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# EXPERIMENTAL STUDY OF SINGLE MODE PANEL FLUTTER

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## ABSTRACT

*Single mode flutter is a type of panel flutter, which cannot be analyzed theoretically using conventional piston theory, and for this reason it is studied very little. In this paper a plate, designed such that it cannot experience "classical" coupled-type flutter, but can experience single mode flutter, is tested. Analysis of the tested data clearly indicates the occurrence of single mode panel flutter.*

## INTRODUCTION

Panel flutter is an aeroelastic phenomenon that is known to cause fatigue damage of flight vehicles. Let us imagine a skin panel of a flight vehicle in a supersonic gas flow (Fig. 1). At low Mach numbers of the flow the flat state of the panel is stable. Once the critical Mach number, $M_{cr}$ is exceeded, the static state of the panel becomes unstable, and the panel vibrates. This vibration occurs due to energy transfer from the gas flow to the panel. The amplitude of this vibration can be large and result in fatigue damage of the panel and the structures attached to the panel.

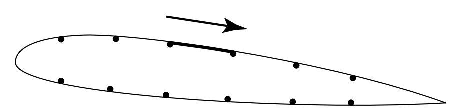

**FIGURE 1**. SKIN PANEL IS A TYPICAL STRUCTURE SUBJECTED TO PANEL FLUTTER.

This problem of panel flutter was first observed during the 1940s and has since had a very rich history. Theoretical solution of the problem consists of an eigenvalue solution of coupled panel-flow equation. Let us assume that the plate deflection is harmonic: $w(x,t) = W(x)e^{-i\omega t}$ (for simplicity we demonstrate up-to-date theory on 2D problem), the dimensionless equation of the plate motion takes the form

$$D\frac{\partial^4 W}{\partial x^4} - \omega^2 W + p\{W,\omega\} = 0 \qquad (1)$$

where $D$ is dimensionless plate stiffness, and $p\{W,\omega\}$ is the pressure acting on the oscillating plate. The theory of potential gas flow gives a very complicated expression [1]. Substitution of this expression into equation (1) yields the complex integro-differential equation. Solving this equation is difficult, however, in the 1950s a relatively simple theory, known as the piston theory, was developed to approximate the gas pressure. This theory, shown in equation (2), is valid only at high Mach numbers and low frequencies:

$$p\{W,\omega\} = \frac{\mu M}{\sqrt{M^2-1}}\left(-i\omega W(x) + M\frac{\partial W(x)}{\partial x}\right), \qquad (2)$$

where $\mu$ is ratio of the air density to the plate material density. This partial-differential equation (1), (2) can be easily solved numerically and studied analytically. Piston theory has been the primary analysis method used by aeroelasticians. An enormous number of panel flutter publications have used the more simplistic piston theory but only a few authors have published work regarding the exact theory of potential flow [2–7]. Up to our days, most complications in studies of panel flutter are related with structures studied, while air pressure is calculated using the piston theory (2).

Though piston theory is a simple approach used to predict flutter it also has a serious problem. Two types of panel flutter are known [8]. First, the coupled-type flutter arising due to the interaction of two eigenmodes. This type has been fully studied through the piston theory, and excellent correlation with experiments at $M > 1.7$ has been observed. The second flutter type is single mode flutter also referred as ”single-degree-of-freedom” or ”high-frequency” flutter. This flutter type can only be analyzed through exact aerodynamic theory of potential flow or more complex theories. Until recently, only in a few publications discussed single mode flutter was mentioned [2, 4, 8], where it was obtained through direct numerical simulations, however, the energy transfer mechanism was not studied. This flutter type has not been thoroughly investigated, some have even suggested that it may not appear in reality. However, over the past few years single mode flutter was studied in detail [9–12], and a simple physical explanation of instability has been derived. This paper explains the analysis method and experiments conducted to confirm the existence of single mode flutter.

Tests focusing on single mode flutter have been conducted at the Institute of Mechanics of Moscow State University. These experiments used a clamped plate, which have been designed such that coupled-type flutter can not occur during wind tunnel testing. At the same time, single mode flutter should occur. Gages used during the experiment allow for monitoring of the plate vibrations and the vibration source. The results clearly show that the plate vibrations correspond to the existence of single mode flutter.

## DESCRIPTION OF THE EXPERIMENT

The experiment setup is shown below in Fig. 2, 3. The tested specimen is a flat plate made from steel and welded to a rigid frame. The frame has been fixed to the wind tunnel wall. The plate size was $300 \times 540 \times 1$ mm. A cavity under the plate allows for gas flow to bypass under the plate, which equalizes the pressure between both sides of the plate.

