=10 000, pronounced concentrations of vorticity arising from the KH instability exist at locations immediately downstream of separation. Moreover, large-scale agglomerations of positive (white) and negative (gray) vorticity, which involve small-scale concentrations of vorticity, are clearly evident. These large-scale structures, which represent the initial stage of formation of the Kármán vortices, are located relatively close to the base of the cylinder. It is evident that there is a strong interrelationship between the development of the KH vortices and the formation length of the Kármán vortices. An important issue is whether artificially generated KH vortices in the shear layers at Re=5000 can induce the onset of the Kármán vortices much closer to the base of the cylinder.

The shear layers at Re=5000 were subjected to controlled perturbations by oscillating the cylinder in the cross-stream direction at an amplitude $A/D=0.04$. The frequency of excitation corresponded to the inherent frequency of the KH instability of the separating shear layer, i.e., $fD/U=1.41$. A detectable response could be attained at amplitudes as low as $A/D=0.001$; in this case, the vorticity concentrations were of smaller scale and appear farther downstream. The effect of A/D is described by Chyu.[20] A value of $A/D=0.04$ ensures that the KH vortices are consistently "locked on" to the cylinder motion.

Figure 2 shows the response of the near wake. Each of the three columns of images corresponds to successive cycles $N=1$, 2, and 3 of the cylinder oscillation. All images were taken at a position corresponding to the maximum positive displacement of the cylinder. The top row of images, representing instantaneous contours of constant vorticity, and the middle row of images, depicting superposition of streamlines and vorticity contours, show that the first two KH vortices from the bottom as well as from the top of the cylinder are essentially "locked-on," i.e., they are spatially repetitive, appearing at nearly the same location from cycle to cycle. It is well known that the lock-on of large-scale Kármán vortex formation is attainable for controlled oscillations of a cylinder at much larger amplitudes and lower frequencies. In this study we demonstrate that such lock-in is attainable for the KH vortices, even under the potential influence of self-excited Kármán vortices.

In order to determine whether well-defined Kármán vortices do indeed coexist with this locked-on state of the KH vortices, the instantaneous velocity fields were subjected to a spatial filter, whereby all length scales smaller than $0.76D$ were filtered out, leaving only scales larger than this cutoff. For filtering at scales smaller than $0.76D$, remnants of the small-scale structures were still detectable. The bottom row of images of Fig. 2 shows patterns of instantaneous streamlines determined from the filtered velocity field. They are superposed on the patterns of locked-on KH vortices. This superposition illustrates the instantaneous relationship between the small and large scales of the near-wake region. Since the excitation frequency $f_e=6.7\ f_{VK}$, in which f_{VK} is the inherent frequency of Kármán vortex formation, the Kármán vortices have a wavelength and scale much larger than KH vortices. The streamline topology shows a Kármán vortex from the bottom of the cylinder at $N=1$. During the second cycle of the cylinder motion, corresponding to $N=2$, the onset of formation of the Kármán vortex from the upper side of the cylinder is evident and, subsequently, the image at $N=3$ shows its further development. Correspondingly, at this same instant, the topology of the Kármán vortex from the bottom of the cylinder is no longer visible within the field of view. This streamline topology associated with the formation of the Kármán vortices, consisting of stable and unstable foci (vortex centers) and saddlepoints is remarkably similar



N=1 2 3

FIG. 2. Flow structure in the near-wake of a circular cylinder perturbed at a frequency corresponding to the inherent frequency of the KH instability at Re=5000 and at an amplitude $A/D=0.04$. Top row of images shows contours of constant, instantaneous positive (white) and negative (gray) vorticity at three successive cycles $N=1$, 2, and 3 of cylinder oscillation. The middle row illustrates the superposition of instantaneous streamline patterns and contours of constant vorticity. Bottom row shows the superposition of contours of constant vorticity and instantaneous streamlines corresponding to low-pass filtered velocity field.

to that observed at much higher Reynolds number by Perry and Steiner,[21] in which vortex formation occurs very close to the base of the body. In fact, the Kármán vortices form even closer to the base than for the case of the stationary cylinder at Re=10 000; the effective Re due to excitation therefore exceeds this value. Moreover, the spiral patterns of the streamlines indicate spanwise three-dimensionality, which remains for further study.

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