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Acta Astronautica 58 (2006) 197 – 208
ACTA ASTRONAUTICA
www.elsevier.com/locate/actaastro

On a more rational specification for the microgravity environment of the International Space Station

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Received 2 June 2004; received in revised form 28 June 2005; accepted 27 September 2005
Available online 28 November 2005

Abstract

The paper evaluates the disturbances on typical Fluid Physics experiments by numerical experimentation and shows how convective motions are originated by two vorticity production terms, one of which is related to the curl of the acceleration field. Isolation mounts may be responsible for the translation of linear g-jitter into pendular motions of the microgravity payload and therefore may induce convective motions also in an isodense liquid medium.

Typical numerical results are shown of the different flow fields induced in an otherwise quiescent fluid cell by the different accelerations that characterize the ISS microgravity environment.

Criticisms are made to the motivations at the base of the current ISS specification and different specifications are proposed that take into account the entire g-jitter spectrum and the presence of pendular motions of the fluid cell.

1. Introduction

Recent measurements carried out by NASA, Boeing, Zinn [1–5] have shown the existence of a very complex microgravity environment on board the Space Station.

The complexity refers to the fact that the acceleration ($\underline{g}$) at each point ($\underline{r}$) of the International Space Station (ISS) is dependent on time (t)

$$\underline{g} = \underline{g}(\underline{r}, t). \tag{1}$$

The effects (or the disturbances) induced by this acceleration on an ISS microgravity experimental process are strongly dependent on the objectives, the geometry, the conditions and the duration of the experiment. Many works are available on the subject aimed at answering the main question of microgravity experimentation: is an experiment worth doing on the ISS? In other words does the ISS microgravity environment (MGE) guarantee that the results of the experiment is sufficiently different (hopefully better) than that obtainable on ground? Apart from the constraints typical of a space platform (limitations in mass, volume, power) that may affect the outcome of the experiment, we want to focus our attention on the "tolerability" of typical experiments with respect to the MGE prevailing on the ISS.

There are many issues to be taken into account, on one hand, and there are many simplifying assumptions, on the other, to be made if one wants to come up with some sort of logically sound and quantitative prescriptions (or requirements) for the ISS MGE. To find conditions that apply to most of the experimentation, one should identify the typology of the experiments that are most sensitive to accelerations. The first assumption here is that the "best" environment for the experiment

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doi:10.1016/j.actaastro.2005.09.007

results would be the ideal weightless (or zero-g) condition; in absence of any boundary condition that induces a velocity field in a fluid cell, the zero-g condition guarantees that energy and species are transported by diffusion only (and not by convection), that seems to be the main motivation for most of the microgravity processings. In these cases a rather simple way to evaluate the effect of the disturbance induced by the acceleration $\underline{g}(r, t)$ is to compute, for each relevant extensive quantity, the amount transported by convection with respect to that transported by diffusion (i.e. appropriate Peclet numbers). Relatively large ratios of these quantities imply non-negligible disturbances for an otherwise purely diffusive process.

The paper wants to revisit the present ISS requirements, that were apparently based (about 10 years ago) on common sense and on empirical criteria more than on sound scientific grounds.

The second objective of the paper is to answer the question: if we had to prescribe today the ISS MGE requirement by taking advantage of all the progresses made in numerical simulations, in instrumentation and of all measurements performed on board the ISS, how would we address the issue?

2. The microgravity relevance

The ISS requirement curve (i.e. the amplitudes of the periodic acceleration g_f at each frequency f) should establish a MGE envelope within which the microgravity relevance of the experiments is ensured. In other words one should guarantee a microgravity environment to each category of experimentation to justify the efforts made to carry experiments on the ISS. Assessing the microgravity relevance for each category of experiments means:

1. Identify the unwanted phenomena caused on ground by gravity and that one would like to suppress (e.g. sedimentation, buoyancy, natural convection, hydrostatic pressure, etc.).
2. Evaluate the acceleration below which the result of the experimental process is sufficiently "better" than that performed on ground.

The second step may be very complex and should be translated into implementable ISS prescriptions. The simplest prescription is the so-called NASA accepted ISS requirement curve prescribing that the acceleration level, at each frequency, be below the curve $g_f(f)$.

The ISS $g_f(f)$ has been evaluated by identifying the tolerable disturbance as the maximum convective transport of species and/or of energy within a fluid cell with respect to the diffusive transports. Even though it appears to be a very specific criterion one must realize that purely diffusive process is the most common requirement for microgravity processings. The amount of convective transport of species and energy is related to the acceleration levels either by an order of magnitude analysis or by appropriate analytical and/or numerical modellings as indicated in the next paragraphs.

In what follows only steady residual-g and periodic g-jitter (related to on board mass dislocations) will be considered with the exclusion of single pulses caused by sporadic events (propulsive pulse, docking, meteorite impact, jettisoning etc.). The disturbances due to these events have been correlated by the so-called G-dose criterion [6,7].

The ISS requirement curve $g_f(f)$ has been provided to facilities/components providers to limit the accelerations produced on board of the ISS by vibrations generated by mass dislocation (machineries, crew activities, etc.).

As will be discussed in the next paragraph, the scientific motivations of the requirement curve are based on a number of simplifying assumptions, the main of which is that the ISS, in absence of any disturbance induced by on board machinery/activities be in a zero-g condition.

This is not true, however, because the large extension of the ISS and its motion along the orbit generate accelerations; the presence of these accelerations cannot be neglected and should be taken into account by the ISS requirement curve, that, at the moment, is related only to the additional accelerations due to the presence on board of men/machineries. The ISS requirement curve (defined as the maximum tolerable accelerations) should be the sum of the existing "empty" ISS acceleration ($\underline{g}_{\text{ef}}(f)$) plus that prescribed by the ISS requirement ($\underline{g}_f(f)$):

$$\underline{g}_{\text{tf}}(f) = \underline{g}_{\text{ef}}(f) + \underline{g}_f(f). \tag{2}$$

The above point is not trivial and may indeed affect the logical derivation of a correct ISS requirement curve because what one could prescribe (in the best circumstances and for each experiment) is the maximum tolerable $\underline{g}_{\text{tf}}(f)$ from which one could derive the $\underline{g}_f(f)$ (Eq. (2)) to prescribe limitations to facilities providers. In conclusion, the prerequisite to compute an ISS requirement should be the knowledge of the existing empty ISS acceleration field. Since the empty ISS