Werner Schmidt[1][2]

Quickly changing acceleration forces (QCAFs) Vibration Analysis on the A300 ZERO-G

Experiments that are done under microgravity, e.g. during space or parabola flights, are invariably accompanied and affected by ubiquitous vibrations of the surroundings. Vibrations induce Quickly Changing Acceleration Forces (QCAFs) that interfere with the perception of the earth gravitational field. To investigate their impact on experiments under microgravity we monitored the vibrations of the airplane A300 ZERO-G during parabola flights and analyzed them in their spectral and frequency domains. Power spectra obtained with Fast-Fourier Transforms (FFT) display a complex pattern of various vibrations whose origin, relative phases and intensities remain unidentified. During the zero-g phases (parabolas), when the engines of the airplane are throttled, the vibrations still elicit residual QCAFs of at least ± 1 g. By means of adequate damping procedures the QCAFs could, however, be reduced by approximately 95%.

1. Introduction

The absence of gravitational force as achieved during free fall in drop towers, parabolic flight maneuvers, by sounding rockets or within space stations is termed "microgravity" rather than "zero gravity". This is because for practical reasons the ideal situation of zero gravity is never reached. The deviation from the ideal inertial system ranges from approximately 10^{-2} g experienced during parabolic flights and 10^{-3} g in the international space station (ISS) down to 10^{-5} g obtained in drop towers. In addition, microgravity on the airbus A300 ZERO-G - or any space craft such as the space shuttle or ISS - is essentially "contaminated" by ubiquitous vibrations, i.e. Quickly Changing Acceleration Forces (QCAFs). Only in free-floating experiments with no contact to the carrier structure or by means of very expensive electronic anti-vibration equipment QCFAs can be essentially eliminated. Generally, QCAFs might interfere with experiments in fields which depend on biological techniques such as microscopy, patch clamp investigations, experiments on gravi-taxis in microorganisms or with molecular movements such as diffusion, crystallization processes etc. Vibrations represent a strong "gravitational background" in the millisecond range for any (molecular) gravisensor, even and particular if isotropic, compared to the common slow anisotropic change in gravity during parabolic flights on the minutes time scale with the gravity vector pointing downwards, orthogonal to the plane's floor. The impact of QCAFs is analogous to optical experiments requiring the measurement of weak light sources on a bright, diffusely illuminated background. Although vibration analysis is quite common and indispensable in material sciences and even though QCAFs are highly relevant for experiments under microgravity, they rarely have been taken into account before [1].

2. Material and Methods

Vibration measurement

A vibration transducer (sensor) is attached to the vibrating surface and converts the mechanical motion into an electrical signal. This is fed to the sound card input of a notebook. The program *Spectrogram* is then used to sample this electrical signal and make various calculations based on the electrical signal's properties. We utilized two physically different types of sensors to monitor QCAFs by power spectra: The *electret condenser foil microphone* which primarily converts air pressure vibrations, i.e. "sound", into electrical signals. Their frequency response extends to much higher frequencies (3db, 30 kHz) than that of gravity sensors (3dB, 5-10 kHz). In addition, due to their operational principle they exhibit much higher signal to noise ratios

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Mail address:

Werner Schmidt, Fachbereich Biologie/Botanik der Universität Marburg, D-35032 Marburg, Lahnberge and Universität Konstanz, D-78438 Konstanz, Fachbereich Biologie, PB M645, w.2.schmidt@surfen.de

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(SNR) for measuring power spectra then gravitational sensors which are not specifically designed for this purpose. The proper calibration of electret microphones in terms of g-values was accomplished by comparison with calibrated g-sensors. The g-sensor (ADXL105) we utilized for measuring QCAFs is a silicon surface-micro-machined component implementing an open loop acceleration measurement architecture. It is calibrated simply by tilting through the angles 90, 0 and -90 degrees corresponding to 1g, 0g and -1g. Both sensors including electronics were placed in a small 10x10x10 cm aluminum cube of 800 g (vibration sensor box) which could either be fixed to a heavy steel plate screwed to the aircraft's rails, or manually kept free floating during parabolas, only connected by a 2 m long safety line to a fixed rail and a 2 m electrical connection to the notebook also fixed to the vibrational board. For the preliminary vibration experiment shown in Fig. 7 we adopted the standard wild-type strain of *Phycomyces blakesleeanus* (Burgeff). Sporangiophores were grown and measured in glass shell vials (1 cm diameter x 4 cm height; Flachbodengläser, AR Klarglas, Münnerstädter Glaswarenfabrik, Münnerstadt, Germany) on a synthetic solid medium. Until the appearance of stage-4b sporangiophores (i.e. with sporangium) of 2.5 cm length the material was kept in transparent plastic boxes at ambient temperature (19-21 C) under white incandescent light fluence rate (0.5 W m^{-2}).

