N87-22771

ANALYTICAL AND EXPERIMENTAL STUDIES OF FLOW-INDUCED VIBRATION OF SSME COMPONENTS*

S.S. Chen, J.A. Jendrzejczyk, and M.W. Wambsganss
Argonne National Laboratory
Argonne, Illinois

Components of the SSMEs are subjected to a severe environment that includes high-temperature, high-velocity flows. Such flows represent a source of energy that can induce and sustain large-amplitude vibratory stresses and/or result in fluidelastic instabilities. Three components are already known to have experienced failures in evaluation tests as a result of flow-induced structural motion. These components include the liquid-oxygen (LOX) posts, the fuel turbine bellows shield, and the internal inlet tee splitter vane. We have considered the dynamic behavior of each of these components with varying degrees of effort: (1) a theoretical and experimental study of LOX post vibration excited by a fluid flow; (2) an assessment of the internal inlet tee splitter vane vibration (referred to as the "4000-Hz vibration problem"); and (3) a preliminary consideration of the bellows shield problem. This paper summarizes our effort in the resolution of flow-induced vibration problems associated with the SSMEs.

1. An Assessment of LOX Post Vibration: The LOX post vibration problem was assessed. Various excitation mechanisms including vortex shedding, fluidelastic instability, LOX flow-induced instability, acoustic resonance, and turbulent buffeting were considered. A scoping experiment was designed and completed; the experimental data agree well with analytical results (ref. 1). It was concluded that the potential excitation mechanisms for unshielded LOX posts are fluidelastic instability and turbulent buffeting.

2. A Mathematical Model for LOX Posts in Crossflow: A general model, based on unsteady flow theory, for LOX post vibration was developed. The model includes both motion-dependent fluid forces and fluid excitation forces (refs. 1 and 2). In the past, studies of the fluidelastic instability of a tube array in crossflow have been based on three different flow theories: quasi-static flow theory, quasi-steady flow theory, and unsteady flow theory. The quasi-static flow theory predicts fluid-stiffness-controlled instability only and is applicable for high reduced flow velocities. (Reduced flow velocity is equal to the flow velocity divided by oscillation frequency and cylinder diameter.) The quasi-steady flow theory predicts both fluid-stiffness- and fluid-damping-controlled instability. It is applicable for high reduced flow velocities; at low flow velocities it does not predict some of the instability characteristics. Only a complete unsteady flow theory is applicable in all cases.

---

*Work performed for NASA under an agreement with the U.S. Department of Energy.

3. Fluid Excitation Forces: The fluid excitation forces acting on a square array were measured as a function of Reynolds number, incoming flow conditions, and tube location (ref. 3). The main conclusions are as follows:

(1) The fluid forces acting on the first few rows depend on the incoming flow conditions. Once the flow has passed through 3 to 4 rows, the flow and its excitation on the tubes reach a steady-state condition.

(2) In a square array, the RMS values of the lift coefficients are larger than the drag coefficients.

(3) As the flow passes through a tube array, both the turbulence intensity and the resulting fluid excitation forces increase.

(4) The power spectral densities of the fluid excitation forces are fairly flat for reduced frequencies of less than 0.1; they reach a peak at the Strouhal frequency and then decrease drastically with an increase in reduced frequency.

(5) The convection velocity for drag force is higher than that for lift force; it varies from 0.5 to 0.7 of the gap flow velocity.

4. Motion-Dependent Fluid Forces: Motion dependent fluid force components g_j and h_j acting on a group of cylinders in crossflow are given in figure 1. Components g_j and h_j consist of fluid inertia, fluid damping, and fluid stiffness forces. Fluid-damping and fluid-stiffness coefficients for a tube row in crossflow were obtained as a function of reduced flow velocity (ref. 4). Typical results are shown in figure 2 as a function of the reduced flow velocity. In addition, the effects of oscillation amplitude, tube alignment, and flow velocity were studied. From the characteristics of the motion-dependent fluid forces, the stability criteria and the effect of various system parameters can be determined.

5. Splitter Vane Vibration: A preliminary assessment of the excitation mechanism(s) associated with a 4000-Hz vibration of the internal inlet tee splitter vane was made from the available information (unpublished data of Chen's, 1985). The most probable mechanism responsible for the 4000-Hz vibration is a "lock-in" oscillation involving the splitter vanes and the vortex formation in the near-wake of the trailing edges of the vanes. A combination of structural and fluid-dynamic attenuation methods is recommended to eliminate the detrimental vibration.

Even though there are significant gaps in our current knowledge, designers have been able to put together complex, interactive components, such as those of the SSMEs, which operate in severe environments (high temperatures, pressures, and flows) and still provide useful service without significant problems. In many cases, some of the obvious flow-induced vibration effects can be avoided by using common sense and experience without detailed study and calculations. However, in the SSMEs, several vibration problems have been identified which require further consideration. As an example, the shields on the liquid oxygen posts, which have served to reduce the flow-induced vibration problems of the posts to an acceptable level, have caused severe additional loads on other structural components. It would be desirable to redesign the injectors with a detailed consideration of flow induced vibration effects so that the flow shields could be removed. Clearly, there is a need to develop and perform a prioritized research agenda in flow-induced vibration which will lead to a comprehensive technology base consisting of design data, prediction methods, and computer codes required in the design and evaluation of SSME components.

