turbulence on the configuration studied have to be regarded as inconclusive at this time.

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Reply by Authors to B. Etkin

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ETKIN raises two major questions concerning our analysis of the response of airships to atmospheric turbulence as presented in Refs. 1 and 2. The first question results from Etkin's misinterpretation of our equation symbology involving relative vs absolute acceleration quantities. The second question takes issue with our assumptions concerning the degree to which gust correlation affects the calculation of the motions and loads on airships.

The authors regret that Eq. (5-4) of Ref. 2, which was presented in the introductory discussion of the turbulence environment (Sect. 5, Art. A), was confused with the actual equations used to calculate the apparent mass and pressure gradient forces (Sec. 8, Art. H). Our sometimes cumbersome system of subscripts and superscripts is needed to distinguish among the many vector quantities, axis systems, and components of the heavy-lift airship system modeled in this study.

Our force equation development carefully distinguishes between *relative* (apparent) *air mass/vehicle* acceleration, denoted in Ref. 2 by $\mathring{V}^a$, and the absolute air mass acceleration, denoted in Ref. 2 by $\dot{V}^{am})_{total}$. The axial component of the *relative* acceleration vector ($\mathring{V}^a$) is given in Ref. 2 [Eq. (8-9)] by:

$$\mathring{u}^a=\mathring{u}_h-\left(\frac{\partial u^{am}}{\partial t}+u^a\frac{\partial u^{am}}{\partial x}+v^a\frac{\partial u^{am}}{\partial y}\right)$$

where

$u^a=u-u^{am}$ = relative axial airspeed

$v^a=v-v^{am}$ = relative lateral airspeed

u^{am}, v^{am} = air mass (gust) velocity components

$\dfrac{\partial u^{am}}{\partial x}$, $\dfrac{\partial u^{am}}{\partial y}$ = air mass velocity gradients

$\mathring{u}_h$ = hull body axial acceleration

The quantity in parentheses is denoted by Du^{am}/Dt in Eq. (5-4) of Ref. 2, and is termed the "relative *air mass* acceleration" in that discussion.

The various quantities in the preceding equations are given in components of the hull center-of-volume axis system (hence, the h subscripts in Ref. 2). Also, the quantities u^{am}, v^{am}, $\partial u^{am}/\partial x$, $\partial u^{am}/\partial y$ are the *effective* quantities at the hull center of volume (hence, the superscripts in Ref. 2), and are obtained from spacial averaging among the four gust input points, as described in Refs. 1 and 2.

The so-called "apparent-mass-type" forces, which are due to the change in momentum of the *relative* flow, depend on $\mathring{V}^a$. For example, [from Eq. (8-195) of Ref. 2],

$$X=-\rho\forall(K_a\mathring{u}^a+K_cqw-K_brv)$$

where $\mathring{u}^a$ is the x component of $\mathring{V}^a$, ρ the atmospheric density, $\forall$ the hull volume, q, r the body axis angular rates in pitch and yaw (excluding air mass motion), v, w the body axis linear velocities (excluding air mass motion), and K_a, K_b, K_c the so-called "apparent-mass" constants.

In contrast to the above "apparent-mass-type" forces, the "dynamic buoyancy pressure gradient," ∇P, depends on the *absolute* air mass acceleration, $(\dot{V}^{am})_{total}$ defined in Eq. (8-18) of Ref. 2. Expanding this quantity in the axial direction yields [from Eq. (8-18) of Ref. 2]

$$(\dot{u}^{am})_{total}=\dot{u}^{am}+u^{am}\frac{\partial u^{am}}{\partial x}+v^{am}\frac{\partial u^{am}}{\partial y}$$

where

$$\dot{u}^{am}=\frac{\partial u^{am}}{\partial t}=\text{acceleration of the air mass}$$

The "dynamic buoyancy" force is obtained from [see Eq. (8-243) of Ref. 2]

$$X_{db}=\rho\forall(\dot{u}^{am})_{total}$$

Thus, the buoyancy force depends on $(\dot{u}^{am})_{total}$ which involves air mass quantities *only*, and does not depend on hull motion, as asserted by Etkin.

Having established the mathematical accuracy of our analysis, we now consider the relative importance of the air mass acceleration terms ($\partial/\partial t$) for airship motions. Conventional aircraft have a very small buoyancy ratio ($\rho\forall g/mg<<1$), and only second-order unsteady aerodynamic contributions. For such aircraft, the "frozen-field" approximation which neglects the air mass acceleration terms ($\partial u^{am}/\partial t$, etc.) yields reasonable results for all but nearly convected flight.[3] However, the airship is a special case since it has a large relative buoyancy ($\rho\forall g/mg\doteq 1$), and very small drag forces at its typically low operational speeds. In fact, this is the secret of their fantastic cruise endurance. This neutral buoyancy condition and large apparent mass renders the

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airship as if it were a particle in the surrounding medium (eloquently illustrated by Prandtl[4]). Thus, the airship responds almost instantaneously (depending on the direction of the gust) to *uniform* acceleration of the air mass. We obtained, for example, in the vertical axis [from Ref. 1, Eq. (1)]

$$a_z \doteq \bar{\dot{w}}_g$$

where $\bar{\dot{w}}_g$ is the averaged gust acceleration at the hull ($\triangleq \partial w^{am}/\partial t$).

The omission of the air mass acceleration forcing function, by adopting the "frozen-field" assumption, eliminates all but the *least* important contributions to airship gust response at low speeds.

We agree with Professor Etkin concerning the limitations of our closed-form model for short-wavelength spectral turbulence. It was acknowledged in our paper,[1] that the calculated spectrum would not be accurate for wavelengths less than twice the hull length ($2\ell_h$). We truncated the spectral calculations at this wavelength, based on DeLaurier's multiple-segment hull analysis. It was further noted in Ref. 1 that since the break frequency for the Dryden turbulence spectrum is one decade below the frequency corresponding to $\lambda = 2\ell_h$, the spectral truncation would not be expected to affect the analysis results significantly.

The second item raised by Professor Etkin concerns our assumption of uncorrelated gust velocities at the four input points. The four-point input model, adapted from the work of Holley and Bryson,[5] allows input of arbitrary correlated or uncorrelated gust time histories. Clearly the gust velocities will be correlated for large-scale lengths (e.g., $L = 1750$ ft) when the hull is not present. However, the question at hand is: What gust inputs spacially-averaged by the hull give realistic hull motions and loads? No full-scale measurements of the complex atmospheric gust environment around an airship have yet been made. As a first attempt, we assummed full noncorrelation. If, however, as Professor Etkin suggests, this yields an underestimation of the resulting loads and motions, our conclusions concerning the high susceptibility of airships to atmospheric turbulence are even more strongly reinforced.

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