Some Tunnel-Wall Effects on Transonic Flutter

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Significant effects of wind-tunnel walls were observed on the transonic flutter boundaries of wall-mounted models during two flutter model research studies, a joint ONERA-NASA-Boeing program and a follow-on NASA exploratory study. In these studies, flutter experiments with cantilevered SST-type wing models were conducted in three different wind tunnels: the ONERA S2 tunnel at Modane, France; the NASA Langley transonic dynamics tunnel; and the NASA Ames 6-ft by 6-ft supersonic tunnel. The experimental results are compared to flutter boundaries calculated for the models in free air. The results indicate that transonic flutter boundaries can be affected by tunnel-wall interference, tunnel resonances, and shock-wave reflections, and that flutter model data accuracy is a function of model/tunnel size and tunnel wall porosity. However, models within the recommended size limits should give accurate results in transonic tunnels with normal ventilation. A flutter trend analysis for a two-dimensional wing demonstrating tunnel wall and resonance effects on flutter is also presented.

I. Introduction

OVER the past two decades, wind-tunnel studies of flutter models have been used extensively to supply design data in the flutter-critical transonic range where analytical prediction methods are least reliable. In the United States, flutter model testing has become an integral part of the development of high-speed aircraft. Today, the flutter model designer is faced with the problem of scaling components of very complex structural and aerodynamic vehicles to a much reduced size. To reduce the design difficulties, flutter models are normally made as large as possible (or practical) within the constraints of obtaining accurate test data in a specific test facility. Flutter model design standards for transonic wind-tunnel tests are not clearly defined although the problem areas are fairly well known[1-9]. It is generally accepted that flutter model tests do not require aerodynamic simulation to the degree of precision required by the aerodynamic performance engineer and upon which many model/tunnel size limits are predicated.

Guidelines more related to flutter have been suggested by research studies of Garner and others[3,5] from which model wing span and planform limits are proposed based on minimal wall interference effects on the unsteady aerodynamics of wall-mounted models. These guidelines are quite general and may not apply to specific wing configurations. The literature indicates few, if any, instances where model flutter at transonic speeds was found to have been directly affected by the tunnel.

Recently, significant effects of wind-tunnel walls have been observed on the transonic flutter boundaries of wall-mounted models during two flutter model research studies, a joint ONERA-NASA-Boeing program and a follow-on NASA exploratory study. The purpose of the present paper is to report these experiences and to identify some problems associated with flutter model testing in transonic wind tunnels.

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II. Joint ONERA-NASA-Boeing Flutter Program

Background

During the Boeing supersonic transport (SST) 2707-300 prototype airplane development, some discrepancies were noted in transonic flutter speeds for cantilevered wing models tested in different facilities. Although the models scaled the same nominal wing design, the experimental differences could not be accounted for analytically. A cooperative ONERA-NASA-Boeing program was initiated to explore this problem. In this program a scaled model of the Boeing SST prototype airplane wing, for which transonic data had been obtained in the NASA Ames Research Center 6-ft by 6-ft (1.8 by 1.8 m) supersonic tunnel, was tested in the NASA Langley Research Center transonic dynamics tunnel (TDT) (4.9 m square test section) and the ONERA S2 tunnel (1.8 m square test section) at Modane, France. The Modane and Ames tunnels were nearly the same size, but differed mainly in that the Ames tunnel had a slotted ceiling and floor whereas the Modane tunnel had perforated walls that could be varied in porosity (or hole size) from 0% (closed) to about 12% open. Thus, the effect on flutter of tunnel porosity, tunnel ventilation geometry, and tunnel size could be examined.

Model and Test Procedure

A photograph of the wing model mounted in the Modane S2 tunnel is shown in Fig. 1. The model was built by Boeing/Seattle and was a 1/20-size version of the proposed Boeing SST semispan wing. It had scaled, replica-type, stressed-skin members constructed of fiberglass and included wet fuel cells in the wing, although in the present program, the empty wing was used. The model span was about 1.07 m, the model root chord was about 2.03 m with the leading-edge strake included and about 1.52 m without it. The wing airfoil had a thickness-to-chord ratio of about 3%. Mounted to the underside of the wing were two flow-through, simulated engine nacelles. Model instrumentation included several strain gages located at various stations on the wing, accelerometers at the wing tip and outboard engine nacelle, and thermocouples at the wing leading-edge and trailing-edge spars.