The vibration analysis program

Most ordinary vibrations are complex combinations of interfering individual frequency components and/or harmonics with a wide range of frequency and intensity. A spectrogram is a power spectrum of the frequency components displayed as a function of time and their intensities (scrolling spectra), thereby revealing the frequency composition of vibration signals. In principle, power spectra can be used to identify sources of vibration and their concomitant contribution to QCAFs. *Spectrogram* was originally developed for sound analyses. The latest issue can be downloaded from http://www.monumental.com/rshorne/gram.html. We have chosen the program, because vibrational analysis largely depends on the same physical and mathematical principles as the analysis of QCAFs, and because it allows an analysis in terms of "power spectra". *Spectrogram* uses a mathematical Fast Fourier Transform (FFT) to perform the frequency analysis. FFTs are usually specified by the number of input data points used in each calculation, which are always powers of two (e.g. 512, 1024, 2048, etc.) The choice of sampling rate depends on the highest frequencies in the vibration signal. We monitored vibrational data on a 12 or 22 kHz basis.

3. Results

Theory

The theory of vibration deals with oscillatory motions of (particularly three dimensional) bodies and the forces associated with them. A vibratory system must, in general, include a means for storing potential energy (spring or elasticity), a means for storing kinetic energy (mass or inertia), and a means by which energy is gradually lost (damping or resistance). Acceleration is defined as the second derivative d^2s/dt^2, with s = distance and t = time. Calculating a sinusoidal acceleration yields the following group of curves as a function of frequency and amplitude (Fig. 1). These curves have been calculated according to

$$dv / dt = g = -\omega^2 \cdot A_0 \cdot \sin\omega t \qquad (1)$$

with v = velocity, g = acceleration, ω = angular frequency, A_0 = vibrational amplitude as curve parameter, and setting sin ωt = maximum = 1. Even an amplitude as small as 2 µm (the length of a bacterium) at a frequency of 300 Hz results in notable QCAFs as high as ± 2g. Vibration analysis can be regarded as sound analysis of the solid state, taking advantage of the well established theory of the latter. Sound, respectively *vibrational intensity I*, is measured in erg/m² s or W/m². For physiological reasons, loudness Λ is known to be proportional to the logarithm of intensity I (law of Weber Fechner):

$$\Lambda = const \cdot \log I \qquad (2)$$

The threshold of human hearing, which is $I_0 = 10^{-12}$ W/m², serves as a reference for I and the loudness of sound is thus expressed as the logarithm of the ratio I/I_0 multiplied by 10:

$$\Lambda = 10 \cdot \log I/I_0 \qquad (3)$$

Loudness Λ is a dimensionless entity and carries the term "phone". E.g., the hearing threshold is defined as 0 phone. And - on the other side of the scale - a sound of 13 orders higher

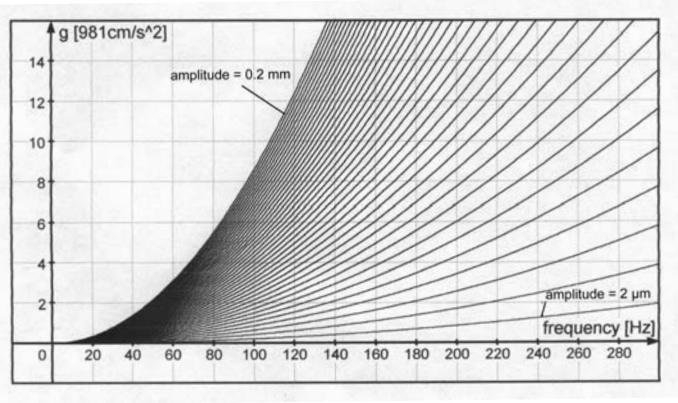


Fig. 1.: Acceleration in g-units generated by vibration (quickly changing acceleration forces, QCAFs): a group of curves representing 2 to 0.2 mm vibration amplitude with steps in A0 of 0.002 mm.

