Horowitz, M.; Williamson, C. H. K.

The effect of Reynolds number on the dynamics and wakes of freely rising and falling spheres. (English) Zbl 1189.76152

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Summary: We study the effect of the Reynolds number (Re) on the dynamics and vortex formation modes of spheres rising or falling freely through a fluid (where $Re = 100 - 15000$). Since the oscillation of freely falling spheres was first reported by Newton (University of California Press, 3rd edn, 1726, translated in 1999), the fundamental question of whether a sphere will vibrate, as it rises or falls, has been the subject of a number of investigations, and it is clear that the mass ratio m^* (defined as the relative density of the sphere compared to the fluid) is an important parameter to define when vibration occurs. Although all rising spheres ($m^* < 1$) were previously found to oscillate, either chaotically or in a periodic zigzag motion or even to follow helical trajectories, there is no consensus regarding precise values of the mass ratio (m^*_{crit}) separating vibrating and rectilinear regimes. There is also a large scatter in measurements of sphere drag in both the vibrating and rectilinear regimes.

In our experiments, we employ spheres with 133 combinations of m^* and Re, to provide a comprehensive study of the sphere dynamics and vortex wakes occurring over a wide range of Reynolds numbers. We find that falling spheres ($m^* > 1$) always move without vibration. However, in contrast with previous studies, we discover that a whole regime of buoyant spheres rise through a fluid without vibration. It is only when one passes below a critical value of the mass ratio, that the sphere suddenly begins to vibrate periodically and vigorously in a zigzag trajectory within a vertical plane. The critical mass is nearly constant over two ranges of Reynolds number ($m^*_{crit} \approx 0.4$ for $Re = 260$ and $m^*_{crit} \approx 0.6$ for $Re > 1550$). We do not observe helical or spiral trajectories, or indeed chaotic types of trajectory, unless the experiments are conducted in disturbed background fluid. The wakes for spheres moving rectilinearly are comparable with wakes of non-vibrating spheres. We find that these wakes comprise single-sided and double-sided periodic sequences of vortex rings, which we define as the 'R' and '2R' modes. However, in the zigzag regime, we discover a new '4R' mode, in which four vortex rings are created per cycle of oscillation. We find a number of changes to occur at a Reynolds number of 1550, and we suggest the possibility of a resonance between the shear layer instability and the vortex shedding (loop) instability. From this study, ensuring minimal background disturbances, we have been able to present a new regime map of dynamics and vortex wake modes as a function of the mass ratio and Reynolds number $\{m^*, Re\}$, as well as a reasonable collapse of the drag measurements, as a function of Re, onto principally two curves, one for the vibrating regime and one for the rectilinear trajectories.

MSC:

76D25 Wakes and jets
76D17 Viscous vortex flows

Full Text: DOI

References:

[1] DOI: 10.2514/2.1686 · doi:10.2514/2.1686
[2] Möller, Physik. Zeit. 39 pp 58– (1938)
[3] DOI: 10.1063/1.2909609 · Zbl 1182.76238 · doi:10.1063/1.2909609
[4] DOI: 10.1146/annurev.fluid.32.1.659 · Zbl 0989.76082 · doi:10.1146/annurev.fluid.32.1.659
[5] DOI: 10.1002/aic.690110130 · doi:10.1002/aic.690110130
[6] DOI: 10.1006/jfls.2000.0356 · doi:10.1006/jfls.2000.0356
[7] DOI: 10.1063/1.1706409 · doi:10.1063/1.1706409
[8] DOI: 10.1063/1.870043 · Zbl 1147.76341 · doi:10.1063/1.870043
[9] Magarvey, Can. J. Phys. 39 pp 1418– (1961) · doi:10.1139/p61-169

