Characteristic Differences Between the Modal Parameters of Cast and Forged Structures

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Introduction

COMPONENT and material manufacturing techniques of complex aerospace systems can often have a significant effect on the modal vibration characteristics of the structure.[1,2] Steel alloys, manufactured by both casting and forging techniques, are used extensively in rocket engine components for their high strength and durability under severe environmental and vibration loading conditions. Modal frequencies and damping of any structure, which are a function of the material characteristics, density, modulus, thickness, size, stiffness, and mass, among others, are often studied for analysis and predictions. When any of these properties vary, it impacts the modal parameters and thus the dynamic behavior of the structure under consideration.

Consider a uniform cantilevered beam. To determine the natural frequencies and vibration modes of the beam, the Bernoulli-Euler equation can be solved under free vibration, uniformity, constant coefficient, and other simplifying assumptions. The resulting solution for the frequency is an inverse function of the length squared, multiplied by the square root of the modulus, times the inertia, divided by the density, times the cross-sectional area. The mode shapes are given, on the other hand, as a combination of sinusoidal and hyperbolic functions of position from the fixed end of the beam. The effects of shear and rotational inertia also contribute to variations in the modal frequencies and shape functions, but their effects are often neglected.[3]

On the other hand, the damping characteristics depend on the material properties, the structural constraints, geometry, temperature, and other factors. Dynamic stability is solely dependent on the internal damping of the structure, unless

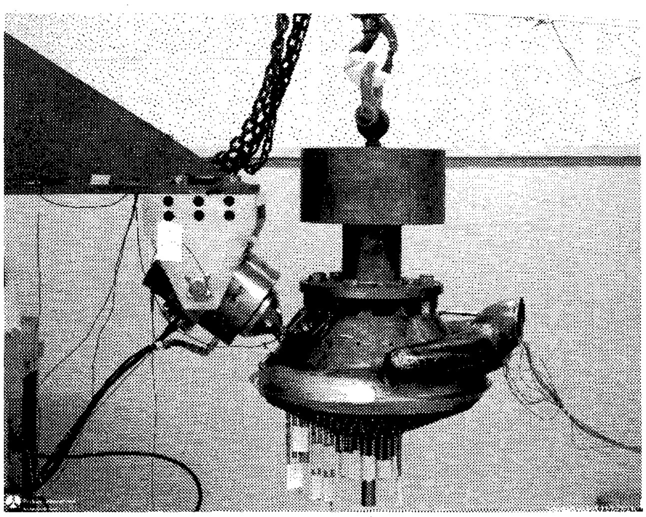

Fig. 1 SSME main injector with LOX posts sticking out the LOX inlet tee with inlet on the right gimbal-bearing simulator on top and shaker on the left.

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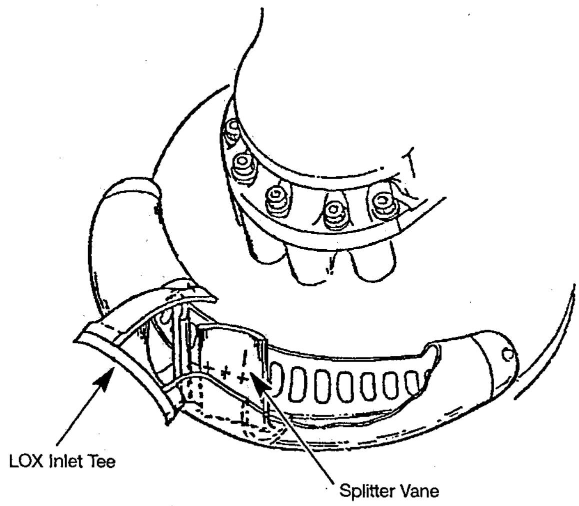


Fig. 2 SSME injector/vane schematic, showing details of the splitter vanes.

there is some form of active or passive damping externally provided for stability enhancement. Thus, it is very critical to evaluate the damping ratios of materials that are used in high stress/strain areas and in severe environments. Rocket engine components, especially those that are near the main injector and the main combustion chamber, experience such severe loads that it is essential to know their modal characteristics, especially the frequency and damping ratios.