The flutter tests generally followed standard procedures in variable density tunnels. A flutter stopper was developed by Mr. Destuynder for the Modane test and proved to be very ef-

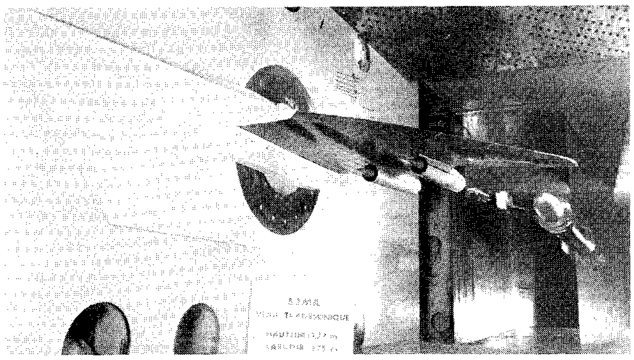

Fig. 1 Model in Franch Modane S2 wind tunnel.

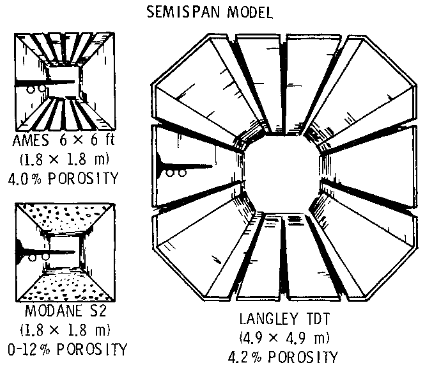

Fig. 2 Sketches of the model installation in the three test facilities.

fective. It consisted of two air-inflatable, spherical bags mounted in a streamlined body at the end of an arm. The arm was attached to the tunnel sting behind the model and could be pneumatically moved fore and aft in the tunnel. At flutter, the arm was extended forward into the open end of the outboard engine nacelle and the bags inflated against the inner nacelle surfaces to provide a restraining force and damping; the entire operation required about 2 sec. The device was triggered by a Boeing-developed, dynamic response actuation system which was also used in the NASA tunnel tests as a flutter indicator. This system would monitor the oscillatory signal from a selected model vibration sensor and, when a preset signal amplitude was reached, would count the cycles that this amplitude was exceeded over a given period of time. By using the same settings for this system in all three wind tunnels, it was possible to insure a consistent definition of the onset of flutter and thus obtain flutter points of comparable quality. At Modane, a frequency spectrum analyzer was used to trace model frequencies and damping in the subcritical region. In most cases, the damping variation with increasing dynamic pressure provided a good indication of the model proximity to flutter and could be extrapolated accurately to the actual flutter point.

Wind Tunnels

Sketches of the model installed in each test facility are shown in Fig. 2. The models and tunnel cross section are drawn roughly to scale. The figure shows the relative model-to-tunnel size as well as the particular ventilation geometry of each tunnel. Each porosity value is the percentage of the open area to total area of the ventilated ceiling and floor. Note that the slotted Ames 6-ft by 6-ft and Langley TDT have a fixed porosity value of about 4%. (The TDT sidewall also has about the same porosity.) In the Modane S2 tunnel, the porosity in the ceiling and floor can be varied from 0% to 12% by sliding a thin cover plate with matching holes over the perforated wall plates. In the present studies, the sidewalls of the S2 tunnel were usually solid.

Some model-to-tunnel size parameters for the model in the three test facilities are presented in Table 1. The recommended values for the model span and planform were adopted from Garner's[3] suggested limits for minimal wall interference on dynamic measurements of wall-mounted models. The model area blockage value of 1% is from Goethert[1]; 1.5% is recommended by Wasserman and Mykytow.[6] The difference between the model size ratios in the Ames 6-ft by 6-ft and Modane S2 was partly due to a slightly different model mounting arrangement and fuselage fairing in the two tunnels.