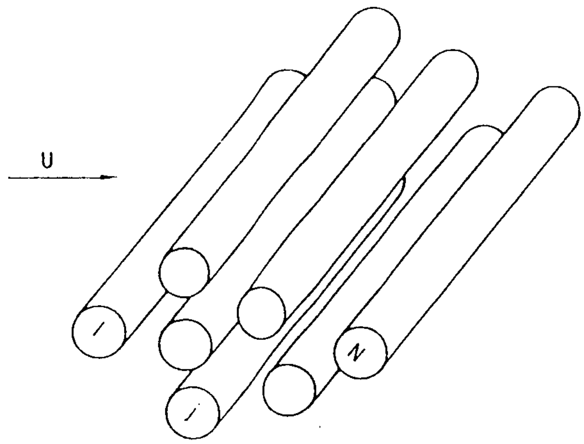
REFERENCES

1. Chen, S.S.; and Jendrzejczyk, J.A.: Flow-Induced Vibration of the SSME LOX Posts. Flow-Induced Vibration - 1986, ASME Publication PVP-Vol. 104, 1986, pp. 119-125.

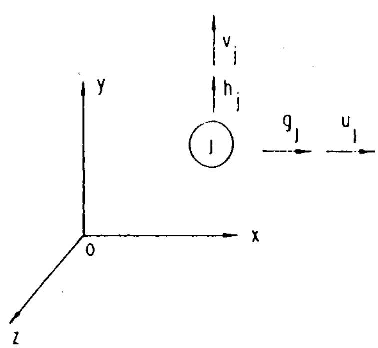
2. Chen, S.S.: A General Theory of Dynamic Instability of Tube Arrays in Crossflow. Journal of Fluids and Structures, vol. 1, 1987, pp. 35-53.

3. Chen, S.S.; and Jendrzejczyk, J.A.: Fluid Excitation Forces Acting on a Tube Array. Measuring and Metering of Unsteady Flows, ASME Publication FED-Vol. 40, 1986, pp. 45-55.

4. Jendrzejczyk, J.A.; and Chen, S.S.: Motion-Dependent Fluid Forces Acting on a Tube Row in Crossflow. Argonne National Laboratory Report ANL-86-48, 1986.



(a) Group of circular cylinders.



(b) Fluid force and cylinder displacement components.

$$g_j = -\rho\pi R^2 \sum_{k=1}^{n} \left(\alpha_{jk} \frac{\partial^2 u_k}{\partial t^2} + \sigma_{jk} \frac{\partial^2 v_k}{\partial t^2}\right) + \frac{\rho U^2}{\omega} \sum_{j=1}^{n} \left(\alpha'_{jk} \frac{\partial u_j}{\partial t} + \sigma'_{jk} \frac{\partial v_k}{\partial t}\right) + \rho U^2 \sum_{k=1}^{n} \left(\alpha''_{jk} u_k + \sigma''_{jk} v_k\right) ,$$

$$h_j = -\rho\pi R^2 \sum_{k=1}^{n} \left(\tau_{jk} \frac{\partial^2 u_k}{\partial t^2} + \beta_{jk} \frac{\partial^2 v_k}{\partial t^2}\right) + \frac{\rho U^2}{\omega} \sum_{k=1}^{n} \left(\tau'_{jk} \frac{\partial u_j}{\partial t} + \beta'_{jk} \frac{\partial v_k}{\partial t}\right) + \rho U^2 \sum_{k=1}^{n} \left(\tau''_{jk} u_k + \beta''_{jk} v_k\right) .$$

Figure 1. - Schematic of a group of circular cylinders in crossflow and fluid force and displacement components.

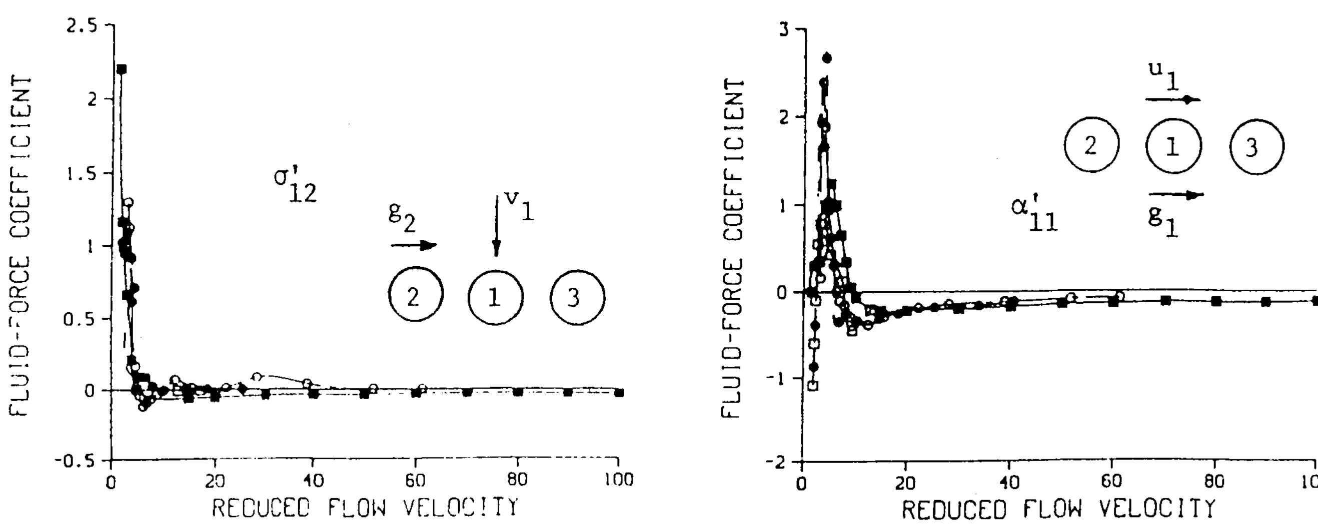


Figure 2. - Fluid-damping coefficients for a row of cylinders obtained at several flow velocities denoted by different symbols.