Extensive modal survey tests were carried out at the Rockwell International, Rocketdyne Division's engineering development laboratory on rocket engine main injectors (see Fig. 1). The main objective of these tests was to gather modal data on the liquid oxygen (LOX) inlet flow splitter vanes. Thus, both an impact hammer and an electromechanical exciter were utilized to excite the structure at different points and acceleration measurements were taken to determine the mode shapes, frequencies, and damping ratios of the above mentioned parts (see Fig. 2). Vibration modes between 3000–6000 Hz were plotted, and the damping ratios were estimated for each mode. There were sets of symmetrically bending, symmetric torsional, opposite bending, and opposite torsional modes for the vanes (see Fig. 3). Tests were performed on several identical injectors in which the LOX inlet tees were made of cast Inconel-718 steel alloy. The dominant bending modes of the LOX inlet tee vanes were found to be clustered between 3300–4000 Hz (a maximum frequency variation from injector to injector of 32 Hz), while the dominant torsional modes were between 4700–5200 Hz (a maximum variation of approximately 37 Hz). The tests were repeated on an identical injector with a forged LOX inlet tee to study the effect of forging on the modal frequencies and damping ratios. It was discovered that the dominant vane bending modes were now clustered between 3600–4300 Hz, while the vane torsional modes were between 5000–5500 Hz. These results indicated an upward shift of frequencies by about 300 Hz, just because of the difference in the material manufacturing technique (forging/casting). The implications of this fact could be that forging is of higher stiffness and lower damping than casting.

In this note, the test results of the forged and cast structures will be compared. Characteristic material differences and similarities of the two structures will be highlighted. Finally, explanations regarding the main differences between the forging and the casting will be provided.

It is believed that these tests directed towards evaluating the characteristic differences between forging and casting of identical materials as it reflects on the modal behavior of a structure has not been performed heretofore. This type of information is critical for accurate analytical modeling and predictions. It is the usual procedure in the aerospace industry