Table 1 shows that the model exceeded the recommended size for transonic testing in the two small tunnels, but was well within those values in the Langley TDT. In defense of the model, it was originally designed to be tested in the Ames 6-ft by 6-ft at supersonic speeds ($M > 1.2$) where a larger size is acceptable, and appears to have provided good results in that Mach number region. During the testing at Ames, the supersonic tests were extended into the transonic region simply to provide a continuous flutter boundary for additional correlation with analysis.

Results and Discussion

General

Some results from the joint study are presented in Figs. 3 and 4. Figure 3 shows the variations of dynamic pressure (q) at flutter against Mach number (M) obtained with the model in the three facilities. Also included in the figure is the calculated flutter boundary for the model in free air. Boeing made the flutter analyses which employed three-dimensional, compressible aerodynamics generated by a kernel function method at $M = 0.6$, 0.8, and 0.9, and Mach box unsteady aerodynamics at $M = 1.13$, 1.2, 1.29, and 1.57.

The general trend of the flutter boundaries for this wing shows a substantial dip at transonic speeds. This dip was very important in the early flutter design studies of the proposed Boeing SST prototype wing. The Ames data were part of the wing design studies and indicated lower flutter speeds than

Table 1 Recommended and actual model-to-tunnel size parameters

	Recommended for transonic testing	Model in: Ames 6×6 ft supersonic tunnel	Modane S2 tunnel	Langley transonic dynamics tunnel
Model span / Tunnel width	0. ≤0.40	0.57	0.65	0.23
Model planform area / Tunnel cross-section area	≤0.15	0.29	0.35	0.04
Model cross-section area / Tunnel cross-section area	≤0.01 to 0.015	0.012	0.018	0.003

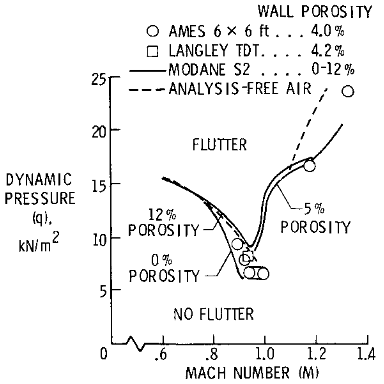

Fig. 3 Model flutter test results and comparison with analyses.

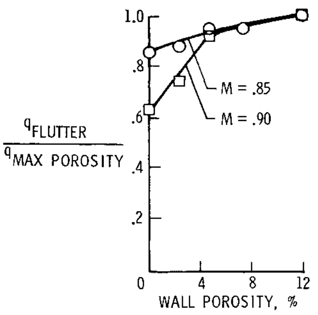

Fig. 4 Variation of model dynamic pressure at flutter with wall porosity in Modane S2 tunnel.

other transonic data. The lowest flutter point ($q = 6.56\ kN/m^2$) of the Ames results occurred during transient conditions in the tunnel and the Mach number was not precisely determined; it lies within the Mach number band ($M = 0.93$ to 1.02) indicated and is most likely near the lowest Mach number.

Only one flutter point could be obtained in the Langley TDT (Fig. 3) near $M = 0.92$. This point represents essentially the upper limit available in air in the TDT over this Mach region. Although this TDT flutter point is close to the Ames boundary, the model did not flutter at the higher Mach numbers (up to $M \approx 1.1$) up to dynamic pressures which exceeded the Ames flutter point near $M = 0.95$ by appreciable amounts.

In the Modane S2 tunnel, model flutter speeds were determined with the ceiling and floor porosity of the test section varied incrementally from 0% to 12% at subsonic Mach numbers, and from 5% to 12% at the higher Mach numbers (Fig. 3). The wall porosity affected the flutter at Mach numbers from about 0.8 to 1.2, with the lowest flutter speed occuring at the lowest porosity value. Figure 4 shows that as sonic speed is approached, the wall porosity in the range of 0% to 5% had an increasingly greater effect on the flutter dynamic pressure. However, the flutter mode remained essentially the same. Limited studies of varying the sidewall (opposite to the model) porosity and adding boundary-layer transition strips to the model indicated no appreciable change in the model flutter characteristics at a number of data points.

