MICROGRAVITY

FREE FALL AND G-FORCE

Microgravity is a special environment: a body is under microgravity (μg) when it is in free fall (or almost).

Free fall is falling under vacuum, i.e. moving under gravitational forces alone, without other disturbances (not even air resistance). The simplest fall is vertically downwards when the body is left to drop, but it may actually be vertically upwards if there is an initial speed in that direction, or with lateral displacement if an initial lateral speed was applied. For very high initial lateral speeds, the body may go around the Earth, or even go far away (always describing a Keplerian orbit).

Acceleration (path acceleration) is the rate of change of velocity of a body, $\vec{a} \equiv \mathrm{d}^2\vec{x}/\mathrm{d}t^2$, and is due to force imbalance; if we group all forces on the body as surface forces $\vec{F}_s$ on the outside and volumetric forces $\vec{F}_v$ on each bit inside the body, then $m\vec{a} = \vec{F}_{\mathrm{net}} = \vec{F}_s + \vec{F}_v$. Surface forces are commonly due to the body being touched by something else (our hand, another solid, or a fluid). Volumetric forces are commonly due to gravitation (weight). Recall that acceleration in a uniform circular motion is $a=v^2/R$ (pointing to the centre) where v is the speed and R the path radius.

Normal gravity is the acceleration of free fall on the Earth surface, of modulus close to g=9.8 m/s^2 and going vertically downwards $\vec{g} = -9.8\vec{e}_z$, where $\vec{e}_z$ is the unit vector along the z-axis, upwards; symbol g is preferred to a_{g} for gravity acceleration, for simplicity.

Weight is the force due to gravity, $\vec{F}_{\mathrm{w}} \equiv m\vec{g}$, where m is the mass of the body (kilograms), and $\vec{g}$ is local gravity, although normal gravity is assumed if not specified otherwise; hence the weight of a 75 kg person is $\vec{F}_{\mathrm{w}} \equiv m\vec{g} = (75\ \mathrm{kg})\cdot(-9.8\vec{e}_z) = -735\vec{e}_z\ \mathrm{N}$, i.e. 735 newton downwards, or in common parlance, a weight of (corresponding to) 75 kg. Weight can be balanced globally in a body by opposing a force on its surface (internal stresses transmit forces to every point), but it is much more difficult to balance weight locally at every point within the body (hence relieving the stresses), the easiest way being to let the body fall under the sole forces of gravity.

Weightlessness is used as a synonym of μg, but only understanding that the ‘apparent absence of weight’ applies to every bit of a body; e.g. a balloon floating in air is not in weightlessness, it is under normal gravity (1g), with the supporting force applied by the air all over its surface (Archimedes’ Principle). A rising balloon weighs too. We should stressed the word 'apparent' in the proper understanding of weightlessness: a 75 kg person floating within the ISS has almost the same weight (89 %) as standing on ground, namely 651 N versus 735 N, because gravity acceleration falls with altitude h according to Newton's general gravitation law $g=F_G/m=GM/r^2=g_0(R/(R+h))^2$, where F_G is the force of gravitational attraction between a body of mass m and the Earth (of mass M and radius R), G is a universal constant, and $r=R+h$ is the distance between centres of mass. A person in an orbiting space station floats not because lack of gravity but because the same gravitational acceleration applies unto the spacecraft.

Non-free-fall acceleration, $\vec{a}_{\rm nff}$, named g-force (though not a force but an acceleration), is defined as path acceleration minus local gravity, $\vec{a}_{\rm nff}=\vec{a}-\vec{g}$, and measures the non-gravitational force per unit mass, which causes stress and strain on the object; e.g.:

- A body standing on the ground, motionless, has $a=0$, but $a_{\rm nff}=1g$ (from $\vec{a}_{\rm nff}=\vec{a}-\vec{g}$). Notice the correct writing of $a_{\rm nff}=1g$, i.e. a number (1) times an acceleration (g=9.8 m/s^2), instead of the writing as $a_{\rm nff}$=1 g, where 'g' would stands as a non-SI unit of acceleration.
- An astronaut during launch to the space station, experiences a small acceleration (starting about 1.5g after launch, i.e. ascending at about 5 m/s^2, and growing to a maximum of 3g, with a total duration of less than 10 minutes), but higher g-loads must be suffered during descent from orbit (though of much shorter duration). The upper safe limit for manned return to Earth from LEO or lunar return is 10g to avoid lung crushing, though impacts of up to 20g have been endured.