intensity I (130 phone) represents the threshold of pain. In vibrational analysis the basic term is the *alternating pressure of vibration*, p (German "Schallwechseldruck"). For an one-dimensional wave of sound of frequency v we obtain

$$p=P\cos^2 2\pi v\,(t-x/v) \qquad (4)$$

with P amplitude of p, x direction of propagation and frequency v. For P we obtain

$$P=\rho v U \qquad (5)$$

where U the velocity amplitude of the vibrating matter, ρ its density and v the velocity of sound in the medium. The *pressure of sound* at the hearing threshold is about $3 \cdot 10^{-4}$ µb, at the threshold of feeling (German "Fühlschwelle") 10^3 to 10^4 µb, i.e. app. 8 orders higher, which renders a logarithmic presentation - similar to sound - meaningful. For simplicity, in our present investigation we define $I_0 = 1$ and - independent of their absolute calibration power-spectra are characterized by their shape, and the relative contributions of various frequencies are easily recognized (Fig. 2). Since I is proportional to p^2 and p proportional to g, and because we measure acceleration g rather than sound intensity I [W/m²], we have to modify formula (3) as follows:

$$decibel = 10 \cdot \log p_0^2/p^2 = -20 \cdot \log p \qquad (6)$$

with $p_0^2 = I_0 \equiv 1$.

QCAFs: considerations and experiments

Earth-bound experiments demonstrated that differences in QCAFs and power spectra observed for the three space coordinates largely depend on the spatial attachment of the sensor to the various components of the individual experimental set-up. Three-dimensional vibrational analysis requires a mathematically complex theory which so far is accomplished only for simple model systems such as spheres, half-spheres or cubes.

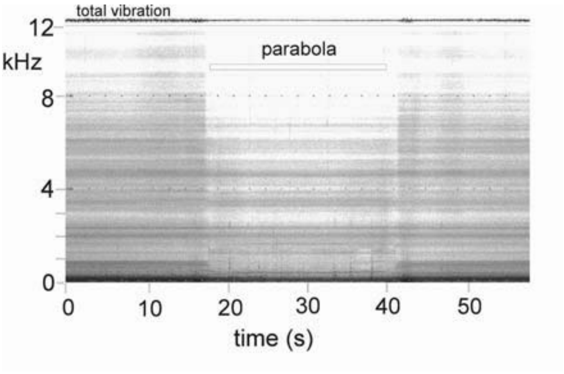


Fig. 2.: Typical "power-scrolling spectrum" including a parabola as indicated (parabola No 8 at the 20th of march 2002). On top the program plots the total vibration (enlarged in Figure 3).

