SIMULATION OF COMBUSTION SYSTEMS WITH REALISTIC g-JITTER

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INTRODUCTION

A number of facilities are available for microgravity combustion experiments: aircraft, drop towers, sounding rockets, the space shuttle and, in the future, the international space station (ISS). Acceleration disturbances or *g*–jitter about the background level of reduced gravity exist in all these microgravity facilities. While *g*–jitter is routinely measured, a quantitative comparison of the quality of *g*–jitter among the different microgravity facilities, in terms of its affects on combustion experiments, has not been compiled. Low frequency *g*–jitter (< 1 Hz) has been repeatedly observed to disturb a number of combustion systems [1]. Guidelines regarding tolerable levels of acceleration disturbances for combustion experiments have been developed for use in the design of ISS experiments. The validity of these guidelines, however, remains unknown.

In this project a transient, 3-D numerical model is under development to simulate the effects of realistic *g*–jitter on a number of combustion systems. The measured acceleration vector or some representation of it can be used as input to the simulation.

BACKGROUND AND TECHNICAL APPROACH

Only a few quantitative studies have considered the effects of *g*–jitter on combustion (e.g., [2,3,4]). Also, the numerical studies to date are limited in the sense that they are not 3-D and can not account for the complex orientation of realistic *g*–jitter. Often time series acceleration data are analyzed through band pass filters and power spectral densities. These techniques are very useful in identifying environmental contributions to *g*-jitter (e.g., crew activity, or thruster use in the space shuttle). But further work is needed to determine the character (e.g., orientation, frequency, magnitude) of *g*-jitter that will not adversely affect a given combustion experiment. The goal of this project is to develop a simulation tool that can be used by experimental investigators to a-priori assess the potential effects of *g*-jitter on their combustion system.

The simulation code, when finished, will be capable of performing both direct numerical simulations (DNS) and large eddy simulations (LES) of combustion. This code is the result of combining two proven codes developed at NIST: a fully 3-D NIST large eddy simulation fire code and a microgravity flame spread code that has some symmetry assumptions. The low Mach number approximation to the conservation equations is used. For the sake of computational efficiency, the gas phase chemical kinetics scheme is either one-step, finite rate reaction or an infinite rate reaction (mixture fraction). The radiation transport equation for a gray gas is solved using a finite volume method. Explicit second-order time stepping with a second order spatial discretization scheme with partial upwinding on a staggered grid is used.

RESULTS

Figure 1 shows the power spectral density (PSD) of the g_z component of the acceleration vector associated with an experimental rig bolted to the frame of NASA's KC-135 aircraft. The measured time trace of g_z is the top curve in Fig. 2. A possible approximate representation of g_z is a sum of sine functions. To obtain such a representation the first five peaks in the PSD were used to determine the frequencies and amplitudes of five sine functions. The amplitude associated with a given peak was found by integrating the PSD over a frequency band containing the peak. Two-dimensional simulations of upwind flame spread over a cellulosic sample were performed using three representations of the acceleration vector $\mathbf{g} = [0,0, g_z(t)]$: the measured g_z, sum of five sinusoids (see Fig. 2), or $g_z = 0$. Negative g_z pointed in the direction of flame spread. Note that the onset of nonzero g_z was delayed until the flame was established. In both cases with nonzero g_z the flame extinguished, but sooner for the measured g_z case. Clearly, the low frequency or transient behavior in the measured g_z was not adequately represented by the sum of sines.

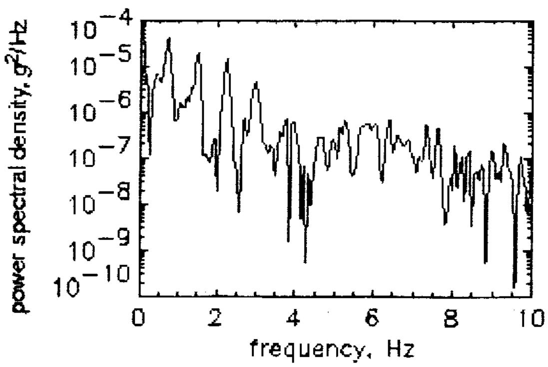

Figure 1: Power spectral density of the g_z component of the measured acceleration in a KC-135 aircraft. The measured g_z is the top curve of Fig. 2.