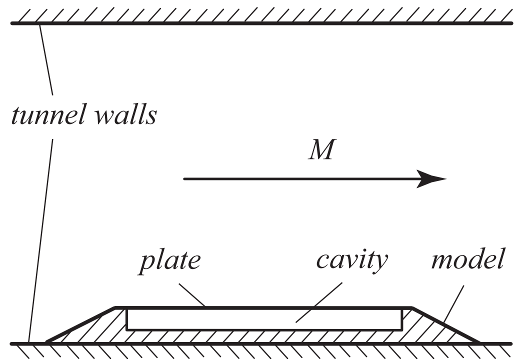


**FIGURE 2**. Sketch of the test.


**FIGURE 3**. PICTURE OF THE MODEL INSTALLED INTO THE WIND TUNNEL.

To monitor plate vibrations, 12 strain gages were installed on the ”cavity” side of the plate. The gage signals were amplified and operated in the range of 20 – 10000 Hz. A vibro gage AP2037 was installed on outside tunnel wall to monitor wind tunnel vibrations. This gage was used with transformator AS02. Flow pressure pulsations were monitored by means of the Honeywell pressure gage, 186PC15DT.

Generally, five sources of high-amplitude plate oscillations could occur during the test:

1. Resonance excited by vibrations of the wind tunnel
2. Resonance excited by pulsations of the flow pressure
3. Responce to noise excitation

4. Coupled-type panel flutter
5. Single mode panel flutter

Identifying the actual plate vibrations type is possible through spectral analysis of the plate strain gages, tunnel vibro gage and the pressure gage spectrum data. Let us describe signs, which allow to exclude or confirm types of the plate oscillations.

Resonance excited by vibrations of the wind tunnel can be easily recognised by comparing the spectrums of the plate strain gages and the tunnel vibro gage. If high-amplitude peaks exist in these spectrums with the same frequencies, then the wind tunnel has caused the plate vibrations. On the contrary, if the plate oscillates at a different frequency than that of the vibro gage, then the first type of vibrations is excluded.

In the same way, resonance excited by pulsations of the flow pressure can be easily detected by comparing spectrums of the plate strain gages and the flow pressure gage.

Noise excitation of the plate vibrations can be detected comparing vibration amplitudes at several regimes of the wind tunnel (for example, at several Mach numbers). If while changing Mach number, $M$, both the amplitudes of noise vibrations of the tunnel and noise pulsations of the flow pressure increase, while amplitude of the plate vibrations decreases or increases at a much faster rate than the noise amplitude (or vice versa), then these vibrations cannot be caused by noise excitation.

Coupled-type flutter can be detected using its main feature: it occurs due to interaction of two eigenmodes, which can be detected by approaching and coalescence of the first and the second eigenfrequencies. Thus, if the amplitude increases sharply, while the two mentioned eigenfrequencies do not approach to each other, we exclude coupled-type flutter from the list of possible sources of vibrations.

## THEORETICAL FLUTTER PREDICTIONS

The plate size was chosen such that coupled-type flutter would not occur. The critical Mach number for coupled-type flutter was computed by applying formula [13] obtained through the piston theory:

$$M_{cr} = \frac{D}{p\gamma L_x^3} \frac{8\pi^3}{3\sqrt{3}} \left(5 + \frac{L_x^2}{L_y^2}\right) \sqrt{2 + \frac{L_x^2}{L_y^2}}, \qquad (3)$$

where $L_x$ and $L_y$ are the plate width and length (air flows along $x$ direction), $D$ is the plate stiffness, $p$ is a static pressure of the flow, $\gamma$ is an adiabatic constant of the air (all parameters are dimensional in this formula). Static pressure in the wind tunnel changes with change of actual Mach number $M$. Using this isentropic formula

$$p(M) = p_0 \left(1 + (\gamma - 1)\frac{M^2}{2}\right)^{-\frac{\gamma}{\gamma-1}}$$

and parameter $p_0$ typical for the used wind tunnel, we obtain function $M_{cr}(M)$. Equation (3) is derived for a pinned plate, which implies $M_{cr}$ is higher for a clamped plate. Fig. 4 shows the plot $M_{cr}(M)$ for parameters of the wind tunnel used, where we can see that $M_{cr} > M$ for any $M$, and thus coupled-type flutter is impossible.