G-force must not be confused with the load factor used in aeronautics, which is the ratio of aircraft-lift to aircraft-weight, $n\equiv L/W$, an appropriately signed non-dimensional scalar (often incorrectly written 'g-units', e.g. n=3g), although both terms (g-force and load factor) are often used undistinguishably in astronautics. Notice that very high g-loads only appear during aerodynamic deceleration (reentry, abrupt manoeuvres), since the acceleration due to the propulsion system is limited to a few gees (the engine specific thrust, $a=F/m$, in the limit).

MICROGRAVITY LEVEL AND DURATION

Zero-g, or zero gravity, is an ideal environment corresponding to free fall in a uniform gravitational field, but the latter is just an approximation to real gravitational fields, better approximated as central-force fields. For that reason, and to better account for other small unavoidable perturbations (like residual gas drag in orbit, and mechanical noise from equipment in the same platform), the term microgravity (loosely understood to be $a_{\rm nff}\approx10^{-6}g$) is preferred to zero-gravity ($a_{\rm nff}=0g$).

Microgravity, contrary to normal gravity, has not precise direction and value, i.e. has jitter, and this g-jitter must be taken into account when performing high-precision analysis of experiment under microgravity. A lesson learnt in the past is that the g-level (amount and direction) must be measured synchronously and close to the experiment.

The aim of microgravity experimentation is to get rid of gravity forces by opposing inertia forces; gravity can never be removed. If only the Earth's attraction were considered, $g=GM/r^2$, with $G=6.67\cdot10^{-11}$ N·m^2/kg^2, $M=6\cdot10^{24}$ kg, $r=\rho R$, and ρ the radial distance in Earth radii, $R=6.378\cdot10^6$ m, it is seen that

$g=g_0=9.8$ m/s^2 at $\rho=1$, but $g=10^{-6}g_0$ would imply $\rho=10^3$, i.e. 1000 Earth radii (the Moon is at a distance of about 60 Earth radii).

In low Earth orbit (LEO), the force of gravity decreases upward by 0.33 μg/m, whereas the centrifugal force increases upward by 1.36 μg/m; besides, a tidal force oscillation of 0.17 μg/m must be added. Sun gravity attraction is already $g=600\mu g_0=6\cdot 10^{-3}$ m/s^2, but this is also compensated by the centripetal acceleration of Earth's orbit. The rest of the Milky Way gives a $200\cdot 10^{-12}$ m/s^2 attraction.

Duration of free fall is limited on the Earth surface by impact on the ground. Effective microgravity duration is also reduced if air drag is not avoided (e.g. by working under vacuum). Different platforms to carry out experiments under microgravity has been developed:

- Drop towers. For very short times, <10s, drop towers and ground shafts can be used. A 700 m drop shaft in Japan, no longer in use, provided 10 s of μg; the ZARM tower in Bremen (100 m high) gives 4.5 s of μg (double if launched upward from the bottom); a typical educational drop tower of 15 m may yield 1.5 s. To get rid of air drag, either the experiment is mounted on a capsule free-falling inside another capsule... to minimise relative speeds, or the tower is air-evacuated. A simple drop from our hand of an object (not too light) in air already experiences half a second of microgravity (or in other words: "Take a coin. Toss it in the air. You have just subjected that coin to microgravity". The μg-level depends on residual air drag and mechanical details of the initial release. A common problem to any short-duration μg experiment is the high mechanical loads at launch or/and at landing.
- Parabolic flights. An aircraft flying a parabolic trajectory may achieve 10..30 s of μg, limited by aircraft performances, and repeat this path many times with intermediate high-g parabola-to-parabola matching periods. ESA's A310 (2017) typically provides for some 30 parabolas per flight, each of 20 s duration, flying at a base latitude of 6.1 km (at 230 m/s), with μg period between 7.6 km and 8.5 km altitude (at about 100 m/s). The μg-level obtained is poor, of order $10^{-2}g$.
- Sounding rockets. They are unmanned instrument-carriers for scientific research in sub-orbital flight, either to measure environmental variables (in the 50..300 km altitude range, because further upwards orbiting satellites are much better, and, below 50 km, balloons and aircraft are the best), or to provide a medium-term microgravity platform in the 20 s to 20 minutes range, since shorter times are best obtained in drop towers and aircraft in parabolic flight, and longer periods require an orbiting spacecraft. Good μg-level, of order $10^{-6}g$, and rapid turnaround (<1 yr), but as expensive as orbiting platforms (about 10 000 €/kg). Details on ESA's sounding rockets used for microgravity research can be found aside (university students can apply for rocket and balloon experiments.
- Orbiting platforms (and any non-propelled spacecraft), presently centred in the International Space Station (ISS). Limited only by spacecraft manoeuvres (e.g. the ISS is propelled every month to rise its orbit since its altitude decays some 30 km/yr by residual gas drag; the ISS must be maintained at an altitude between 350 km and 450 km, what consumes some 5000 kg/yr of propellants). The μg-levels expected to apply at the structural interface between the laboratory module and the International Standard Payload Racks (ISPR), i.e. the limits on the disturbances imposed from outside and on the disturbances created inside the experiment rack when the ISS is in microgravity mode are:

- At very low frequencies, $0.01 \leq f/\text{Hz} \leq 0.1$, the root-mean-square microgravity disturbance, a_{dis}, is bound to $a_{dis}<1.8\cdot 10^{-6}g$ (i.e. $a_{dis}<18\cdot 10^{-6}$ m/s^2, often written as $a_{dis}<1.8$ μg).
- For $0.1<f/\text{Hz}\leq 100$, the disturbance divided by the frequency is bound to $a_{dis}/f<180\cdot 10^{-6}$ (m/s^2)/Hz), such that for f=0.1 Hz it is $a_{dis}<18\cdot 10^{-6}$ m/s^2).
- For $100<f/\text{Hz}\leq 300$, the disturbance is bound to $a_{dis}<1.8\cdot 10^{-3}g$ (i.e. $a_{dis}<18\cdot 10^{-3}$ m/s^2).
- Besides, it is possible to use vibration isolation systems, active or passive, at rack and sub-rack levels (MIM, PARIS, ARIS), as well as standard accelerometer systems available to experimenters (SAMS, MAMS).

Neutral buoyancy, as used to train astronauts in large pools, or to perform experiments in a Plateau-tank, is not really microgravity but floating like a balloon, or swimming under water like divers; in neutral buoyancy, weight is matched globally (by surface forces), and not at every portion of a body.

Exercise. Find the μg period in a 100 m free-fall tower, and in a 100 km sounding-rocket flight, assuming there is no air drag.

Sol.: The time lapse in a 100 m fall is $\Delta t=\sqrt{2H/g}=\sqrt{2\cdot 100/9.8}$=4.5 s, whereas the up-and-down flight-time to 100 km altitude is $\Delta t=2\sqrt{2H/g}$=286 s (4.8 min).

Notice that μg period can be doubled in a drop tower if some catapult device is used to throw the capsule from the bottom in an up-and-down flight under vacuum (but the shot must be very precise). In practice, large drop towers are operated in drop mode only, and with ambient air, using two capsules, one inside the other, the inner holding the test cell for μg experimentation, and the outer being streamlined for minimum air drag, with extra space to allow the relative axial displacement of the two capsules during free fall.

MICROGRAVITY EXPERIMENTATION

In the beginning of μg research, in the 1970s (the European Low Gravity Research Association (ELGRA) was established in 1979), we naively spoke of "zero gravity" with fantastic expectations (elimination of weight and convection would produce perfect materials that would justify manufacturing in space). But the microgravity environment proved to be much more complex that envisaged. The complexities associated to the new environment (scarce flight opportunities, prohibited ground trials on the expensive space-qualified equipment, difficult air-to-ground communications...), forced to get down off one's high horse.