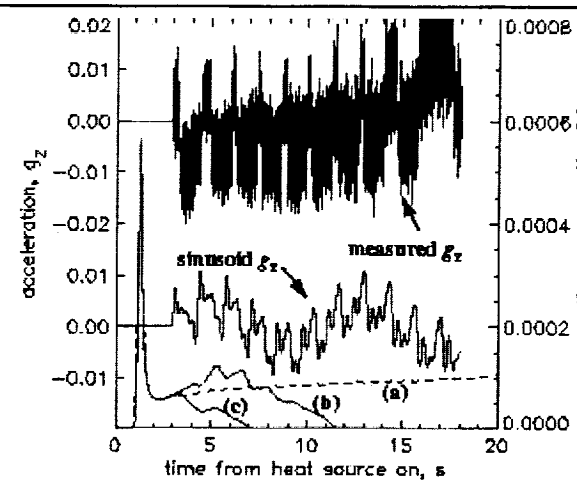

Figure 2: Measured and sinusoid approximation of g_z from KC-135 bolted down experimental rig. Reaction rate from 2-D simulation with g_z from experiment (c), sum of sines (b) and $g_z = 0$ (a).

The simulation results shown in Fig. 2 were obtained from the preexisting 2-D flame spread code which assumes the cellulosic sample is a plane of symmetry. Barring the effects of holes in the sample, this assumption is reasonable in zero gravity or when g-jitter occurs only parallel to the direction of flame spread. Flame spread results from the 2-D version of the code under development are shown in Figs. 3 and 4. In these figures, the acceleration vector, $\mathbf{g} = [g_x(t), 0, g_z(t)]$, is from measured acceleration levels in the KC-135 aircraft with the experimental rig bolted down (Fig. 3) and free floated (Fig. 4). In both figures an ambient 0.5 cm/s wind blows from left to right. Acceleration levels in the free floated experiments are approximately two orders of magnitude lower (~ 5 x 10^{-4} g_e, where g_e is normal gravity) than for the bolted down experiments. As a result, the flame is unaffected by the g-jitter in the free floated experiment. It should be noted that if the investigators wanted to measure steady state flame spread they may not choose the free-floated platform since reduced gravity lasts for only about 7 s – approximately to the time it takes for the simulated flame to reach steady state. Reduced gravity levels in the bolted down experiments last for 18 s to 20 s. But, as seen is Fig. 3a, g-jitter associated with the bolted down experiments affected the simulated flame and eventually caused it to quench (at t = 11 s). These simulations were made on uniform grids 12 cm horizontal and 41