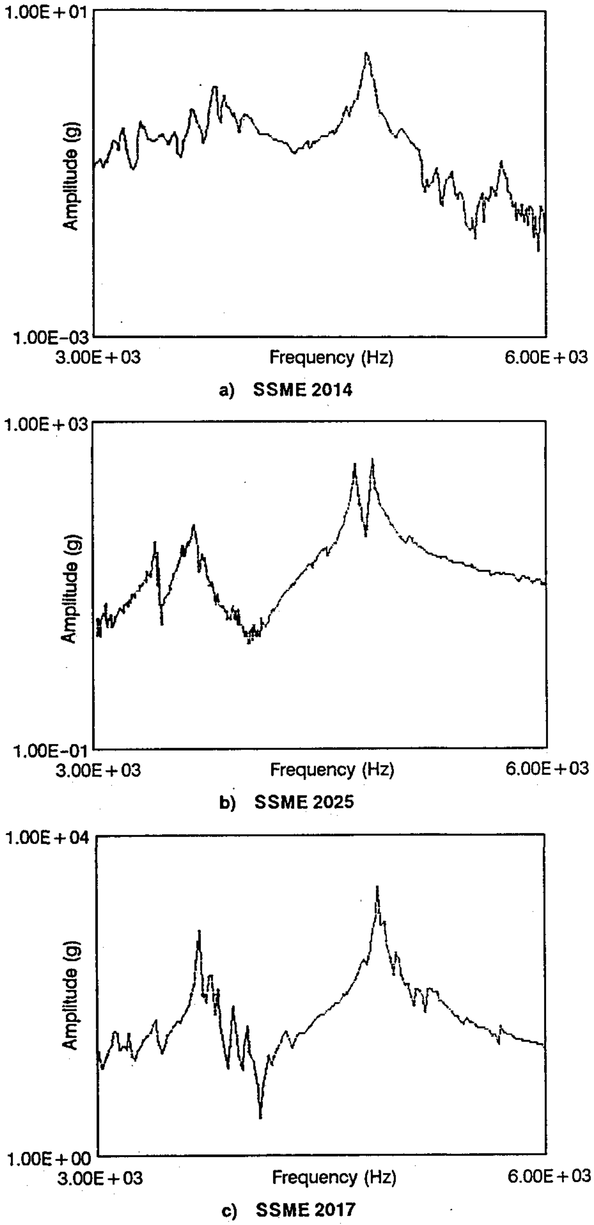


Fig. 3 SSME LOX inlet tee splitter vane frequency response function and phase plot for the forged tee.

to consider forged and cast structures made of the same materials as having identical characteristics. Simulations and predictions are thus carried out under this assumption. This study reveals that the manufacturing process, which is the only difference between the two LOX inlet tees considered, can have a significant effect on the modal characteristics. This fact should be taken into consideration when performing analyses and predictions.

Background

Extensive modal and vibration tests were performed on a specially designed test article that had a forged LOX inlet tee attached to a torus. The tests were done under ambient conditions, and the forged LOX inlet tee was 1) filled with freon and pressurized, 2) filled with liquid nitrogen and pressurized, and 3) slowly filled with water and freon under ambient temperature and pressure conditions. In all of these tests the frequencies of the torsional modes of the LOX inlet splitter vanes were significantly higher than those on other injectors or powerheads. One explanation to this fact was that the torus attached to the tee stiffened the structure, raising the frequencies. However, this reasoning could not completely explain the large difference in frequencies.

The material characteristics of forgings and castings were studied for steel structures and significant differences in their micrograin structures were identified. These differences served as fundamental reasons for performing modal tests on an injector with a forged tee to compare the modal characteristics with those of cast tees from previous tests.

Description of Tests

The test article consisted of the main injector with the LOX posts attached and exposed from outside, and the LOX inlet tee with the elbow cutoff for exposure of the two splitter vanes (see Fig. 1). The test article was bolted to a gimbal-bearing simulator and suspended from a hoist to simulate free-free conditions. The excitor, Wilcoxon Research D125L electromechanical shaker, was fixed to a rigid fixture on the ground, while the tip, with a PCB load cell on, was attached to the thrust cone midspan, at several locations. Flat, random, band-limited (3000–6000 Hz) inputs were used to excite the structure. Measurements were also taken by accelerometers on 25 uniform grid points on each vane. In addition, a hammer was used to impact the right vane at a point on the leading edge near the midpoint to generate modal data consistent with data from previous tests on similar injectors and a few Space Shuttle Main Engine (SSME) powerheads. Thus, vane mode shapes and damping ratios were generated and stored in various computer files.

Test Results

Numerous vane modes were excited (see Fig. 3) and a sample of the strongest ones are shown in Fig. 4. Two major types of vane vibration modes were identified: bending and torsional. These modes can be divided into two groups: sym-

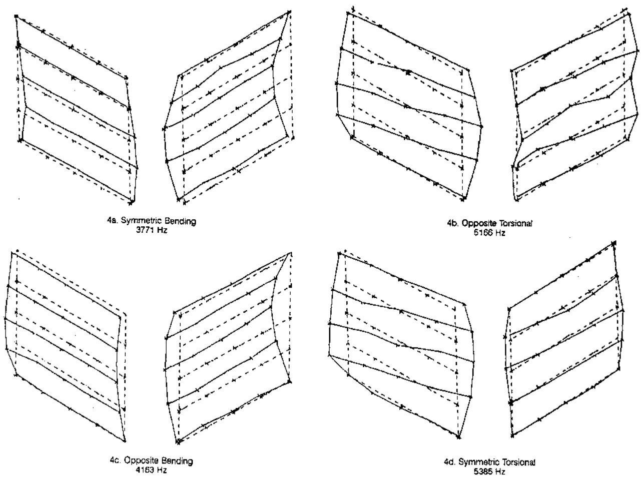


Fig. 4 SSME LOX inlet tee splitter vane FRFs of cast tee from three different engines.

