CSA Pneumatic/Magnetic Suspension System Application Note No. 2: Comparison to Buoyancy Devices (Helium Balloons)

1. Overview

Helium-filled balloons are sometimes used as suspension devices to simulate zero-gravity in dynamic testing of space structures. This application note compares the performance of balloons with that of the CSA pneumatic-magnetic suspension devices in terms of mass added to the test article by the suspension. Such added mass degrades the fidelity of the zero-G simulation by changing the normal modes of the payload.

The situation is shown in Figure 1. A test article, such as a solar array, is suspended from above by a number of light vertical cables, each connected to a hard point of the test article. The upper end of each cable is connected to either a pneu-mag suspension device or a helium balloon. Horizontal restraint is provided by simple pendulum action or, in the case of balloons, is absent completely.

Performance of balloons is estimated by best-case calculations from a simple, first-principles model. Measured data is used for CSA pneu-mag devices. It is shown that helium balloons mass-load the test article by 16-20% of its own mass, compared to 2-5% for pneu-mag devices. Significant corruption of the free-free normal modes of a flexible payload typically starts when the added mass of the suspension reaches about 5%.

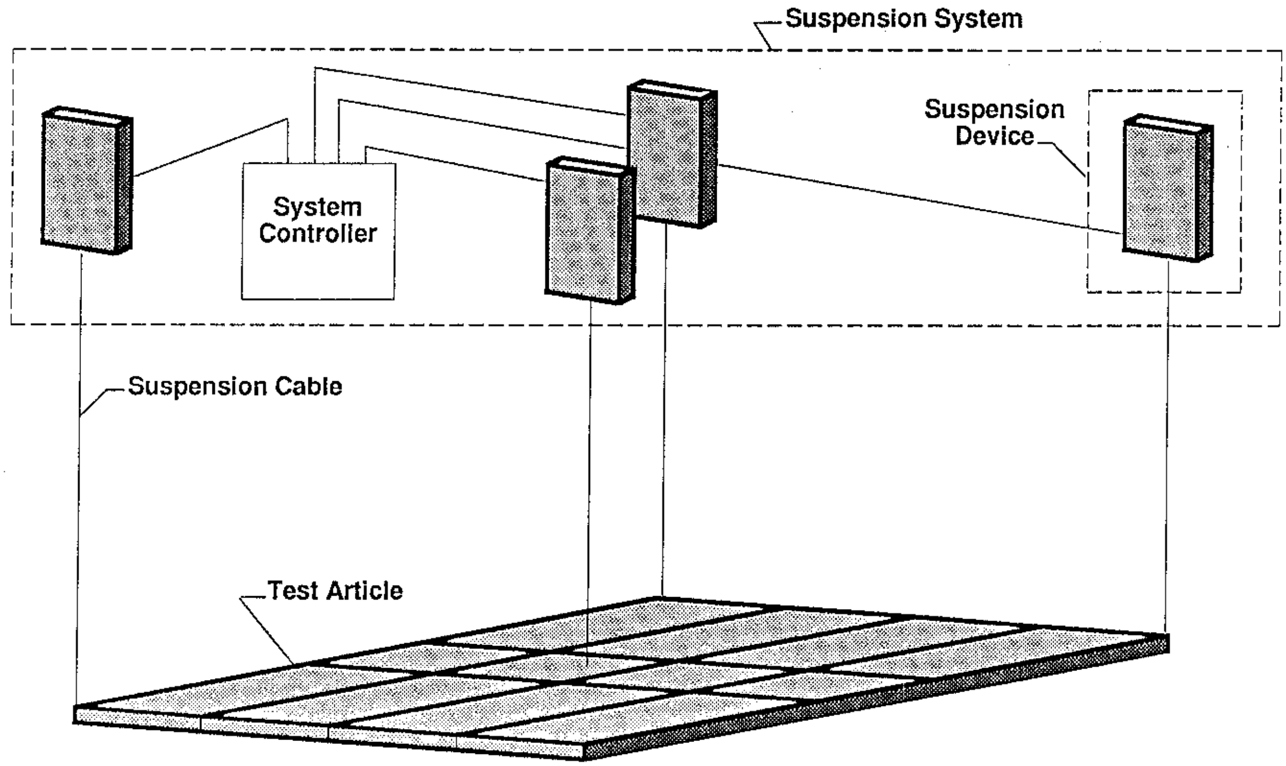
2. Background

Performance of zero-G suspension devices can be quantified in terms of a number of parameters, all related to constraint forces imposed on the test article by the suspension.[1] [2] Since these forces of constraint would not exist in space, figures of merit for a suspension are usually measures of the degree to which such forces are avoided: the smaller the better.