Nowadays, μg research is concentrated in the ISS, with several international centres channelling the effort (e.g. ESA's Erasmus and low-gravity research, US Center for the Advancement of Science in Space, CASIS...), and main activity has shifted from materials sciences to life sciences. Not to mention that research in the ISS (and other platforms) is not restricted to microgravity, but, besides the classical astrophysical observations, it includes fundamental physics (e.g. quantum physics, plasma physics, soft matter state), space radiations (high-energy physics), and technology development and demonstration.

If experimental results are to be of any value, they must be repeated to examine reproducibility (most results to date are the product of single experiments).

Suggested stages to initiate microgravity research:

1. Find an idea of μg-relevance, i.e. the experiment concept (e.g. liquid jet formation at the end of a tube at low Reynolds number). Make an initial browsing of the state-of-the-art of your concept.
2. Think on data to be measured, and stimuli to be applied in the experiment. It is difficult nowadays to justify a look-and-see type of experiment.
3. Think on how the fluid configuration may be managed (e.g. how establish and control the initial and boundary conditions, and how to overcome the launch or landing problem). Plan a draft step-by-step procedure to prepare, execute, and recover the experiment.
4. Think on minimum HW and SW requirements. Can the experiment be tried in a short-duration platform? Can it be accommodated in an existing facility? Can it be operated automatically? Can it be finished with minimum waste and encumbrance?
5. Think on a timeline (and budget), from conception to final reporting, and on how to convince the evaluators and the sponsors.

Concerning the budgetary effort (in time, personnel, and other resources) to be devoted to μg experimentation, an evolutionary approach should be followed, starting by simple preparatory work on ground. It is relatively easy to arrange in a laboratory a free-falling platform incorporating a small test cell with a remote data and video acquisition system, to let it drop (on a cushion) from a few metres high. Using a simple dynamometer with a load, transparent box half-filled of a coloured liquid, may show the workings of μg experimentation.

Details of microgravity experiments with liquid bridges performed by the author and collaborators can be found aside.

SOME MICROGRAVITY EFFECTS

We live on the Earth surface under normal gravity conditions, and, though we have got accustomed to seeing astronauts floating inside orbiting space stations, it is not easy to realise other effects of microgravity than this amusing 'diving in the air'.

Effects of μg can be grouped as:

- Physiological (on animals and plants). The first and most common effect on humans is space sickness, i.e. in the initial hours of weightlessness, about 50% of astronauts suffer the space adaptation syndrome (SAS). Other effects on humans are: legs-to-head shift of body fluids, and, for prolonged exposure, reduction of muscle mass and strength (the most on weight-bearing muscles and those that help with posture; even with regular exercise on board, there is a 1..2 % per month loss of calf muscle mass), and bone decalcification, increasing the risk of bone fractures and kidney stones. Effects on other animals and plants have already been studied, including reproduction. An initial conclusion is that forced air movement is essential to grow healthy plants in space, but only when multiple generations are grown in space will we get a clearer picture of plant and animal response to microgravity.
- Thermal (and thermochemical). The lack of natural thermal convection under microgravity, modifies the behaviour of many systems, starting from our inability to get rid of body heat and

odours (forced air ventilation is a must in any habitable module in space). A [candle flame] cannot burn under microgravity (or does it in the most precarious and astonishing manner); smouldering is also hindered, but the forced air convection always used in habitable spaces helps to sustain polymer combustion (a shutoff of the flow retards the process); the onset and extinction of flames is of vital importance both in space and on ground, and μg research may help to isolate effects. Any active system must dissipate energy, and particularly hot devices like lamps, which get hotter under μg by the absence of convection, particularly those like halogen lamps, where convection inside the lamp is important. [Pool boiling] is very inefficient (critical heat flux soon appears). An experiment on frying potatoes in parabolic flight, performed in 2017 [Lioumbas-2023], has shown that the non-uniform steam outflow generated at the pores of the heated potato, can be enough to stir the nearby fluids and prevent a vapour layer to keep oil away of the potato surface. Heating a pool of liquid from above, on Earth, hardly produce any motion (on normal liquids, that expand when heating) and was ignored on materials processing, but under microgravity, small thermal gradients along a fluid interface generate a large bulk motion (enhanced [Marangoni convection]).