Comparison of the results (Fig. 3) indicates that at Mach numbers up to 0.9, the Ames and Modane data for comparable wall porosity (5%) are consistent with the analysis and TDT flutter point. At higher Mach numbers up to sonic speeds, both the Modane and Ames data become suspect because of the relatively large model size and the observed large effects of wall porosity.

At supersonic speeds, the Ames and Modane experimental data are in reasonably good agreement. The experiments predict lower flutter speeds than analysis although the Mach number trend is about the same. It should be remembered that the unsteady aerodynamics in the analysis was generated by the Mach box method and its applicability at low supersonic Mach numbers is uncertain.

Test Problem Areas

With these results on hand, problem areas associated with transonic wind-tunnel testing were reviewed in an effort to identify the probable cause of the observed experimental effects. The review included the effects of tunnel-wall interference, shock reflections, Reynolds number, tunnel resonances, and background noise spectrum. These are well-known phenomena [1-9] and it is not the intent in this paper to discuss these effects in any detail but only as they might apply to the present studies.

The Modane flutter results for wall porosity values less than 5% demonstrate typical evidence of wall interference as characterized by a gradually increasing effect of wall porosity as sonic speed is approached. The suspect low Ames flutter point near $M = 0.95$ is also probably due to wall interference although reflected shock waves may also be partially involved. In the present wind-tunnel studies, the Reynolds numbers of the flutter points range from a low of about 1.0×10^6 to over 5×10^6 (based on the model chord at three-quarter semispan), certainly sufficiently high for the boundary layer to be turbulent. At Modane and at Langley, limited tests with transition (trip) strips on the model showed no significant effect on the flutter characteristics.

Any tunnel resonance effect would be expected to produce variations in flutter speed and/or flutter frequencies over limited and relatively narrow Mach number ranges. This did not seem to occur at Modane. A whistle occurs in the Modane tunnel at a frequency of the order of 500 Hz at certain porosity values (the whistle frequency and intensity vary with porosity and test condition), but compared to the model flutter frequency of about 30 Hz, this resonance should not affect the flutter. Background noise spectra available from the tunnels did not indicate any unusual power concentrations in the frequency range of interest, and no test data from these tunnels heretofore have given any indication of a particular noise problem. Therefore, resonance and background noise is not believed to have been a significant factor in the present studies.

Actual Flutter Boundary

It is concluded that wall interference at transonic speeds caused the variations of flutter speed with wall porosity measured at Modane and the low flutter point ($M \approx 0.95$) at Ames (Fig. 3). The flutter boundary for this wing is believed defined at subsonic speeds by the analysis trend with a minimum flutter dynamic pressure occurring at the TDT flutter point near $M = 0.92$. At supersonic speeds, the wing flutter boundary is believed to follow the Modane and Ames experimental results because of the good agreement in the experiments.

III. Follow-On NASA Exploratory Model Study

Purpose

With the results of the joint ONERA-NASA-Boeing program in mind, a follow-on study was initiated at NASA Langley. The purpose of this study was to explore wall porosity effects on a small model which was well within the recommended size limits (Table 1). In this study an available, simplified model of the proposed Boeing SST wing design was flutter tested in the TDT with the tunnel wall slots open and closed. The study was to have been conducted with both Freon and air as the test medium, but the model was damaged during the tests in air and only results in Freon were obtained.

Model and Test Procedure

A photograph of the simplified wing model mounted in the wind tunnel is presented in Fig. 5. Note that floor and ceiling

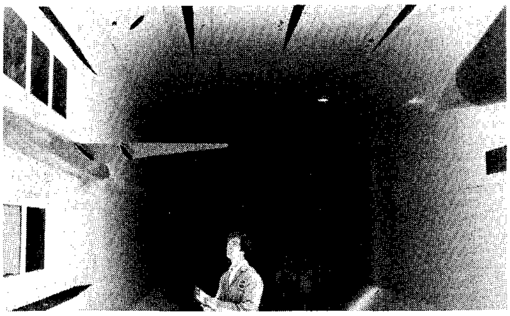

Fig. 5 Simplified wing model mounted in Langley TDT. View is from rear of model.