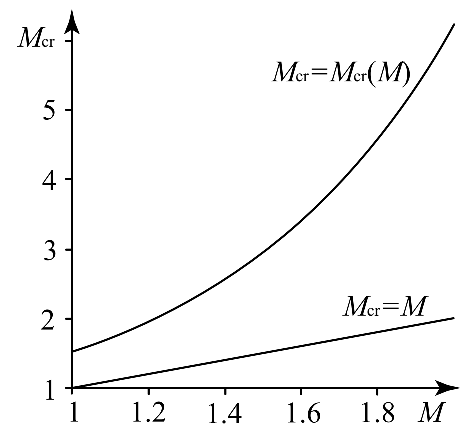


**FIGURE 4**. PLOT $M_{cr}(M)$ DEFINED BY (3). ADDITIONALLY A LINE $M_{cr} = M$ IS SHOWN.

On the contrary, single mode flutter should arise at the test conditions. For theoretical analysis the method [10] is used. Following that paper, for each eigenmode $(m,n)$ (the first number in brackets is quantity of semi-waves in the mode along the flow (short) direction, the second number is the one along the long direction) there is a region of single mode flutter $M_1(m,n) < M < M_2(m,n)$. We consider only modes fluttering at $M < 1.3$, as the tests were conducted at $M < 1.3$. Calculated values of $M_1$ and $M_2$ are shown in Table 1.

Thus, during the test in spectrum of the plate oscillations we should see some of 7 modes: (1,1), (2,1), (2,2), (3,1), (3,2), (4,1), (4,2) at corresponding frequencies. More detailed analysis shows that increments of amplification are the biggest at modes (1,1) and (2,1), in other words, these modes are most unstable.

In Table 1 we did not take into account influence of the cavity under the plate. Due to the cavity air, which work as "aerodynamic spring" at symmetrical plate modes, the frequency of the mode (1,1) is higher, and this mode should excite at higher $M$ than shown in Table 1, while flutter region for the mode (2,1), which is not affected by the cavity air, is the same.

**TABLE 1**. THEORETICAL FLUTTER BOUNDARIES $M_1$, $M_2$.

| $m$ | $n$ | Frequency $\Omega$ (Hz) | $M_1$ | $M_2$ |
|---|---|---|---|---|
| 1 | 1 | 65 | 1.19 | 1.56 |
| 2 | 1 | 167 | 1.17 | 1.48 |
| 2 | 2 | 190 | 1.28 | 1.61 |
| 3 | 1 | 321 | 1.20 | 1.48 |
| 3 | 2 | 344 | 1.26 | 1.54 |
| 4 | 1 | 526 | 1.25 | 1.49 |
| 4 | 2 | 549 | 1.29 | 1.53 |

## RESULTS OF THE EXPERIMENT

The test was conducted at eleven regimes of the wind tunnel. Corresponding Mach numbers are $M = 0.857$, 1.147, 1.167, 1.169, 1.285, 1.286, 1.292, 1.293, 1.294, 1.298, these values are intentionally shown with accuracy 0.001. Of course, the pressure gage did not allow to conduct measurements with such a high accuracy. But important is the fact that ordering of the regimes by $M$ is correct. In other words, despite Mach number values are inaccurate, from inequality $M_1' < M_2'$ (where stroke denotes inaccurately measured value) it follows ineqaulity $M_1 < M_2$ for exact values. This is the goal of usage of three digits after decimal point.

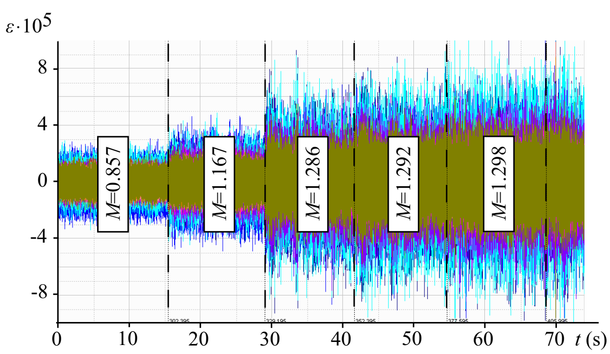


**FIGURE 5**. AMPLITUDE OF THE PLATE VIBRATIONS DURING LAUNCH 1 (TUNNEL VIBRATIONS WERE NOT RECORDED).

In Fig. 5, 6 shown are the plate strain amplitudes vs time for two launches of the wind tunnel. Plate strain amplitudes vs Mach number for these tests are shown in Fig. 7.

