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Luis Blay Esteban

# Dynamics of Non-Spherical Particles in Turbulence

Doctoral Thesis accepted by  
University of Southampton, UK

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*To Mum and Dad...*

# Supervisor's Foreword

One of the beautiful things about fluid mechanics is the discovery of complexity in the most simple things. In this thesis, we investigate the motion of falling planar objects in still and turbulent fluid—much like a coin being dropped into water and this descending down describing a “fluttering” type of motion. The project was inspired by a supporting company, who reprocess mixed waste that contains metal, plastics, glass, and organics to separate out these streams and then sell the metal and washed glass. They use a turbulent water tank and make use of the different ways in which metal, glass, and plastic particles move in this flow to separate them. This thesis provides interesting findings that help to understand how particle shape and background turbulence affect the particle descent style.

The Ph.D. research was entirely experimental and makes use of the power of modern-day digital cameras. These were used to record the descending particle and bespoke software to track the particle position, velocity, and acceleration along the 3D trajectory. In still fluid, we found that the motion of disks follows a pendulum motion where the origin of the “string” connecting the particle is falling with the mean fall velocity of the particle. Further studies investigated the effect of other planar shapes, such as squares and hexagons and compared these to the classical disk shape. It was found that the particle shape has an impact on the key characteristics of the particle trajectory. Also, 3D flow field measurements behind the particle revealed the influence of the frontal shape on the wake structure shed.

The work on particle descent in turbulent flows required a large volume of controlled isotropic turbulence in which to study the motion of the particle. A large tank agitated by a dual array of bilge pumps was constructed and this permitted the study of the decaying isotropic turbulence for a far longer time that is possible in typical wind tunnel configurations. The turbulence generated was characterized in detail, and the evolution of the decaying turbulence was carefully investigated.

Finally, the study of particle motion in turbulent flows revealed that the falling style becomes a combination of “noisy” pendulum motions and “rare” events; these being sections at high velocity or “levitating” states, before being “caught” and resuming the “noisy” pendulum motion.

Southampton, UK  
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Prof. John Shrimpton

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2. **L.B. Esteban**, J. S. Shrimpton, B. Ganapathisubramani. Edge effects on the fluttering characteristics of freely falling planar particles. *Physical Review Fluids* 3, 064302 (2018)
3. **L.B. Esteban**, J. S. Shrimpton, B. Ganapathisubramani. Study of the circularity effect on drag of disk-like particles. *International Journal of Multiphase Flow*, 110: 189–197 (2019)
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I met Prof. John Shrimpton once this project was done and after a few meetings he accepted my application to undertake my Ph.D. studies under his (and Bharath's) supervision. I only have nice words to explain how they treated me during these 3 years. They gave me very good guidance but always with the necessary freedom that allows you to fail, learn, and improve. They supported my ideas and they were always there when I needed them. Thanks for all these moments, from the long discussions in the faculty to the always welcomed visits to the lab.

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# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Aim of the Industrial Research Project	1
1.2	The Need for Fundamental Research	2
1.3	Introduction to Multiphase Flows	3
1.3.1	Scope of the Literature Review	4
1.3.2	Plan of the Chapter	5
1.4	Equations of Motion for an Arbitrary Object in a Continuum Fluid	5
1.4.1	Spherical Shape and Stokes Flow Simplification	6
1.4.2	'Heavy' Simplification	7
1.5	Validity of 'Small' 'Heavy' Spheres in Turbulent Flows	10
1.5.1	Physics of 'Small' 'Heavy' Particles in Homogeneous Turbulence	11
1.6	'Large' 'Light' Spheres	13
1.7	Aspherical Objects	16
1.7.1	Geometrical Classification of Shape	16
1.7.2	Shape Factors for Quasi-spherical Objects	17
1.7.3	Drag Correlations	19
1.7.4	Secondary Motion	21
1.8	Aspherical Particles in Turbulence	23
1.9	Summary of the Literature Review	24
1.10	Case Study of the Problem	25
1.10.1	Aquavitrum Technology	25
1.10.2	Aquavitrum Water Tank	25
1.10.3	Working Principle	26
1.10.4	Particle Characterization	27