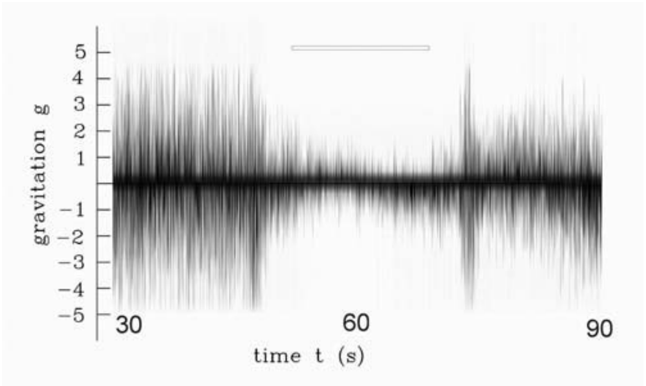


Fig. 3.: QCAFs as monitored for 90 s, including a parabola of 22 s as indicated

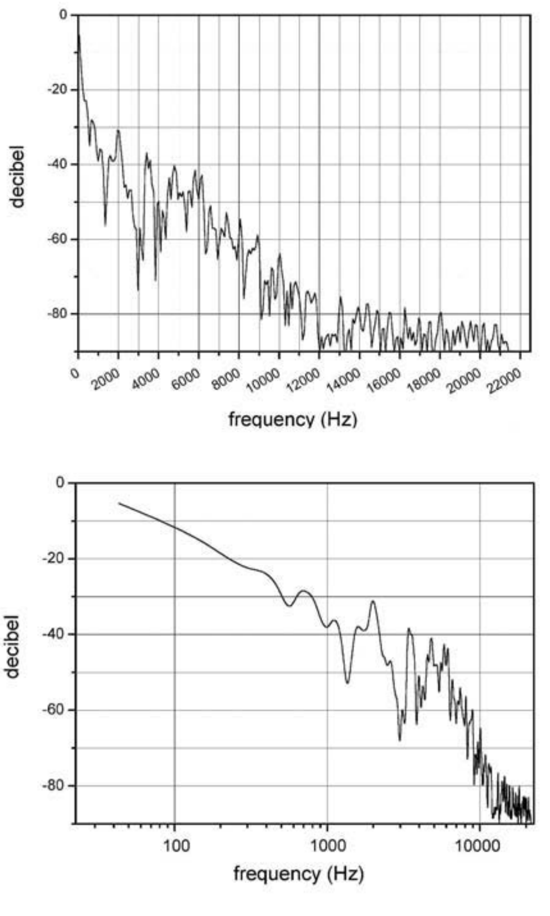


Fig. 4.: Top. Linear vibration power spectra as deduced from a scrolling spectrum such as shown in Fig. 3, plotting the vibration strength vs. frequency at one specific time. Bottom: the same power spectrum plotted on a logarithmic scale.

Thus, the highly complex vibrational patterns in the A300 ZERO-G are theoretically not accessible, only on an experimental basis. E.g., with a simple set up (function generator, amplifier and vibrational sensor) in ground-based experiments we obtained for some locations of our experimental aluminum box - besides hundreds of smaller contributions - resonance frequencies at 70, 80, 120, 140, 170, 200, 400, 500, 600, 6000 or 8000 Hz. Figure 2 shows the power spectrum up to 12 kHz recorded by the electret foil microphone fixed to the aircraft's rails, including a "zero-g-phase" during a flight parabola lasting 25 s. Many individual vibrational modes are exhibited which are significantly weaker during the parabola when the aircraft's engines are throttled. Figure 3 shows the concomitant QCFAs. Depending on the individual flight situation these show spikes of ± 4g and higher during cruise flight (particularly during the start they easily surmount 20g), but even during the parabolas spikes of ± 1g take place. *Spectrogram* allows a frequency domain display deduced from the power spectrum as in Figure 2. For this purpose the vibrational amplitudes are plotted in the linear (Figure 4, top) or in the logarithmic frequency mode (Figure 4, bottom). Clearly, the dominant (approximately 90%) contribution of QCAFs is caused by low frequencies below 200 Hz, frequencies between 200 and 1000 Hz contribute only a few percent and below 1 kHz only dwindling little.

Free Floating

Even if some well flown parabolas offered as many as 28 seconds of "zero g", we managed to have the free floating situation for a maximum of only 8 seconds. This is because we are dealing with "microgravity" rather than true "zero g" within the Airbus 300 ZERO-G, causing free floating parts - as the human body itself - always to drift, finally hitting a fixed structure like the wall experiencing large g-values. This also holds true in space stations. The power spectrum during free floating (Figure 5, right) is compared to the typical situation where the experiment (sensor) is immediately fixed to the aircraft's rails (Figure 5, left).

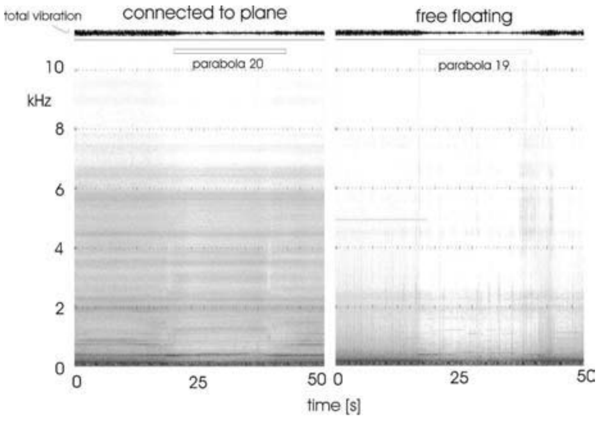


Fig. 5.: Comparison of scrolling spectra as measured in the A300 ZERO-G for 50 s, including parabolas as indicated. Left: With the gravitational sensor fixed to the aircraft's rails. Right: Free floating experiment.