We can see rapid amplitude growth in region $1.2 < M < 1.3$. Let us now analyse source of this growth.

In Fig. 8, 9 shown are typical spectrums of the plate strain gages, tunnel vibro gage, and static pressure gage. In Fig. 9 we

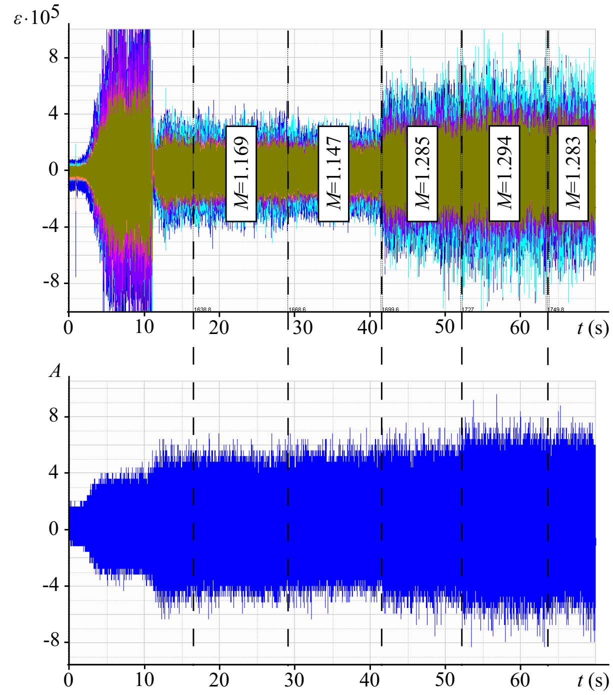


**FIGURE 6**. AMPLITUDE OF THE PLATE (TOP) AND THE WIND TUNNEL WALL (BOTTOM) VIBRATIONS DURING LAUNCH 2.

see that amplification of plate oscillations occurs due to amplification of five spectrum peaks: 170 Hz, 215 Hz, 320 Hz, 400 Hz, and 505 Hz. At the same time, flow pressure and tunnel vibration spectrums have no notable spectrum peaks at all regimes, and thus plate oscillations are not of the first two types (resonances) listed above.

Let us now consider the third possible source of amplification of the plate vibrations, noise excitation. If the amplification occurs due to this reason, then noise amplitude (pressure pulsations or tunnel vibrations, depends on which one excites the plate) at different regimes should have the same trend as the plate amplitude. But measurements (from Fig. 6, for example) show that amplitude of pressure pulsation and tunnel vibrations increase not more than 1.3 times at launch 2, while the plate amplitude increases more than 2 times. Thus, the third source of excitation of the plate vibrations, noise, is also excluded from the list of possible sources.

The forth source of amplification of the plate vibrations, coupled-type flutter, is impossible due to theoretical analysis (Fig. 4). This also can be proved using test data only. Indeed, let us consider sequence of spectrums of plate vibrations at $M$ increasing, showed in Fig. 9, 8. If coupled-type flutter occurs, then, following theory, frequencies of modes (1,1) and (2,1) should aprroach to each other and merge. Analysis of amplitude distribution along strain gages shows that in the spectrums the peak with frequencies 190 Hz at $M = 1.147$, 180 Hz at $M = 1.167$,

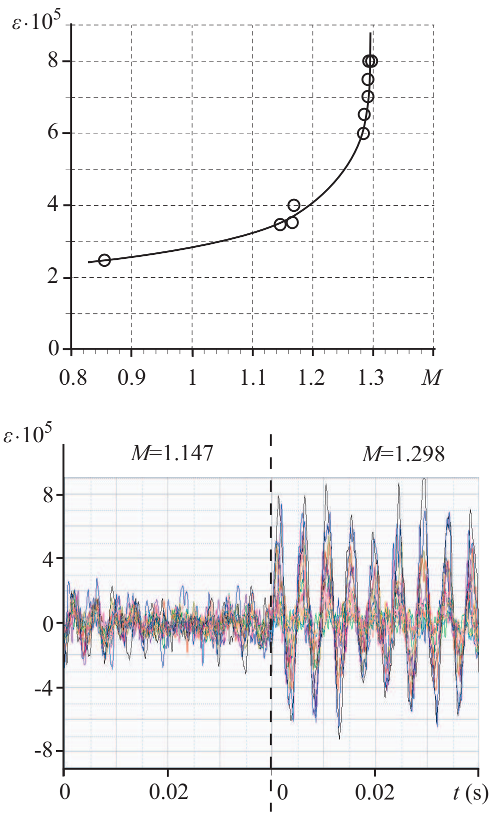


**FIGURE 7**. TOP: DYNAMIC STRAIN AMPLITUDE VS MACH NUMBER. TEST DATA IS SHOWN BY POINTS, THE CURVE IS AN INTERPOLATION. BOTTOM: TEMPORAL STRAIN DATA AT $M = 1.147$ (STABILITY) and 1.298 (FLUTTER).