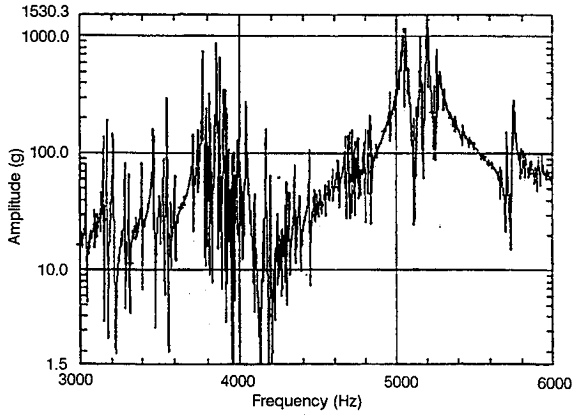
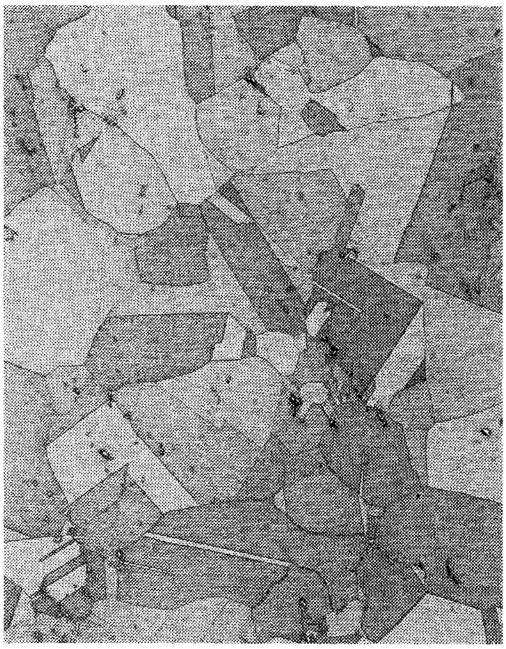


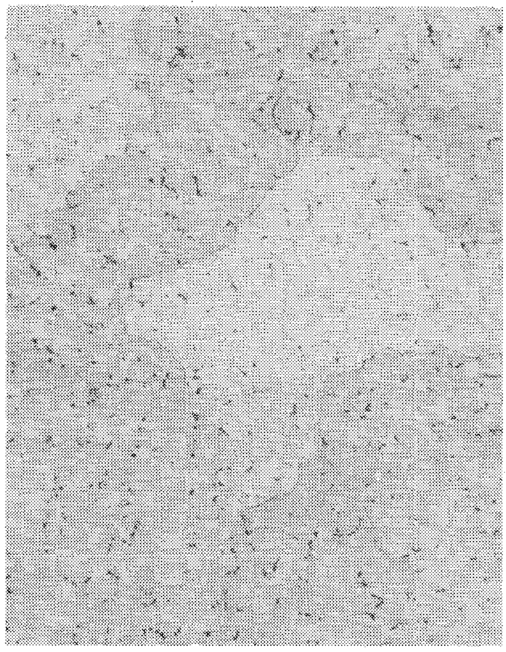
Fig. 5 SSME LOX inlet tee splitter vane dominant mode shapes.

a)