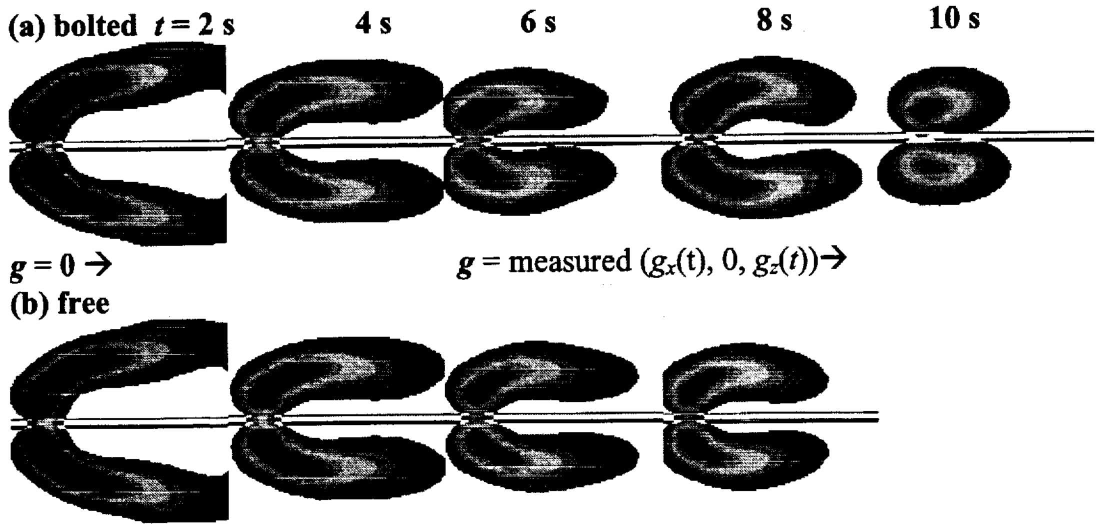

Figure 3: Time sequence of cross sections of heat release rate from a 2-D flame spread simulation. A 0.5 cm/s wind blows from left to right. Acceleration **g** = [g_x(t), 0, $g_z(t)$] measured in a bolted-down (a) and a free-floated (b) experimental rig on the KC-135 aircraft were used. Times are It = 2 s, 4 s, 6 s, 8 s and 10 s. The acceleration vector was imposed starting at t = 6 s (after flame reached an approximate steady state). Case (b) is not shown at 10 s since low-g only lasted for 4 s in free-floated case. No affects of g-jitter are seen in the free-floated case (b). Flame quenched for case (a) at t = 11 s.

cm vertical of 2/3 mm resolution and cost about 80 μs/(time step x grid cell) using an SGI 270 MHz R12000 (single processor).

A preliminary analysis of spherical flames has begun. A very challenging simulation is a flame ball. In the simplest form of the experiment, air and hydrogen are mixed in a combustion chamber. For a certain range of equivalence ratio, stable spherical flames that are 5 to 10 mm in diameter will form [8]. The aim of the numerical simulation in this case is not necessarily to produce a detailed picture of the chemistry within the ball, but rather to evaluate the effect of g-jitter on its formation and stability. The goal is to model the combustion process as a single-step, finite rate reaction or some reduced mechanism involving a few reaction steps. Since the calculations need to be done in three dimensions to account for the g-jitter, the number of transport equations to solve must be held to a minimum. Sawyer and Glassman [7] proposed a single-step reaction for hydrogen mixed with air

$$2\,H_2 + O_2 = 2\,H_2O \quad ; \quad d[H_2]/dt = -k[H_2] \quad ; \quad k = 10^{10.71}\exp(-39.5/RT) \;\; s^{-1}$$

Calculations are underway to determine if this reaction mechanism will yield stable flame balls. Thus, far a stable flame ball has not been produced, but it may not necessarily be due to the simplicity of the reaction scheme. Boundary conditions are of concern simply because one dimensional calculations of flame balls have used very fine numerical grids extending more than 10 cm from the center of the ball [8]. We will need comparable domain size in three dimensions to accommodate far-field boundary conditions plus flame ball drift due to g-jitter. To address these issues, simpler calculations are being performed based on infinite rate chemistry along a flame sheet. From these calculations we obtain temperature fields comparable to that of a flame ball, but without the need to stabilize the flame. Sample temperature fields for a flame ball held in one position under the effect of g-jitter typical of the KC-135 aircraft are shown in Fig. 4.

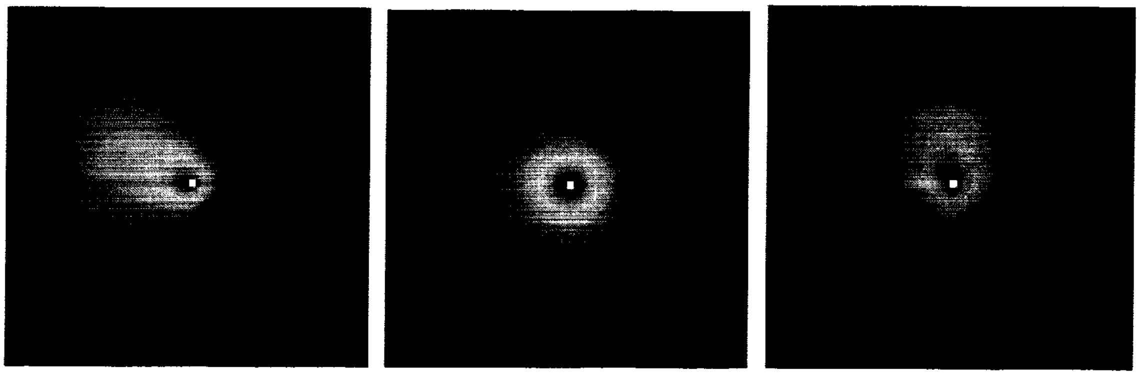

Figure 4: Three snapshots of a simulated flame ball under g-jitter characteristic of a rig bolted down in the KC-35 aircraft. Shown are contours of temperature surrounding a small fixed ignition point.

ACKNOWLEDGMENTS
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