160 Hz at $M = 1.286$, and 170 Hz at $M = 1.298$, corresponds to the mode (1,1). Another peak, with frequencies 260 Hz at $M = 1.147$, 230 Hz at $M = 1.167$, 200 Hz at $M = 1.286$, and 215 Hz at $M = 1.298$, corresponds to the mode (2,1). We see that these peaks move along spectrum with change of $M$ due to plate temperature effects, but not approach to each other. That is why there is no couled-type flutter.

Thus, all items, except single mode flutter, are excluded from the list of possible sources of amplication of the plate oscillations listed above. We therefore conclude that we observe single mode flutter at the region $1.2 < M < 1.3$.

## COMPARISON WITH THEORETICAL RESULTS

As was theoretically shown above, at single mode flutter the most unstable modes are (1,1) and (2,1). This is exactly what we see in test spectrums (Fig. 8, 9): peak lying in region 160...190 Hz corresponds to the mode (1,1), peak lying in region 200...260 Hz corresponds to the mode (2,1).

Experimental single mode flutter boundary $M_{\text{cr}} \approx 1.2$ is very

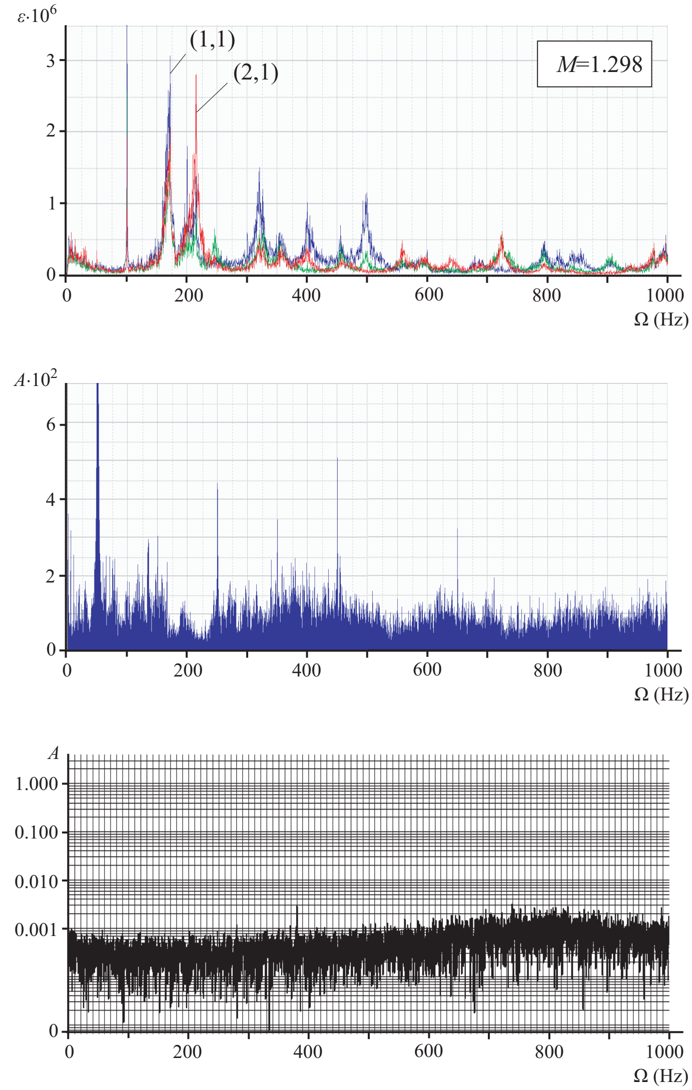


**FIGURE 8**. SPECTRUM OF THE PLATE VIBRATIONS AT $M =$ 1.298 (TOP), TYPICAL TUNNEL WALL VIBRATION (MIDDLE), TYPICAL AIR PRESSURE PULSATION (BOTTOM). ALL SHARP PEAKS WITH FREQUENCIES PROPORTIONAL TO 50 AND 100 Hz ARE ELECTRICAL INTERFERENCES AND SHOULD BE IGNORED.

close to the theoretical $M_{\text{cr}} = \min\limits_{m,n} M_1(m,n) = 1.17$ (see Table 1).