Vibrations in aqueous environment

Since we are searching for the biological g-sensor present in *Phycomyces* the question was raised whether the aquatic environment within the cell ("cytoplasm") would be capable of further damping QCAFs. To answer this question we performed following experiment: The (technical) g-sensor was placed in a water tight plastic bag which was sucked empty of air tightly covering the sensor and electronics. This covered sensor was placed free hanging in a glass of water warranting excellent contact to the water body. Half a meter apart an electrical drill as a test vibration source was fixed. The power spectra of the running drill and the total QCAFs both were measured with the sensor fixed immediately to the table (Fig. 6 right) or with the same sensor submersed in the glass of water (Fig. 6, left). We obtained a clear-cut result: the water body does *not* damp the QCAFs; these are rather fortified by the vibration conductor "water", compared to the "solid connection" of the table plate.

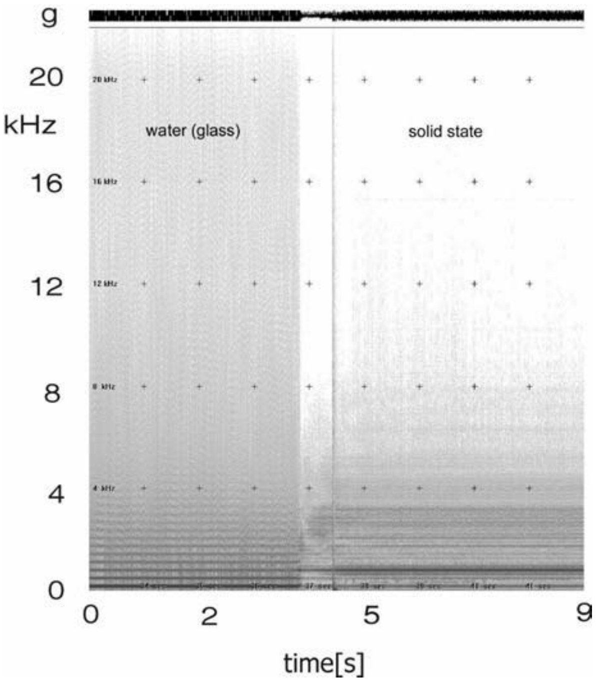


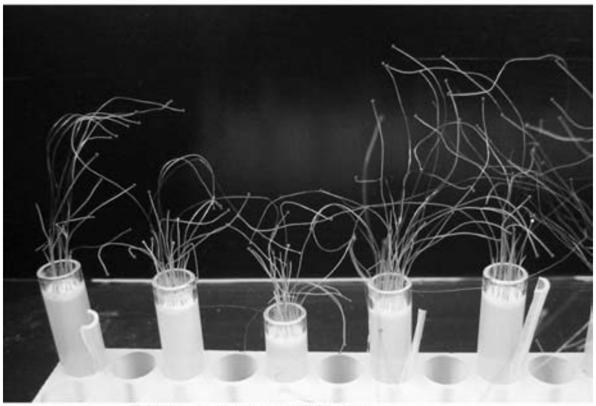
Fig. 6.: Comparison of scrolling spectra of a test noise generated by an electric drill (0.5 m distance from the sensor on a lab-table): Left: mediated by water, with the gravitational sensor immersed in a glass of water standing on the table. Right: the same sensor, immediately fixed to the table. As indicated by the total vibration (top), QCAFs are significantly larger and more evenly spread through the whole spectrum with water as vibrational conductor than in the solid state.

Interestingly, in aqueous environment the energy of the main vibration component of the drill near 800 Hz is evenly spread over many equidistant harmonics ranging from 20 Hz up to 22 kHz (the upper limit of our detection systems). Particularly smaller frequencies are increasingly enforced giving rise to stronger QCAFs. Of course, the cytoplasm of cells is not structured as simple as a glass of water and its viscosity is different. Nevertheless, the principle of intensification of QCFAs and spreading of frequencies by aqueous environments most likely can be generalized.

