THEORETICAL AND EXPERIMENTAL INVESTIGATION ON AEROACOUSTIC FATIGUE OF PANELS*

by

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Summary

We consider the correlation of acoustic pressure loads induced by a turbulent wake on a nearby structural panel; this problem is relevant to the acoustic fatigue of aircraft, rocket and satellite structures. Both the correlation of acoustic pressure loads and the panel deflections, were measured in an 8-meter diameter transsonic wind tunnel. Using the measured correlation of a acoustic pressures, as an input to a finite element aeroelastic code, the panel response was reproduced. The latter was also satisfactory reproduced, using again the structural code, with input given by a theoretical formula for the correlation of acoustic pressures; the deduction of this formula, and the semi-empirical parameters which appear in it are included in this paper. The comparison of acoustic responses in aeroacoustic wind tunnels (AWT) and progressive wave tubes (PWTs) shows that much work needs to be done to bridge the latter gap.

§1- Introduction

The problem of acoustic fatigue occurs for structures exposed to sound of very high intensity (more than 150 dB, and as much as 170 dB); the corresponding acoustic pressure is sufficient to cause the vibration of structures, until cracks, either pre-existing or newly-formed, grow, leading to eventual failure. Such high noise levels, well beyond the threshold of pain (110 dB) and damage (130 dB) to the human ear, occur for at least two kinds of aerospace vehicles: (i) near the exhaust of rocket engines of large space launchers, as the american Space Shuttle or european Ariane, noise levels can exceed 170 dB, requiring verification that parts of the vehicle, such as the satellite payload, can stand acoustic fatigue; (ii) the exhaust of jet engines of modern aircraft, as well as the turbulent wakes of control and high-lift surfaces, such as flaps, slats or spoilers, can also cause acoustic fatigue of nearby structures. Although acoustic fatigue is a major design issue for aerospace structures, the subject is almost wholly empirical, due to the lack of adequate models of acoustic pressure loads; the latter are random, and need to be specified as a spectrum correlated in space. The lack of prediction methods, leads to design for acoustic fatigue, being based on tests in progressive wave tubes (PWT), where noise levels up to about 155 dB can be generated; this still a little too 'low' for some applications. Another, more serious issue, is whether the distribution of acoustic pressure loads in a PWT adequatelly represents the aeroacoustic excitation of a structure in the vicinity of a turbulent wake.

Among the aims of the project Acoufat (acoustic fatigue of composite and metal structures) was a careful investigation of the mechanisms of acoustic fatigue, to assess whether current testing techniques are reliable, and also if reasonably accurate prediction metheods could be developed. It is not the aim of the present paper to cover such a broad range of issues (Tougard et al. 1993), and in fact we concentrate on three related aspects: (i) the testing of a representative structural panel in large high-subsonic wind tunnel, to measure both acoustic pressures and panel deformations; (ii) the prediction of the deformations, using the finite-element Elfini (Nicot & Petiau 1989) code for the panel structure, and the correlation of acoustic pressure spectra measured in the wind tunnel; (iii) the prediction of the deformations, using the same

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structural code, and correlation of acoustic pressure spectra specified by an analytical model, with semi--empirical parameters. The satisfactory agreement of the three sets of data must be rated as a step forward in the understanding of acoustic fatigue, beyond the empirical methods in current use, since: (§A) the agreement of (i) and (ii) shows that existing structural codes (such as Elfini) are capable of predicting acoustic response, provided that the correct spatial correlation of acoustic pressure spectra be fed in as an input; (§B) the good agreement of (i) and (iii) is a first success at analytical modelling of acoustic fatigue, since, although the analytical model involves semi-empirical parameters, the estimation or fitting of the latter, still represents some progress, relative to the totally empirical approach of the past.

§2- Acoustic Response of a Structural Panel

A typical aircraft structural panel, is of multi-bay construction. Since it is symmetric, only one-half need be modelled by finite elements (Figure 1): a finer mesh is used in the central cell, since in this region the deformations may be greatest. The method of calculation of response uses a finite element discretization, which represents the panel by a system of second-order, linear, coupled differential equations for the displacement X_n:

$$n, m = 1, \ldots N: \quad A_{mn}\ddot{X}_n + B_{mn}\dot{X}_n + C_{mn}X_n = Q_m(t), \tag{1}$$

where A_{mn}, B_{mn}, C_{mn} are mass, damping and stiffness matrices, and $Q_m(t)$ the forcing load. In the absence of the latter, the natural modes have frequencies ω_n and dampings λ_n, specified by the roots of:

$$\xi = \omega + i\lambda: \quad \mathrm{Det}\left(A_{mn}\xi^2 + iB_{mn}\xi + C_{mn}\right) = 0. \tag{2}$$