1.10.5	Homogeneous Isotropic Turbulence . . . . .	28
1.10.6	The Turbulent Box Assumption . . . . .	29
1.11	Organisation of the Thesis . . . . .	32
	References . . . . .	32
<b>2</b>	<b>Planar Particles in Quiescent Fluid . . . . .</b>	<b>37</b>
2.1	Introduction . . . . .	37
2.2	Experimental Techniques . . . . .	39
2.2.1	Particle Tracking . . . . .	39
2.2.2	Volumetric PIV . . . . .	41
2.3	Settling Dynamics of Disk-Like Particles . . . . .	42
2.3.1	Methods . . . . .	42
2.3.2	Results . . . . .	44
2.3.3	Drag Correlation for Planar Irregular Particles . . . . .	50
2.3.4	Summary . . . . .	52
2.4	Planar $N$ -Sided Particles in Quiescent Flow . . . . .	53
2.4.1	Methods . . . . .	54
2.4.2	Determination of Non-dimensional Parameters and Phase Diagram . . . . .	54
2.4.3	Results . . . . .	56
2.4.4	Revisiting the Phase Diagram . . . . .	65
2.4.5	Simple Pendulum Approach: Planar Flutter . . . . .	67
2.4.6	Simple Pendulum Approach: Transition Motion . . . . .	68
2.4.7	Andersen Approach to Planar Flutter . . . . .	70
2.4.8	Summary . . . . .	74
2.5	Wake Characteristics Behind $N$ -Sided Polygons Settling in Quiescent Flow . . . . .	76
2.5.1	Methods . . . . .	76
2.5.2	Results . . . . .	77
2.5.3	Trajectory Characteristics . . . . .	77
2.5.4	Wake Characteristics . . . . .	80
2.5.5	Summary . . . . .	85
2.6	Conclusion . . . . .	87
	References . . . . .	87
<b>3</b>	<b>Facility for Turbulence Generation . . . . .</b>	<b>89</b>
3.1	Introduction . . . . .	89
3.1.1	Turbulence in Zero-Mean Flow Facilities . . . . .	90
3.1.2	Decay of Homogeneous Turbulence . . . . .	91
3.1.3	Confinement Effects on Decay of Homogeneous Turbulence . . . . .	94
3.2	Experimental Setup and Measurement Technique . . . . .	95
3.2.1	Facility Description and Firing Protocol . . . . .	95
3.2.2	Particle Image Velocimetry (PIV) Measurements . . . . .	97

- 3.3 Results for Stationary Turbulence . . . . . 98
  - 3.3.1 Single-Point Statistics and Flow Quality . . . . . 98
  - 3.3.2 Multi-point Statistics and Flow Scales . . . . . 99
- 3.4 Results for Decaying Turbulence . . . . . 104
- 3.5 Summary . . . . . 114
- References . . . . . 116
- 4 Disks Falling Under Background Turbulence . . . . . 121**
  - 4.1 Introduction . . . . . 121
    - 4.1.1 Spherical Particles Settling Under Turbulence . . . . . 122
    - 4.1.2 Quasi-spherical Particles Settling Under Turbulence . . . . . 123
  - 4.2 Experimental Setup . . . . . 124
  - 4.3 Results . . . . . 126
    - 4.3.1 Disks in Quiescent Flow . . . . . 126
    - 4.3.2 Disks in Turbulent Flow . . . . . 131
  - 4.4 Summary . . . . . 153
  - References . . . . . 153
- 5 Conclusions . . . . . 157**
  - 5.1 Future Work . . . . . 159
  - References . . . . . 159
- Appendix: Equations of Motion . . . . . 161**