Damping of the experiment

The aluminum boxes we used for our experiments were fixed between "Sylomer brown" (a special damping material, GuK-GmbH, Berlin, www.guk-berlin.de) washers warranting metallic-free contact to the aircraft's rails ("free floating"). In addition - all components inside the experimental boxes including the *Phycomyces* sample itself were mounted on heavy steel plates "floating" on mats of "Sylomer yellow". Generally, depending on frequency and the individual set-up of the experiment, in our experiments damping by the brown Sylomer washers decrease QCAFs up to approximately 70%, and with the additional yellow (i.e. softer) Sylomer mat only approximately 10% of the QCAFs as measured on the planes fixing rails remained. In addition, the agar used as growing substrate and matrix for the sporangiophores generally further damped the vibrational g-values significantly with a remaining, not removable contribution of approximately 5%.

Phycomyces wildtype, control



Phycomyces wildtype,
12h, 180 Hz, 75 dB, appr. 4g

Fig. 7.: Top, Control: Wildtype SPPHs grown in darkness for 12 h without QCAFs. Bottom: Wildtype SPPHs grown in darkness for 12 h under the impact of sinusoidal QCAFs (corresponding to 75 dB).

Impact of QCAFs on biological experiments

On A300 ZERO-G performing parabolic flights thereby allowing experiments under microgravity, depending on the type of experiment QCAFs might be counter-productive. These include biological experiments involving natural gravi-sensors such as those in SPPHs, but possibly all experiments where microscopically thin "boundary layers" (surface physics, crystallography) and those where diffusion-controlled reactions are involved. Thus, the impact of QCAFs should be minimized, in order to guarantee "microgravity". These arguments apply also for spacecrafts where all types of aggregates are a source of QCAFs. There are only a few publications available demonstrating the influence of QCAFs (sound and vibration) on biological specimen. E.g., the promotion of germination of mustard seeds by as much as 385% [2], or the effect of mechanical vibration on seed germination of *Arabidopsis thaliana* [3]. Roots and shoots of sunflower and maize respond to mechanical stimulation [4]. Growth of rice and cucumber seedlings is promoted by vibrations of 50 Hz [5]. Cubano and Lewis investigated the effect of vibrational stress on the regulation of heat shock proteins hsp70 and hsp27 in human lymphocytes (Jurkat) and observed the up-regulating of the corresponding genes by spaceflight but not by vibration [6]. A simple preliminary vibration experiment on SPPHs of wild type Phycomyces appears to reflect the impact of QCAFs on their gravitational sensor: Normal growth of SPPHs is impaired when they are grown under sinusoidal vibrational impact of 180 Hz and 4 g (approximately 75 dB loudness as measured by a sound level meter. VOLTCRAFT) as generated by a function generator, amplifier and load speaker (Fig. 7). *Possible vibration impact to microorganisms:* The Reynolds-number *R* is dimensionless and describes basically the ratio of inertia and friction of moving bodies in gas or liquid. R determines the mode of movement. The transition of the energetically favorable laminar to turbulent movement occurs between R = 1200 to 2000. Some relevant R-values: blue whale 10^8, human 10^6, sperm/Euglena 10^{-3}, bacteria 10^{-6}. The stop distance from full speed is, e.g., for Euglena 10^{-6} µm. I.e., microorganisms don't glide like fish they rather screw through the water. Due to their low *R* microorganisms stop immediately if their propulsion motor is stopped. In other words due to "missing" inertia microorganisms experience all disturbances of their environment, particularly QCAFs, completely and immediately. Of course, this does not exclude, it rather postulates, some kind of biophysical "averaging" mechanism allowing microorganisms to detect stationary g-values as small as 10^{-1} (*Euglena*) inspite of strong QCAFs as backgroun (cf. "discrimination threshold" defined below).

Estimate of Size of the Gravi-Receptor

The described vibration experiment in Fig. 7 yields a crude estimate of the responsible size of the gravisensor of *Phycomyces*. The estimate is based on a thermodynamical argument: The external mechanical vibration source causes a medium velocity of the vibrating tissue of $v \sim 2 * 10^{-3}$ m s^{-1} (cf. Fig. 1). Selecting only one dimension, this corresponds to a medium kinetical energy which must be larger than that caused by thermodynamic vibration in order to be recognized by the system as a gravitational stimulus:

$$kT \leq mv^2 \qquad (7)$$

Assuming a density for the responsible (spherical) gravisusceptor of $\rho = 1.2$ g cm^{-3} eq. 7 yields an estimate of its effective radius r > 10 µm.