[10] DOI: 10.1016/j.euromechflu.2005.10.001 · Zbl 1093.76014 · doi:10.1016/j.euromechflu.2005.10.001
[11] DOI: 10.1063/1.1485767 · Zbl 1185.76401 · doi:10.1063/1.1485767
[12] Boillat, J. Hydraul. Div. ASCE 107 pp 1123– (1981)
[13] DOI: 10.1098/rspa.1928.0077 · Zbl 54.0912.04 · doi:10.1098/rspa.1928.0077
[14] DOI: 10.1016/S0889-9746(88)90058-8 · doi:10.1016/S0889-9746(88)90058-8
[15] DOI: 10.1017/S0022112064000726 · Zbl 0119.41703 · doi:10.1017/S0022112064000726
[16] DOI: 10.1098/rspa.1926.0017 · Zbl 52.0865.01 · doi:10.1098/rspa.1926.0017
[17] DOI: 10.1146/annurev.fluid.36.050802.122128 · Zbl 1125.74323 · doi:10.1146/annurev.fluid.36.050802.122128
[18] DOI: 10.1002/andp.19273870405 · doi:10.1002/andp.19273870405
[19] Wieselsberger, Physik. Zeit. 22 pp 321– (1921)
[20] Allen, Phil. Mag. 50 pp 519– (1900) · doi:10.1080/14786440009463941
[21] Leweke, Phys. Fluids 11 pp S12– (1999) · doi:10.1063/1.4739162
[22] DOI: 10.1088/0951-7715/18/1/000 · Zbl 1109.76025 · doi:10.1088/0951-7715/18/1/000
[23] DOI: 10.1016/j.ijmultiphaseflow.2009.01.005 · doi:10.1016/j.ijmultiphaseflow.2009.01.005
[24] DOI: 10.1016/S0045-7930(99)00023-7 · Zbl 1012.76052 · doi:10.1016/S0045-7930(99)00023-7
[25] DOI: 10.1143/JPSJ.52.3373 · doi:10.1143/JPSJ.52.3373
[26] DOI: 10.1016/j.ijmultiphaseflow.2007.05.002 · doi:10.1016/j.ijmultiphaseflow.2007.05.002
[27] DOI: 10.1063/1.866937 · doi:10.1063/1.866937
[28] DOI: 10.1063/1.2090327 · Zbl 1188.76069 · doi:10.1063/1.2090327
[29] DOI: 10.1002/aic.690420630 · doi:10.1002/aic.690420630
[30] DOI: 10.1080/14786441108635254 · doi:10.1080/14786441108635254
[31] DOI: 10.1017/S0022112098003206 · doi:10.1017/S0022112098003206
[32] DOI: 10.1017/S0022112004009164 · Zbl 1065.76068 · doi:10.1017/S0022112004009164
[33] DOI: 10.1029/JZ069i004p00591 · doi:10.1029/JZ069i004p00591
[34] DOI: 10.1017/S0022112004008778 · Zbl 1163.76348 · doi:10.1017/S0022112004008778
[35] Schmiedel, Physik. Zeit. 17 pp 593– (1928)
[36] Schmidt, J. Fluid Mech. 61 pp 633– (1920)
[37] DOI: 10.1063/1.2992126 · Zbl 1182.76328 · doi:10.1063/1.2992126
[38] Schlichting, Boundary Layer Theory (1955) · Zbl 0065.18901
[39] DOI: 10.1115/1.2909415 · doi:10.1115/1.2909415
[40] DOI: 10.1016/j.jfluidstructs.2006.04.012 · doi:10.1016/j.jfluidstructs.2006.04.012
[41] DOI: 10.1002/zamm.19230030202 · Zbl 49.0615.06 · doi:10.1002/zamm.19230030202
[42] Richardson, Trans. Inst. Chem. Engrs 32 pp 35– (1954)
[43] DOI: 10.1135/cccc19930961 · doi:10.1135/cccc19930961
[44] DOI: 10.1002/aic.690321213 · doi:10.1002/aic.690321213
[45] DOI: 10.1017/S0022112000008880 · Zbl 1156.76419 · doi:10.1017/S0022112000008880
[46] DOI: 10.1103/PhysRevE.77.055308 · doi:10.1103/PhysRevE.77.055308
[47] DOI: 10.1017/S0022112005003757 · Zbl 1156.76315 · doi:10.1017/S0022112005003757
[48] DOI: 10.1017/S0022112096004326 · doi:10.1017/S0022112096004326
[49] DOI: 10.1017/S0022112002002318 · Zbl 1024.76507 · doi:10.1017/S0022112002002318
[50] Newton, Philosophia Naturalis Principia Mathematica (1726)
[51] DOI: 10.1017/S0022112000001233 · Zbl 0988.76027 · doi:10.1017/S0022112000001233
[52] DOI: 10.1017/S0022112093002150 · Zbl 0780.76027 · doi:10.1017/S0022112093002150
[53] DOI: 10.1063/1.1761531 · doi:10.1063/1.1761531
[54] DOI: 10.1175/1520-0450(1965)004<0131:SIBM>2.0.CO;2 · doi:10.1175/1520-0450(1965)004<0131:SIBM>2.0.CO;2
[55] DOI: 10.1017/S0022112004001831 · Zbl 1065.74020 · doi:10.1017/S0022112004001831
[56] DOI: 10.1017/S0022112006002266 · Zbl 1165.76325 · doi:10.1017/S0022112006002266
[57] DOI: 10.1017/S0022112006003685 · Zbl 1108.76310 · doi:10.1017/S0022112006003685
[58] DOI: 10.1103/PhysRevLett.88.014502 · doi:10.1103/PhysRevLett.88.014502
[59] DOI: 10.1002/(SICI)1097-0363(19990815)30:7<921::AID-FLD875>3.0.CO;2-3 · Zbl 0957.76060 · doi:10.1002/(SICI)1097-0363(19990815)30:7<921::AID-FLD875>3.0.CO;2-3