# Abbreviations

BBO	Basset, Boussinesq, and Oseen equation
CDF	Cumulative Density Function
CSF	Corey Shape Function
DNS	Direct Numerical Simulation
FOV	Field of View
HD	Homogeneity Deviation
HIT	Homogeneous Isotropic Turbulence
LES	Large Eddy Simulations
MEF	Mean Flow Factor
M-R	Maxey-Riley equation
MRF	Material Recovery Facility
MSRF	Mean Strain Rate Factor
OU	Ornstein Uhlenbeck process
PDF	Probability Density Function
PIV	Particle Image Velocimetry
PLA	Poly lactide
SFT	Structure Function Fit
TKE	Turbulent Kinetic Energy

# Non-dimensional Quantities

$Ar$	Archimedes number
$C_D$	Drag Coefficient
$Fr$	Froude number
$G$	Galileo number
$Q$	Isoperimetric quotient
$Re$	Reynolds number
$St$	Stokes number
$St$	Strouhal number
$X$	Best number

# Roman Symbols

$b$	Particle body force
$d$	Particle diameter
$d_{eq}$	General particle equivalent diameter
$d_{V_{eq}}$	Sphere diameter with equivalent volume
$f$	Frequency
$g$	Acceleration due to gravity
$k$	Turbulent kinetic energy
$\ell$	Particle equivalent diameter ( $D_c/Q$ )
$m$	Mass
$t$	Particle thickness
$t_L$	Eddy turnover time
$A_p$	Projected area
$D$	Disk diameter with equivalent particle volume
$D_c$	Diameter of circumscribed disk
$E$	Energy spectrum
$F_D$	Drag force
$I$	Mass moment of inertia
$L$	Integral length scale
$P$	Particle perimeter
$Q_{dis}$	Water discharge
$R$	Distance from origin
$S$	Skewness factor
$T$	Energy transfer spectrum
$T_i$	Torque
$T_{v_z}$	Timescale of descent velocity fluctuations
$U$	Velocity
$U_t$	Terminal velocity

# Greek Symbols

$\alpha_{v_z}$	Std. of descent velocity fluctuations
$\beta$	Thickness-to-width ratio
$\epsilon$	Energy dissipation rate
$\eta$	Kolmogorov length scale
$\theta$	Particle nutation angle
$\theta_0$	Max. angle of pendulum model
$\kappa$	Kurtosis
$\lambda$	Taylor length scale
$\mu$	Viscosity
$\nu$	Kinematic viscosity
$\rho$	Density
$\sigma$	Total stress tensor
$\tau$	Response time
$\tau_d$	Fluid timescale at scale $d$
$\tau_{p\text{eff}}$	Measured particle response time
$\tau_f$	Fluid response time
$\tau_v$	Viscous relaxation time
$\tau_w$	Wall shear stress
$\phi$	Fractional number of pumps in operation
$\phi_v$	Fractional volume of the dispersed phase
$\psi$	Sphericity
$\omega$	Angular velocity
$\Lambda$	Production rate of total kinetic energy



# Subscripts

$d$	Based on particle diameter scale
$f$	Fluid magnitude
$min$	Smallest value
$med$	Intermediate value
$max$	Maximum value
$p$	Particle magnitude
$q$	Magnitude in quiescent flow
$r$	Relative to disk magnitude
$z$	Vertical magnitude
$L$	Based on integral scale
$\eta$	Based on Kolmogorov scale
$\lambda$	Based on Taylor scale
$\parallel$	Parallel to the motion
$\perp$	Perpendicular to the motion
1	Along the horizontal direction
2	Along the vertical direction

# Superscripts

- .\* Non-dimensional value
- ./ Root mean square

# Operators

$\nabla$	Divergence
$\langle \cdot \rangle$	Spatial average
$\bar{\cdot}$	Time average
$\mathbf{v}$	Vector form of $v$