Unfortunately, modes of other peaks presented in the spectrums were not recognized. The reason is residual stresses in the plate left after welding: natural modes were distorted due to presence of those stresses. Among distorted modes we are not able to distinguish number of semi-waves in modes, because there are no more semi-waves. But we have theoretical results in Table 1, and we may assume that other peaks at flutter spectrums correspond to some of theoretically unstable modes (2,2), (3,1), (3,2), (4,1), (4,2).

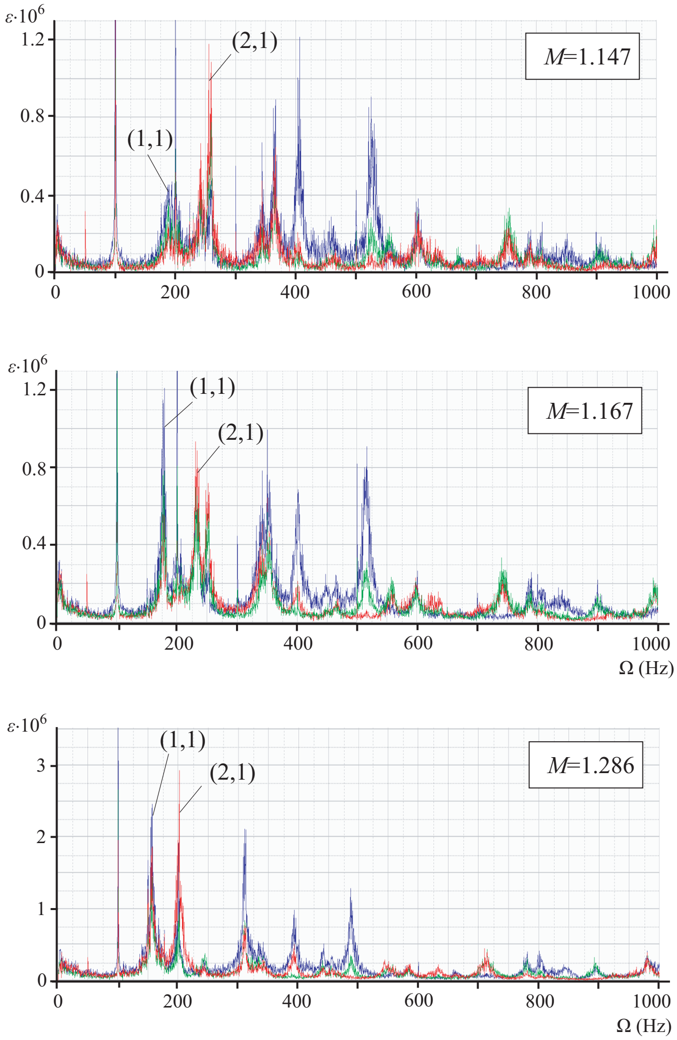


**FIGURE 9**. SPECTRUM OF THE PLATE VIBRATIONS AT $M = 1.147$, $M = 1.167$, $M = 1.286$. ALL SHARP PEAKS WITH FREQUENCIES PROPORTIONAL TO 50 AND 100 Hz ARE ELECTRICAL INTERFERENCES AND SHOULD BE IGNORED.

There are two reasons why we are not worried about residual stresses distorting plate eigenmodes. First is the fact that the most flutter unstable modes (1,1) and (2,1) are not really affected by those stresses, and physical mechanism of single mode flutter excitation [10] works. Another reason is that analysis and conclusions are made through test data only, not utilizing theoretical results. We investigated type of the plate vibration, in series excluding possible sources of vibrations from the list of possible sources of vibrations, using only logical arguments based on the test data.

## CONCLUSIONS

A clamped steel plate is tested in a supersonic wind tunnel. The plate size is intentionally chosen such that single mode flutter should occur, while "classical" coupled-type flutter is impossible. During the test, plate vibrations amplified in region $1.2 < M < 1.3$. Analysis of spectrums of the plate strain gages, pressure gage and wind tunnel vibro gage showed that the plate experienced single mode flutter. Test results excellently agreed with theory [10]: during the tests flutter occured at modes which are theoretically most unstable. Experimental flutter boundary $M_{cr} \approx 1.2$ is very close to theoretical value $M_{cr} = 1.17$.

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