Reduction of Cabin Noise and Vibration by Intrinsic Structural Tuning

G. SenGupta*
Boeing Commercial Airplane Company, Seattle, Wash.

Abstract

CONTROL of low-frequency interior noise has been difficult in all commercial and general-aviation aircraft, since the existing sound attenuation techniques are less effective at these frequencies. For this reason, a concept based on intrinsic tuning and damping of the fuselage structural elements has been under development at Boeing for some time. The purpose of this paper is to describe the results of some laboratory and field tests that were conducted for evaluation of the concept.

Contents

The concept of intrinsic structural tuning was developed by considering the response of a periodic skin-stringer structure, simply supported at the frames, to a highly correlated and coherent near-field engine noise environment. For typical skin-stringer structures, the frequency of peak response is very close to the natural frequency (f_p) of the individual skin-bay, clamped along the stringers and simply supported along the frames. This is because of strong reflection of skin flexural waves due to the discontinuities provided by the stringers. The process of reflection and transmission of skin flexural energy due to the stringers depends on the stringer stiffness in bending. The dynamic bending stiffness of the stringer is a function of frequency. At the natural frequency (f_s) of the stringer, the stringer dynamic bending stiffness is zero, since the static stiffness term is canceled by the inertia term. Therefore, if the stringer and the panel dimensions are chosen in such a way that the condition $f_s = f_p$ is satisfied, the panel response at f_p should be reduced substantially. If the stringers and panels are designed so that they satisfy the usual static strength requirements and also are tuned to each other according to the preceding equation, the structure should be efficient under both static and dynamic loading conditions. This is the basis of the intrinsic structural tuning concept, which is discussed in more detail in Refs. 1 and 2.

The concept was verified initially by analytical methods. The effect of structural tuning on the dynamic response of a stiffened panel was studied by changing the stringer spacing and also by changing the stringer cross section. It was found that, when the structure was tuned, the response near the frequency f_p was reduced, but there were two other modes that responded strongly (Fig. 1). The lower-frequency mode (mode 1) was such that the adjacent skin bays as well as the stringers vibrated in phase. The higher-frequency mode (mode 2) was such that, although the adjacent skin bays vibrated in phase, the skin and stringers vibrated out of phase. For this reason, a certain amount of stringer damping treatment was necessary. With damped stringers, the responses of these two modes were reduced substantially. It was found that the rms response of the structure could be reduced further when the structure was "fine-tuned," i.e., when the responses of the preceding two modes were equal. An optimum stringer damping also was found to exist. The response increased if the stringer damping was increased beyond this optimum level. For example, if the stringer damping loss factor was infinitely large, the stringers did not respond, and there was a strong reflection of skin bending waves due to the stringers. Modes 1 and 2 then converged to each other, giving rise to a strong response at the classical stringer bending mode frequency, i.e., at the frequency f_p.

After analytical verifications, an experimental program was initiated. In order to design the tuned panel, it was necessary to know the exact frequency of the stringer with and without any damping treatment. A series of tests were conducted to develop stringer damping methods. These were based on the application of constrained layer viscoelastic damping treatment on the stringer flanges (Fig. 2). The results of the stringer damping test are described in detail in Ref. 2. Based on these test results, a damping treatment consisting of a 0.025-cm (0.010-in.)-thick 3M ISD 112 viscoelastic layer and a 7.9- × 0.2-cm (3.125- × 0.08-in.) constraining aluminum strip was chosen to give a stringer loss factor of 0.17. The stringer was 62.5 cm (24.6 in.) long and was approximately simply supported at the two ends. The natural frequency of the stringer with the damping treatment was found to be 241 Hz, and the change in the stringer frequency between the damped and undamped conditions was small.

The next step was to design the tuned panel for which the natural frequency of the individual skin bay matched with the natural frequency of the stringer as measured from the foregoing test. From Ref. 3, the natural frequency of a rectangular panel with two long sides clamped and two short sides simply supported is given by

$$f_p = \frac{\pi}{2\sqrt{12(1-\nu^2)}}\left(\frac{E}{\rho}\right)^{1/2} \times \frac{t}{b^2}\left[\left\{1+(1.506)^2\left(\frac{b}{a}\right)^2\right\}^2 - 2.04\left(\frac{b}{a}\right)^2\right]^{1/2} \tag{1}$$

where

a = length of the shorter side
b = length of the longer side
t = panel thickness
E, ρ, ν = Young's modulus, density, and the Poisson ratio of the panel material

In the present case a is the stringer spacing, and b is the frame spacing (and also the stringer length). The panel thickness was chosen to be 0.16 cm (0.063 in.), and the frame spacing was chosen to be 62.5 cm (24.6 in.). The panel material was aluminum. Equation (1) was then solved for a, so that the skin-bay frequency f_p was equal to the measured stringer frequency (i.e., 241 Hz). In this manner, the stringer spacing for the tuned panel was found to be about 19 cm (7.5 in.).

Presented as Paper 77-444 at the AIAA Dynamics Specialist Conference, San Diego, Calif., March 24-25, 1977; submitted April 11, 1977; synoptic received March 6, 1978. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.**

Index categories: Noise; Vibration.