One type of constraint force is due to stiffness of the suspension, i.e., the force

[1]Kienholz, D.A., Crawley, E.F., and Harvey,T.J., "Very Low Frequency Suspension Systems for Dynamic Testing," Proc 30th Structures, Structural Dynamics, and Materials Conference, Mobile, AL, April, 1989

[2]Kienholz, D.A., "A Pneumatic/Electric Suspension System for Simulating On-Orbit Conditions," ASME Paper 90-WA/Aero-8, presented at the ASME Winter Annual Meeting, Dallas, TX, November, 1990



The purpose of the suspension system is to support the test article in 1-G without changing its free-free dynamics.

Figure 1: Suspension systems for simulating zero-gravity.

component proportional to vertical displacement of the payload support point from an equilibrium position. Suspension stiffness is usually described in terms of the ratio of the suspension plunge frequency to the natural frequency of the first flexural mode of the payload. The former is the natural frequency of the mode wherein the payload moves vertically as a rigid body on the compliance of the suspension. A well-known rule-of-thumb is that if this ratio is 0.1 or less, the free-free dynamics of the payload are essentially unaffected by suspension stiffness. Analytical examples using finite element models of flexible space structures have shown that a ratio as high as 0.2 may be acceptable if the orientation of the payload relative to vertical is chosen carefully.[3]

Several types of suspension devices, CSA's among them, have demonstrated the capability of meeting the stiffness criterion for realistic payloads. However it is incorrect to consider only stiffness in assessing a suspension method. This common error seems to stem from the oversimplified notion that a suspension device can be modeled as a massless spring. Any real suspension device, including a balloon or a CSA pneu-mag, will impose other constraint forces as well. In particular, added mass (inertia constraint force) must be considered since it usually has as least as much

[3]Gronet, M.J., Crawley, E.F., and Allen, B.R., "Design, Analysis, and Testing of a Hybrid Scale Structural Model of a Space Station," Proc. 30th Structures, Structural Dynamics, and Materials Conf., Mobile, AL, April, 1989

effect on payload normal modes as does stiffness constraint. Inertia constraint force increases with the square of frequency for constant displacement, unlike stiffness constraint force which remains constant. Inertia force from the suspension device will therefore exceed stiffness force for all frequencies above $\sqrt{k/m}/2\pi$, where k and m are respectively the stiffness and added mass of the suspension device. This frequency is invariably within the band of interest for modal testing of flexible space structures. At the upper end of the band, which typically falls between 20 and 40 Hz, inertia force from the suspension added mass will usually dominate suspension effects.

Analytical investigations of added mass effects have indicated that corruption of free-free normal modes typically starts to become serious at about 5% added mass and that 2-3% is a good design target for a true, high-fidelity suspension system.[4] For example, a suspension device supporting 100 pounds should have internal moving elements weighing no more than five pounds and preferably less than three. This conclusion was obtained by examining the shifts in natural frequencies and the loss of cross-orthogonality between modes calculated for free-free boundary conditions and conditions including suspension mass and stiffness.

3. Calculation of Mass Added by the Suspension

3.1 Helium-Filled Balloons

This section gives a simple derivation for the theoretical minimum mass added by a helium balloon. It is shown that the added mass will always be at least 16.3% of payload. The discussion is confined to helium balloons, as opposed to hydrogen, on the assumption that safety concerns would immediately prohibit the latter.

Figure 2 shows a payload of mass M supported by a single helium-filled balloon. For simplicity, the payload is treated as rigid. We wish to calculate the ratio m/M where m is the mass of the helium. The mass of the cable and balloon skin are ignored to obtain best-case results (minimum added mass).

Archimedes buoyancy principle states that the system will be in vertical equilibrium when:

$$\mathrm{V}\left(\rho_{air} - \rho_{He}\right) = \mathrm{M} \tag{1}$$

where:

V = balloon volume, ft^3

ρ_{air} = air mass density, lbm/ft^3

ρ_{He} = helium mass density, lbm/ft^3

M = payload mass, lbm

[4] op cit Gronet, et al

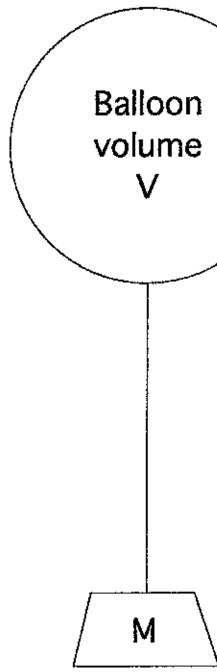


Figure 2: Payload supported by helium-filled balloon.

Equation (1) can be rearranged to read

$$\frac{V\rho_{He}}{\mathrm{M}} = \frac{V\rho_{air}}{\mathrm{M}} - 1 \qquad (2)$$

where the left hand side of (2) is the desired mass ratio. This will next be reduced to a simple expression by rearranging the right hand side.