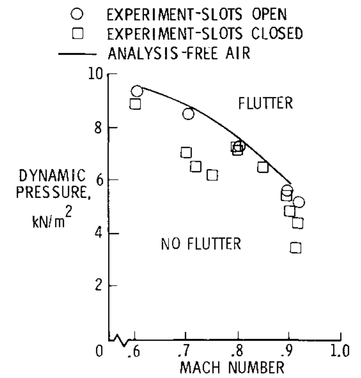

Fig. 6 Experimental and analytical flutter results for simplified wing model.

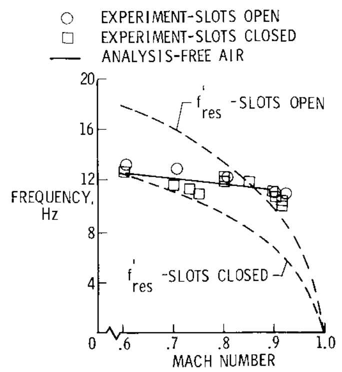

Fig. 7 Comparison of model flutter frequencies and primary tunnel resonant frequencies.

slots begin considerably ahead of the side slots. The floor and ceiling slots are those required for transonic operation of the tunnel; the side slots allow flow expansion and reduce flow distortion about the model. The model was 1/17-size and had roughly 15% higher model/tunnel size ratios than those given in Table 1 for the 1/20-size model in TDT, still well below the recommended size limits for transonic flutter testing. Previous flutter tests with a similar model had indicated that the flutter mode was comparable to that for the scaled wing model used in the joint ONERA-NASA-Boeing study.

The present wing was basically the same as wing C of Ref. 10 which contains details of the wing construction and physical properties. Briefly, the wing was constructed of an aluminum alloy plate covered with balsa wood that was contoured to an airfoil shape comparable to the proposed Boeing SST prototype wing. The plate tapered in thickness spanwise and was milled to simulate a rib and spar pattern. Streamlined bodies representing the under-slung engine nacelles were weighted to provide reasonable simulation of the vibration modal characteristics of the SST wing with engines.

Flutter tests were conducted at Mach numbers from 0.6 to 1.0 with the slots open and closed, and the results are presented in Figs. 6 and 7. All slots were sealed including those in the floor, ceiling, and sidewalls. The usual test procedure was to hold Mach number constant and slowly increase the Freon density (and dynamic pressure) until flutter occurred. Several no-flutter points were obtained at the higher Mach numbers to establish that the transonic minimum flutter dynamic pressure had, in fact, been measured. For the slots-closed tests at $M \approx 0.90$, the tunnel total pressure was held nearly constant and the Mach number (and dynamic pressure) varied until the model fluttered or until $M = 0.95$ was reached. An interesting observation was that the tunnel choked at a Mach number of 0.97, a considerably higher value than would be expected with the present model blockage area. Also presented in Fig. 6 and 7 are the results of the flutter analysis for this model, which employed lifting-surface (kernel function) unsteady aerodynamic theory and was essentially the same as that of Ref. 10.

Results and Discussion

General

The slots-open results (Fig. 6) were in good agreement with analysis and, in general, were consistent with the previous results for the scaled Boeing SST wing. However, the slots-closed experiments indicated lower flutter dynamic pressures in two Mach number regions, one region extending from $M = 0.6$ to 0.75 and the other near $M \approx 0.91$. These were rather unexpected results. To establish confidence in the model structural integrity following these low flutter points, the model was retested at $M = 0.8$ with slots closed, and flutter occurred at an almost identical dynamic pressure and frequency as before.