*Senior Specialist Engineer, Interior Noise Research.

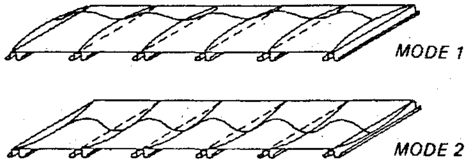

Fig. 1 The two principal modes of an intrinsically tuned panel.

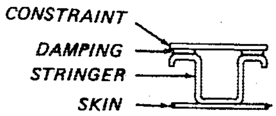

Fig. 2 Use of constrained viscoelastic layer damping on the stringers.

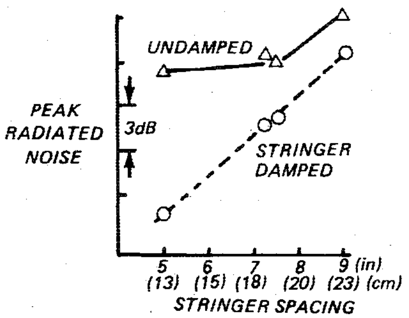

Fig. 3 Reduction of peak low-frequency noise radiation by tuning and damping.

In order to verify the concept, four skin-stringer panels were built. They were all identical except in their stringer spacing. The tuned panel had a stringer spacing of 19 cm (7.5 in.); another had 18.4-cm (7.25-in.) stringer spacing. Two others were built with 22.8-cm (9-in.) and 13-cm (5-in.) stringer spacings. Each panel was chosen to have five bays.

These panels were then tested by mounting them between a reverberent room and an anechoic box. A set of lightweight electromagnetic shakers was used to excite the panels. These shakers were connected in series and fed by current from a white noise generator to simulate a highly correlated and coherent near-field jet noise environment. The panels were instrumented to measure the acceleration and strain responses. In addition, the noise radiated into the anechoic box also was measured.[2]

The principal results of the laboratory test are shown in Fig. 3, which shows the variation of the noise radiated by the most dominant low-frequency mode as a function of the stringer spacing. With no damping treatment, the radiated noise level decreased by about 3 dB as the stringer spacing was reduced from 22.8 cm (9 in.) to 19 cm (7.5 in.). With a further reduction of stringer spacing, the level of radiated noise remained essentially at the same level. Thus, for an undamped structure, the tuning condition defines the point of diminishing return for reducing cabin noise by fuselage structural modifications aimed at increasing the fuselage structural stiffness. Further reductions were possible by applying damping treatment on the stringers. Under damped conditions, the radiated noise level, measured in decibels, decreased almost linearly as the stringer spacing was reduced.

These results show that, under undamped conditions, there is a limit to the noise reduction that can be achieved by changing the structural parameters. This limit can be achieved by designing the structure so that the skin panel and stringers are tuned to each other. However, further reductions are possible by choosing structural dimensions so that the uncoupled skin panel frequency is higher than that of the uncoupled stringer frequency and then applying damping treatment on the stringer flanges. Under this condition, the skin acts like a relatively stiff member supported on relatively flexible stringers. As a result, damping treatment on the stringers becomes very effective in reducing the response. In contrast, skin damping would have been less effective in reducing the peak response of the panel with 13-cm (5-in.) stringer spacings. The low-frequency response of this panel is controlled primarily by the stringer resonance. The acceleration and stress responses of these panels also followed trends similar to those shown in Fig. 3.

Three of these panels then were exposed to the near-field noise environment generated by the full-scale, upper-surface-blown, YC-14 engine-wing-flap test rig, under a joint NASA/U.S. Air Force contract. The trends observed from the field test were similar to those observed from the laboratory test.[2]

The results of this study show that low-frequency cabin noise and sonically induced stresses can be effectively reduced by using the following criteria based on the tuned structure concept. Damping should be applied on the skin if the skin-bay frequency f_p is lower than the stringer frequency f_s. Damping can be applied on the skin and on the stringers if the structure is intrinsically tuned. For maximum noise reduction, the structure should be designed so that the skin-bay frequency f_p is greater than the stringer frequency f_s. Then damping should be applied on the stringers, since the low-frequency panel response then is controlled primarily by stringer resonance, with the skin panel acting like an attached mass.

Acknowledgments

The initial analytical work and the laboratory tests were performed under the Boeing IR&D program. The field test was performed under a NASA/U.S. Air Force Contract (F33657-72C-0829, Contract Change P00028). The author wishes to thank all of the Boeing personnel involved in the test program.

References

[1] SenGupta, G., "Current Developments in Interior Noise and Sonic Fatigue Research," *Shock & Vibration Digest*, Vol. 7, Oct. 1975, pp. 3-20.

[2] SenGupta, G., "Low Frequency Cabin Noise Reduction based on the Intrinsic Structural Tuning Concept," NASA CR-145262, March 1978.

[3] Warburton, G. B., "Vibration of Rectangular Plates," *Proceedings of the Institute of Mechanical Engineers*, Vol. 168, No. 12, 1954, pp. 371-384.