Thresholds

Important for our consideration is the threshold for gravitropism. Which absolute values of gravity are still recognized by gravi-sensitive organisms respectively their sensitive organelles? For gravitropism in *Phycomyces* the threshold was determined by Galland et. al. [7] on a clinostate centrifuge (10^{-2} g). The threshold for the graviperception in the phytoflagellate *Euglena* of 10^{-1} g was determined by Häder et al. [8] during a space shuttle flight. The thresholds for gravitropism in Avena-seedlings as measured by Shen-Miller et al. [9] is only 10^{-3} g. The so-called discrimination threshold indicates by how many percent two spatial or temporary opposite stimuli must differ to elicit a response. This threshold typically is about 2-5 % [10]. E.g. if the QCAFs generate an isotropic background of 1g, an anisotropic gravistimulus of 0.02 to 0.05 g should still be recognized. The linear plot of calculated values of g as a function of amplitude and frequency as shown in Fig. 1 is reproduced on a logarithmic basis in Fig. 8. Clearly, even minute vibrational amplitudes of 2 µm yield QCFAs at gravitational thresholds of $g = 10^{-3}$ at 11 Hz and $g = 10^{-2}$ at 34 Hz.

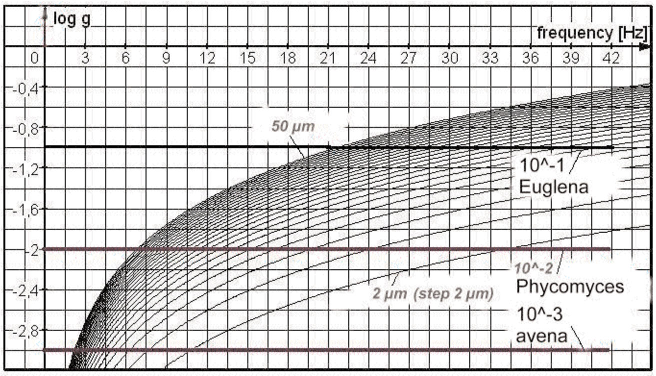


Fig. 8. Logarithmic plot of the very first part of Fig. 1 showing small QCAFs including threshold levels of various gravi-sensitive organisms as indicated.

4. Discussion, Final Remarks

Since experiments in various fields such as fluid physics, material, combustion and life sciences are performed under microgravity conditions quasi-steady accelerations and vibrations are suspected to interfere with the obtained results. However, the majority of experiments determining vibration intensity and frequency distribution cover the low frequency range from 0 to 100 Hz and identify crew activity, crew exercise, experiment component mixing activities, experiment centrifuge operations, refrigerator/freezer operation and circular pump operations as main vibration sources. Only QCAFs in the low range of 10 nano-g up to 25 milli-g have been published so far [cf. 11]. The power spectra between 0 and 22 kHz as measured in the A300 ZERO-G during various flight maneuvers and reported here exhibit many individual vibrations ("modes") of different frequency, strength and width. Their spatial distribution, their relative phases as well as their spectral damping and dispersion are unknown. These parameters lead to a complex pattern of interference yielding a total vibrational amplitude and consequently QCAFs. The bulk contribution (>90 %) of QCAFs comes from low frequencies below 200 Hz. Proper damping procedures allowed us to reduce QCFAs by 95%. The results indicate that experiments done under microgravity require to consider QCAFs being present in airplanes, rockets and space shuttles. Calculations show that a vibrational amplitude of only 10 µm (three times the length of a bacterium) and 300 Hz leads to an acceleration as large as ± 10 g. Vibrations of an amplitude of 2 µm and a frequency of 16 Hz generate an acceleration of $2.5*10^{-3}$ g, which is well above the gravitropic threshold of plant roots.

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Abbreviations

DLR:	Deutsche Agentur für Luft- und Raumfahrt
ESA:	European Space Agency
FFT:	Fast Fourier Transform
GIAC:	Gravity-induced absorbance change
ISS:	International Space Station
QCAF:	Quickly Changing Acceleration Force
SPPH:	Sporangiophore of Phycomyces

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