Again, potential transonic testing problems were reviewed. Wall interference such as occurred in the scaled wing tests discussed above was considered unlikely because of the present small model-to-tunnel size and the fact that the wall porosity effects occurred at limited Mach number regions, including relatively low Mach numbers. Tunnel resonance effects were now more closely examined.

Tunnel Resonances

Theoretical treatments of tunnel wall effects on oscillating wings in compressible flow have indicated that large effects of the walls may be experienced under certain conditions identified as tunnel resonances. Tunnel resonance is defined in Ref. 7 as an acoustic phenomenon which occurs when a disturbance from the oscillating wing is reflected from the tunnel wall back to the wing with such a phase relationship that it reinforces a succeeding disturbance. Resonance conditions have been demonstrated experimentally to exist and can be predicted theoretically for closed, partially closed, and open tunnels.[7,8] Model flutter in a tunnel would be expected to be affected by tunnel resonances when the flutter frequency and/or vibration mode frequency (with air loads) was near a tunnel resonance frequency.

Tunnel resonance frequencies (f_{res}) are determined from the following relationships:

Closed tunnel[7,8]

$$f_{res}(Hz) = (a/2H)(1-M^2)^{1/2}(2n-1) \quad n = 1,2,3,\ldots \tag{1}$$

Slotted tunnel[8]

$$f_{res}(Hz) = (a\lambda/\pi)(1-M^2)^{1/2} \tag{2}$$

where

$$\lambda = -(H/2c)\tan\lambda$$

$$c = (\mathcal{L}/\pi)\ln[\text{cosecant}(\pi e/2\mathcal{L})]$$

In Eqs. (1) and (2), a = speed of sound in test medium, H = tunnel height, M = Mach number, $\mathcal{L}$ = slot spacing, e = slot width. For the TDT with Freon and average operating conditions ($a = 152$ m/sec, $H = 4.88$ m, and $\mathcal{L} = 1.61$ m, $e/\mathcal{L} = 0.0426$), the primary resonant frequency equation is for the slots closed and open, respectively.

Slots closed: $f'_{res}\,(Hz) = 15.6\,(1-M^2)^{1/2}$

Slots open: $f'_{res}\,(Hz) = 22.2\,(1-M^2)^{1/2}$

The tunnel resonant frequencies are compared to the experimental and analytical frequencies for the model in Fig. 7.

Considering first the analytical (free-air) and slots-open experimental data (Fig. 7), the model flutter frequencies from experiment and analysis are in good agreement. The flutter frequency variation and tunnel resonance frequency curve intersect near $M = 0.85$ where, unfortunately, no experimental flutter data were obtained, but there was no noticeable effect on the model flutter frequency and dynamic pressure level (Fig. 6) at adjacent Mach numbers ($M = 0.8$ and 0.9). It is concluded that there were no resonance effects on the model flutter characteristic with the slots open.

For the slots-closed condition, in the Mach number region from 0.6 to 0.75, the model flutter frequencies are close to the tunnel resonance frequencies and even appear to be following along the resonance curve (Fig. 7). At $M = 0.8$, the model flutter frequency increases rather sharply to near the slots-open frequency, and the flutter dynamic pressure shows corresponding closer agreement with the slots-open data. Thus, it is concluded that the proximity of the tunnel resonance frequency to the flutter frequency near $M = 0.6$ to 0.75 was the likely cause for the lower flutter speeds with the slots closed.

This does not appear to be the case near $M = 0.91$ where the slots-closed flutter frequencies are much higher than the primary tunnel resonance frequencies. Although higher tunnel resonances (Eq. (1), $n = 2,3, \ldots$) may be approaching the flutter frequency, they are still considerably higher than the flutter frequencies near $M = 0.91$. Tunnel resonances are not considered, therefore, to be the primary cause of these reduced flutter speeds.