- Mechanical. The most obvious effect of μg is apparent weightlessness (a gentle push, and flying starts, with gentle rebounds on opposite surfaces). But there are other mechanical effects on solids, liquids, and gases. Focusing just on the effects on liquids, one may still split the field in several categories:
    - Large liquid interfaces (capillarity). Liquids do not stand at the bottom of vessels; they tend to creep along the walls, and can be floating around like the astronauts. Containerless processing may be a great advantage to avoid crucible contamination, but the uncertainty in liquid location complicates liquid handling under microgravity. How to get only liquid or only vapour from a two-phase tank? How to gauge a tank? A way out may be fully-filled containers, which must be flexible (like bladders); another possibility is to make a short manoeuvre to impose an artificial gravity; but the simplest solution relies on capillary forces of cohesion and adhesion. The Bond number measures the ratio between weight forces and surface tension: $Bo \equiv \Delta\rho g L^2/\sigma$; $\Delta\rho$ and σ cannot be changed appreciable by the choice of fluids, and reducing L to the submillimetric range may add too much complexity on cleanliness and accuracy, hence, reducing g may be the only way out.
    - Small liquid interfaces (dispersions). There is no sedimentation of second-phase particles, drops or bubbles in a liquid. Foams, which are particularly sensitive to gravity, are more stable in microgravity. Similarly, solids grown in space tend to trap gas bubbles within. Dispersions being more stable under μg, contamination is more difficult to clean.
    - Liquids without a fluid interface. The highly-reduced convection under microgravity, may be advantageously used to analyse diffusion effects, vibration-induced secondary motions, etc.

Fluid behaviour under microgravity is not only of interest per se (e.g. liquid management in spacecraft), but to all other physical and life science experiments (biology, physiology, molten materials, combustion...) and to present and future environmental control and life support systems (ECLSS).

From another perspective, one may think on what normal gravity means on science and technology. Gravity is a strong volumetric force in macroscopic systems (at atomic level, gravity is negligible: about 40 orders of magnitude smaller than electromagnetic forces). Its effect on solids is basically the tendency to fall to the ground. Its effect on gases is almost irrelevant at typical engineering sizes. But the effect of gravity in fluids is very important and varied:

- Gravity shapes bulk-fluid boundaries, e.g. partially filled liquid reservoirs have a quasi-horizontal free surface.
- Gravity settles heterogeneous fluids, e.g. falling of drops, rising of bubbles.
- Gravity creates motion by buoyant convection (and onset of buoyant instabilities).
- Gravity compresses different fluids at different levels, what means, for instance, that fluid-critical-point region cannot be properly studied on ground due to compressibility effects.

As a final remark, notice that not all experimental results have yet been satisfactorily explained, neither under μg nor on ground, and as an example of major fundamental and applied interest (both on 0*g* and 1*g*), consider the wetting of a solid surface by a liquid, already modelled by Thomas Young (1805) as $\cos\theta = \sigma_{SV} - \sigma_{SL})/\sigma_{LV}$, relating the contact angle θ with the surface tensions between the three phases: solid, liquid and gas. We know many details:

- This is just a horizontal force balance applicable to partial (or finite) wetting; the vertical force balance can only be detected on soft solids (like gels), or after some specific process (e.g. a drop of water put on a fresh paint, after it evaporates, indeed leaves a circular ridge on the paint).
- Complete wetting. There are some liquids of low surface tension (such as silicone oils) that wet most surfaces (glass, or steel, or even plastics), and adhesion to the solid may spread the liquid to all the available solid surface, or to a monolayer on larger surfaces.
- Non-wetting. There is not evidence of θ=180º for a liquid drop (but for a bubble, yes; a bubble of air rising in a box filled with a silicone oil, reaches the top of the box with a contact angle of 180º). For a given liquid (water) a surface with θ>150º is said superhydropobic.
- Contact-angle hysteresis. Droplets generally remain stuck on a tilted substrate on ground (e.g. on vertical windows), proving that, though the drop is static, different angles can coexist along the contact line: large ones at the front of the drop, and smaller at the rear, what generates a capillary force able to balance the weight of the drop.
- But the physics of advancing and receding contact angles, precursor films, and related phenomena, still hide unsolved problems.

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The Scientific American’s review “Looking Up: Europe’s Quiet Revolution in Microgravity Research” (2008) is warmly recommended for an overview.