The inverse of the same matrix:

$$\delta_{\ell m} = D_{\ell m}\left(A_{mn}\xi^2 - i\,B_{mn}\,\xi + C_{mn}\right), \tag{3}$$

where $\delta_{\ell m}$ is the identity matrix, specifies the non--resonant response to a load of spectrum $\tilde{P}(\omega)$:

$$\tilde{X}_n(\omega) = \sum_m D_{nm}(\omega + i\lambda)\,\tilde{P}_m(\omega). \tag{4}$$

The correlation of loads at two points:

$$< \tilde{X}_n\tilde{X}_r > = \sum_{m,s} D_{nm}\,D_{rs} < P_m P_s >, \tag{5}$$

specifies the correlation of displacements. The mode shapes are divided into symmetric and skew--symmetric, and one of each is shown in Figure 2. In the case of interest the loads are of aeroacoustic origin.

§3 - Set-up in an 8-Meter Transsonic Wind Tunnel

The most realistic simulation of aerocoustic loads, short of real flight conditions, is provided by a wind tunnel; the facility used was one of the largest in Europe, the Modane S1 transsonic wind tunnel, which has a circular cross-section with 8-m diameter. The sketch on Figure 3, shows the arrangement: (i) a flap is used to generate a turbulent wake; (ii) behind the flap there a flat surface, where the test panel lies flush; (iii) the whole assembly is mounted in a box, supported on the tunnel wall by means of struts. The design takes into consideration the following points: (i) the flap interchangeable, with choice of three heights and two widths; (ii) the ensemble is set at some distance from the tunnel wall, so as to avoid the boundary layer, and to lie in the 'potential core' of the test section; (iii) the small frontal area minimizes the 'blockage' of the wind tunnel, which can lead to unsteady measurement comditions and limit the Mach number achievable in the test section. The set-up is not representative of typical aircraft situations, in two respects, which represent deliberate simplifications, to allow a clearer interpretation of results. First, in a real aircraft flap, slat, or spoiler, there is a gap between the moveable surface and the wing; this additional effect was omitted here, by mounting the flap on the structure. Second, both the structure, and the test panel lying flush on it, are relatively thick, to minimize aeroelastic coupling; thus the sound field should not be affected by the panel deflection, i.e. we have not a fluid-wall coupling problem.

§4 - Wake of, and recirculation behind, a flap

Returning to the Figure 3, it shows a sketch of the flow pattern behind the flap, with the recirculation bubble covering most of the test panel. In a real aircraft application, the slot between the flap and the wall, would give rise to a detached re-circulation bubble instead. The location of the recirculation bubble can be seen in the plots of r.m.s. pressure versus longitudinal coordinate, as a bulge, the end of which indicates the start of the re-attachment region. Although the largest flap, of height 300mm and width 1300mm, would appear to be a relatively 'small blockage' of an 8m-diameter wind tunnel, it did in fact load to a very unsteady wake, which would 'hit' the panel, and cause strongly oscillating pressure signals; for this reason, r.m.s. pressure measurements were made for the other three, 'not so large' flaps. In all cases the r.m.s. pressure increases with Mach number, being higher for the higher flaps or those of larger span. Even for the smaller flaps, the blockage effect was sufficient to limit the attainable Mach number to little over M = 0.9. The recirculating flow in the wind tunnel involves random phase shifts, with a Gaussian distribution, and this a resonable feature for modelling most turbulent shear layers.

§5 - Location of strain gauges and microphones

The wind tunnel set-up, was used for two test panels, which were mouhted into the assembly: (i) one panel has imbeded 15 strain gauges and 8 accelerometers, which are the sensors for the measurement of panel response, which is the data of prime practical interest; (ii) the other panel contains 40 flush-mounted microphones, to measure pressure loads, which are important for the understanding of acoustic fatigue, in two ways: (a) by providing the load input to the structural code, for computation of response; (b) by providing the correlation of loads, for comparison with the theoretical model, and determination of semi-empirical parameters. Note that two microphones were placed outside the test panel, to serve as a reference; of the remaining 38 microphones, 35 were placed on the longitudinal axis or to one side of it, leaving 3 on the other side, to check for symmetry. The two test plates, viz. the one instrumented with microphones, and the other instrumented with sträin gauges and accelerometers, are not much affected structurally by the inserts, and remain similar. Both are quite stiff in bending, so that fluid-wall coupling is insignificant, and it is reasonable to take as main effect, for the modelling of loads, the phase interference of acoustic signals.