Shock-Wave Reflections

A possible cause is suggested by the model behavior in this Mach number region near 0.91. In the slots-open tests, the model was lowly damped over a considerable dynamic pressure region prior to flutter. With the slots closed, the model flutter was of a benign, limited amplitude type, with the flutter amplitude gradually increasing with dynamic pressure. Although there may be other explanations, it is suggested that shock waves, which are nearly normal to the model surface at these Mach numbers, are reflecting from the tunnel walls back on the wing so as to reduce the basic aerodynamic damping forces. Increasing dynamic pressure in the tunnel would intensify the shocks and cause the model oscillation amplitudes to enlarge.

IV. Flutter Analysis of Tunnel Wall Effects

Some significant effects of tunnel-wall interference and resonances on flutter have been reported analytically by Bland, and some results from Ref. 9 are replotted in Fig. 8. The mathematical model was a two-dimensional wing with a wing-chord-to-tunnel-height ratio of 0.13. Compared to the recommended size limits of Table 1, this model had a relatively small planform but obviously oversize span. The analysis considered model rigid plunge and pitch degrees of freedom and employed unsteady aerodynamics which were derived from an inviscid potential flow method involving a kernel function analysis of tunnel-wall effects. Wing thickness effects were neglected. Flutter speeds were calculated for the model in free air and in a closed tunnel at subsonic Mach numbers up to 1.0.

The analysis was made for a constant fluid density which means that at a fixed Mach number increasing velocity is

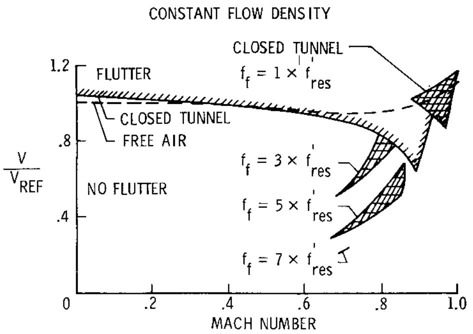

Fig. 8 Analytical results showing wind-tunnel wall effects on a two-dimensional wing flutter speed.

realized by increasing the speed of sound of the fluid. This differs from a tunnel test where for a constant Mach number increasing dynamic pressure is accomplished by increasing the test fluid density.

Comparison of the free-air and closed tunnel (no resonance) boundaries in Fig. 8 shows that the tunnel wall proximity reduced the model flutter speed appreciably at $M = 0.7$ to 0.95, with the maximum reduction occurring near $M = 0.90$. The analysis predicts several pockets of low flutter speeds near $M = 0.6$ to 0.85, and low flutter speeds near $M = 0.95$ to 1.0. In these instances, the calculated flutter frequency was close to a tunnel resonance frequency and the wing fluttered in a single-degree-of-freedom (primarily pitch) mode. Apparently, as the pitch mode frequency approached a tunnel resonance, the aerodynamic damping in pitch decreased sufficiently to cause flutter.

As mentioned before, the analysis was made for a constant fluid density whereas in the wind tunnel the density is variable. It is difficult to apply these analytical results directly to a wind-tunnel model test but some general comments can be made. The analytical tunnel-wall effects (aside from resonances) appear consistent with the Modane S2 tunnel tests discussed earlier in that the flutter speeds were decreased sizably from free-air results in a closed (0% porosity) tunnel at transonic Mach numbers. The analysis also indicated that resonances can reduce the flutter speeds significantly. In actual wind tunnels,[7] wall boundary layers, flow turbulence, and viscosity would tend to prevent pure resonances from occurring. This would be especially true of the higher frequency resonances. Tunnel ventilation would also tend to inhibit pure resonant conditions. For these reasons, any resonance effects on flutter would be expected to be limited to the low-frequency fundamental resonances in closed tunnels and to be reduced or eliminated in normally ventilated tunnels.

V. Conclusions

The results of two flutter research studies employing wall-mounted models and related flutter analysis have indicated the following conclusions: 1) Transonic flutter speeds of wall-mounted models can be significantly affected by a) tunnel wall interference, b) tunnel resonance, and c) shock-wave reflections. 2) These effects are related to model-to-tunnel size and tunnel wall porosity. 3) Tunnel ventilation eliminated effects of tunnel resonances and shock-wave reflections. 4) Models within recommended size limits should give accurate data in transonic tunnels with normal ventilation.

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