The pressure inside the balloon may be slightly higher than atmospheric due to the tension in the balloon skin. This will slightly increase the helium density and thus increase the mass of helium required to support a given weight. Consistent with the best-case assumption, the helium pressure will be taken as equal to atmospheric. In that case we may use the ideal gas law to write, for the gas densities:

$$\rho_{air} = \frac{\mathrm{P}}{\mathrm{R_{air}T}} \qquad (3)$$

$$\rho_{He} = \frac{\mathrm{P}}{\mathrm{R_{He}T}} \qquad (4)$$

where

P = atmospheric pressure, 2117. lbf/ft^2

T = ambient absolute temperature, 535 degrees R

R_{air} = gas constant for air = 53.34 ft-lbf/(lbm-deg R)

R_{He} = gas constant for helium = 380.0 ft-lbf/(lbm-deg R)

The gas constants are the universal gas constant, 1545 ft-lbf/lb-mole-deg. R, divided by the respective average molecular weights.[5]

Equations (1), (3), and (4) may be combined to find the required balloon volume in terms of payload mass and the gas parameters.

$$V = \frac{TM}{P}\left(\frac{R_{air}R_{He}}{R_{air} + R_{He}}\right) \qquad (5)$$

Combining equations (2) and (5) shows that the helium mass is always proportional to the payload mass and that the minimum mass ratio is determined completely by the gas constants for air and helium.

$$\begin{aligned} \frac{V\rho_{He}}{M} &= \left(\frac{R_{air}}{R_{He} - R_{air}}\right) \\ &= \frac{53.34}{380.0 - 53.34} = 0.163 \end{aligned} \qquad (6)$$

The calculated mass ratio of 16.3% is best-case since the mass of the balloon skin was ignored as was any compression of the helium. A value of 18-20% is probably more realistic. This mass loading would be unacceptable in any ground vibration test where accurate simulation of true, on-orbit dynamics was required. The fact that the balloon is itself a flexible structure only makes the problem worse. The balloon will have numerous low-frequency vibration modes of its own within the test band. These will interact with payload modes to produce dynamics quite different from the test article alone under true, free-floating boundary conditions.

3.2 CSA Pneumatic/Magnetic System

There is no theoretical method for determining a minimum moving mass of a pneumatic-magnetic suspension device. Moving mass of the device is simply a function of the structural efficiency of its moving carriage. However we can use the actual measured value for the most current version. The Model 60350-D has a nominal load capacity (at 55 psig working pressure) of 350 lb. At proportionately higher pressure it will support up to 500 lb. Its moving carriage has a measured mass of 6.00 lbm, exclusive of the load cable. The mass fraction at nominal payload is thus 6/350 x 100 = 1.7%, far better than the minimum for a helium balloon and well within acceptable limits

[5]Van Wylan and Sonntag, Fundamentals of Classical Thermodynamics, Table A-8, pg. 600, Wiley, 1965

for simulation fidelity. The 60350-D will stay within the nominal 5% added-mass limit for payloads down to 6.00/0.05 = 120 lb.

Special versions such as the 25350-DA have been built for suspending payloads less than 120 lb with good zero-G fidelity. A lightweight carriage (3.4 lb including cable) is used with a positive acceleration feedback loop added to the active magnetic subsystem. By test, the active loop can cancel about 80% of the carriage mass with good stability margin, thus reducing the effective value of added mass to 0.68 lbm. The light-carriage, mass-cancelling devices are typically used with payloads on the order of 25-50 lb, resulting in an added mass fraction of 1.4%-2.7%.

4. Closure

It has been shown that a suspension system based on helium balloons is not even theoretically capable of producing a high-fidelity simulation of free-free dynamics for a flexible test article. This conclusion is due to the 16-20% mass added by the balloons, rather than by added stiffness. It thus holds regardless of the size of the test article or its natural frequencies. The CSA pneu-mag suspension device, by contrast, is designed to impose no more than about 5% added mass. In its best operating range, it typically adds 2-3%. Special versions can use active mass cancellation to allow these performance levels to be attained even for very light payloads, down to as low as 20 pounds.

Finally, it is instructive to compare the physical size of a hellium balloon with that of a CSA pneu-mag device of equal lifting capacity. The model 60350-D can readily float a payload of 500 lb. Its external envelope is approximately 36 x 14 x 8 inches plus a 30-gallon external air tank. Total volume of the pneu-mag device is thus about 6.4 cubic feet. Using Eq. (1), (3), and (4) we can calculate that a spherical helium balloon of equal lifting capacity would have a volume of 7,812 cubic feet and a diameter of 24.6 feet. For even moderate payloads, the logistical advantages of the pneu-mag system are substantial, in addition to its overwhelming performance advantage.