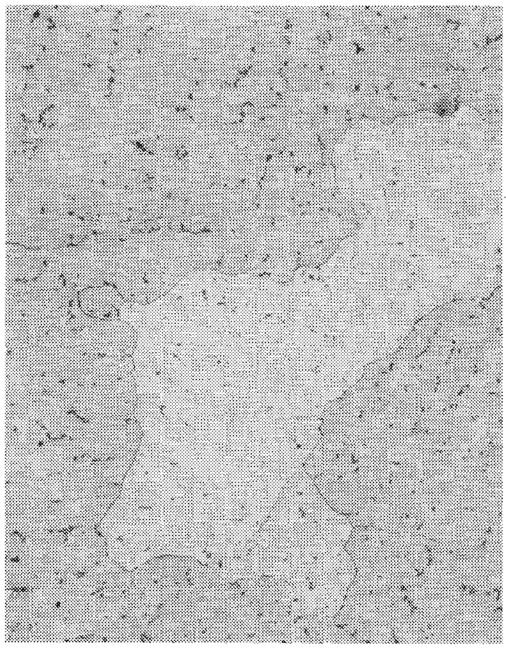


b)

Fig. 6 100 × magnified micrograph of forged Inconel 718 alloy showing a) longitudinal grain size and b) transverse grain size.



a)



b)

Fig. 7 100 × magnified micrograph of cast Inconel 718 alloy showing a) longitudinal grain size and b) transverse grain size.

metrical bending and opposite bending, as well as symmetrical twisting and opposity twisting. Some modes comprise a mixture, and may be under the effect of external shell motion that distorts the shapes. These two major kinds of modes were clustered around 3300–4000 Hz for bending modes and 4700–5200 Hz for torsional.

Figure 5 shows the general frequency response function for the forged tee vanes where the first cluster of high-peaked modes are the bending and the second group of high-peaked modes are the torsional. The frequency range for bending modes in the forged tee was 3600–4300 Hz and for torsional modes at 5000–5500 Hz. Thus, there is a general shift upwards of vane frequencies by as much as 300 Hz, due to the forged manufacturing of the LOX inlet tee as opposed to the casting process. Moreover, the percent damping of previously tested cast LOX inlet tee splitter vanes (see Fig. 3) was an average of 0.1%, derived from test data from several injectors with virtually similar configurations. The average damping for the forged tee vanes was 0.04%, which is about 60% that of the cast tee vanes, thus indicating significantly lower damping.

Discussion

The appreciable differences in the modal-frequency and damping-ratio values of the cast and the forged structures considered are definitely related to the micrograin consistency of their materials. Thus, a forging has much smaller grains (Fig. 6), with a much lower degree of porosity, which could explain the lower damping ratio. On the other hand, a casting (Fig. 7) has several orders of magnitude larger grains that provide more porosity to the material, thus resulting in higher damping values. Moreover, forging with its higher-grain concentrations, and with more but smaller particles at a unit volume, forms a stiffer structure, and has higher overall frequencies. Casting, with its large granular structure and higher porosity, provides less stiffness, and results in lower overall frequencies.

Conclusions

The modal survey test results reported herein indicate significant differences in modal frequencies and damping ratios of the forged SSME LOX inlet tee splitter vanes relative to those of the cast tees. The difference in overall frequencies is a shift upwards (for the forged tee vanes) of about 300 Hz as compared to the vane frequencies of the previously tested cast tee vanes. The damping ratio of the forged tee vanes was also found to be lower as compared to the cast tee vane damping ratios, in general.

These differences are only due to the difference in the manufacturing processes involved in forging vs casting of the same material. The photomicrographs indicate significant grain-size differences between the forging and the casting of Inconel 718, the material with which the tees are made.

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Accurate Prediction of Drag Using Euler Methods

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Introduction

THE problem of aerodynamic design for optimal performance in flight is a very important and demanding task in the development process of an aircraft. One of the most important parameters in the aerodynamic design process is the lift-to-drag ratio L/D. This ratio governs the efficiency of an aircraft in cruising flight for a given Mach number. Thus, both the lift and the drag must be accurately predicted for given flight conditions in order to be able to maximize L/D of an aircraft by refining and improving its shape.

Presently, computational methods based on the potential-flow equations are routinely being used to design and analyze simple (e.g., a wing) as well as complex (e.g., a complete airplane) configurations. One of the main advantages of potential methods is that fully converged solutions can be obtained in less than 1 min of CPU time on current supercomputers for typical three-dimensional problems. However, methods based on the potential-flow equations do not allow for the accurate prediction of lift and drag at higher Mach numbers. In addition, the potential-flow equations do not allow for distributed vorticity fields. Thus, rotational flow regions can only be modeled through the use of singularities which must be positioned a priori. The latter constraint is especially significant for flow calculations around three-dimensional lifting configurations. In that case, the trailing vortex sheet that originates at the trailing edge of a lifting wing with attached flow must be positioned before the flowfield can be calculated. The position of the sheet has a noticeable effect on the surface pressures and, thus, on the lift and drag force generated by the configuration.[1] Specifying the position of this vortex sheet becomes especially cumbersome for a wing body or a complete airplane configuration.

Computational methods based on the Euler equations can provide a more accurate modeling of the vortical field necessary to improve the prediction of the surface pressures as well as the lift and drag. Unfortunately, recent experiences with Euler methods have been less than encouraging. In 1988, the AGARD Fluid Dynamics Panel held a Technical Status Review on CFD-based drag prediction and analysis.[2] One of the main conclusions of the meeting was that "the application for drag prediction purposes of the current generation of Euler codes, in particular in 3D, is hampered by (over)sensitivity to grid density and quality through spurious (artificial) dissipation. For 3D wings and wing-bodies with attached flow only full potential methods with or without boundary layers appear to have some success."[2] More recent Euler results obtained by Hicks et al.[3] for commercial wing and wing-body configurations also indicate that current codes may be unacceptable for design because they are not capable of predicting drag or drag increments accurately enough.

Part of the Euler drag prediction problem may stem from the use of surface pressure integration to determine the drag. For methods based on the potential-flow equations, the integration of surface pressures can give reasonable drag values if the surface grid distribution is sufficiently fine and the numerical solution is fully converged.[4] However, for Euler methods an additional problem is the inherent numerical viscosity which affects the surface pressures especially in the stagnation region near the leading edge of a wing and in the recovery region near the trailing edge. Errors in the surface pressures in these two regions will hardly affect the lift prediction, but will significantly affect the drag prediction.

The purpose of the present paper is to review several drag prediction techniques and to compare them by applying these techniques to three-dimensional Euler solutions.

Lift and Drag from Momentum Theorem

Let us analyze the lift and drag of a wing in an unbounded fluid. The wing can be placed inside a typical control volume V, where V is bounded by a singly connected surface S. The inlet and exit faces of V are normal to the freestream vector $\boldsymbol{v} = \boldsymbol{i}U_\infty$, whereas the side faces run parallel to this vector. Applying Newton's law and the Gauss theorem and limiting the problem to inviscid, steady flows while ignoring gravity forces results in the following momentum balance:

$$\int_S \{p\boldsymbol{n} + \rho\boldsymbol{v}(\boldsymbol{v}\cdot\boldsymbol{n})\}\,\mathrm{d}S = 0 \tag{1}$$

where $\boldsymbol{n} = \boldsymbol{i}n_x + \boldsymbol{j}n_y + \boldsymbol{k}n_z$ and $\boldsymbol{v} = \boldsymbol{i}u + \boldsymbol{j}v + \boldsymbol{k}w$. In turn, Eq. (1) can be written as the sum of a near-field, a cut, and a far-field integral:

$$\int_{S_{\text{body}}} \{p\boldsymbol{n} + \rho\boldsymbol{v}(\boldsymbol{v}\cdot\boldsymbol{n})\}\,\mathrm{d}S + \int_{S_{\text{cut}}} \{p\boldsymbol{n} + \rho\boldsymbol{v}(\boldsymbol{v}\cdot\boldsymbol{n})\}\,\mathrm{d}S + \int_{S_{\text{far}}} \{p\boldsymbol{n} + \rho\boldsymbol{v}(\boldsymbol{v}\cdot\boldsymbol{n})\}\,\mathrm{d}S = 0 \tag{2}$$

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