§6 - Measured power and cross-correlation spectra of sound

The measured power spectra vary significantly with microphone position. There is broadband noise in the range 0-400 Hz, with a peak at about 100 Hz, more or less marked. The frequency of the peak is Doppler shifted, as the Mach number of the test is varied. The peak is more marked for microphones near the axis, at some distance from the flap. The power spectra look more like a broadband at other positions, e.g. for microphones near the axis close to the flap, or for microphones off-axis far from the flap. The number of pairs of microphones, for which cross-correlation spectra can be measured, is quite large (40 x 39:2 = = 780), and only one shown is shown on Figure 4; the jagged lines are measurements in wind tunnel and the smooth lines theoretical prediction. Although they do not agree in detail, the inferred panel response will be similar, because it depends on many such correlations, and average rather than local consistency turns out to be most important. It is seen that the imaginary part of the cross-correlation is small in almost every case, and averages about zero; the real part of the cross--correlation is larger, but it seldom exceeds 0.6, even for closely spaced microphones. The correlation is larger for closer microphones, and decays faster at high-frequency for longitudinal than for transversal pairs. This suggests that the correlation length is between one and three microphone grid spacings; also it is larger in the direction transverse to the flow, as should be expected, from the fact that gradients are smaller in this direction. The preceding remarks relate to the estimation of the 8 semi-empirical parameters of the theoretical model (Appendix) by comparision with measured power and cross-correlation spectra.

§7 - Eight semi-empirical parameters of theoretical model

The values taken for the parameter in the model are as follows:

- double reflection coefficient: $D = 0$. This equivalent to neglecting multiple scattering, i.e. only the first reflection of sound waves between the structural panel and turbulent wake contributes to random phases and wave interference;
- excitation frequency: $\omega_0 = 2\pi x\ 100$ Hz. This is the observed main peak in AWT (Aeroacoustic Wind Tunnel) test;
- longitudinal excitation wavenumber: $k_0 = 1.11\ m^{-1}$. If we use the formula $k_0 \sim K_x = (\omega_0/c) \cos\theta$, with a sound speed $c = 340\ m\ s^{-1}$, this gives $\theta \simeq 53°$ for the angle of sound waves with the plate;
- transverse excitation wavenumber: $K_0 = 0.05$. Using the formula $K_0 \sim K_y = (\omega_0 /c) \cos\Phi = 0.05$, gives $\Phi = 8°$ for the angle of sound waves with flow;
- root mean square phase shift: $\sigma = 2$. Since $\sigma \geq 1$ the effects of random phase shifts are significant.
- longitudinal correlation scale: $L = 25$ cm. This should be compared with the remark that in AWT test the coherence became quite small for distances of more than 20 cm.
- transversal correlation scale: $\ell = 50$ cm. This should be larger than the longitudinal one $\ell > L$, because the flow is less disturbed transversally to the flap than in the flow direction.
- correlation time: $T = 0.003$ s is of the order $2\pi\ L/c = 0.005$ s, taking for the phase speed of interaction the sound speed.

In conclusion, the values taken for the eight parameters appear reasonable.

§8 - Comparison of experimental, empirical and theoretical response

The panel response, at one of the eight strain gauge positions, is shown in Figure 5, which consists of three plots: (center) the 'exprimental' response, measured by strain gauges imbedded in the test panel, in the wind tunnel; (bottom) the 'empirical' response, calculated by the finite element code, using as input the correlation of acoustic pressures measured by the microphones, inbedded in the test panel in the wind tunnel; (top) the 'theoretical' response, again calculated by the finite element code, using as input the correlation of acoustic pressures specified by the analytical formula in (Appendix), with the values of the parameters indicated in §7, which arise from a comparison with experiment. The designations 'experimental', 'empirical' and 'theoretical'response are not exact, since all three involve experimental data, but they do indicate that experimental input is gradually smaller relative to the computational and theoretical part. There is quite good agreement of the three panel responses, both for gauge 1, where there is one dominant peak, and for other gauges, where there are several peaks. The good agreement concerns the height (dB level) and location (frequency) of the peaks, their separation in frequency and difference in level, and the shape of the remaining spectrum.

§9 - Comparison of measured and calculated correlation of loads

The good agreement of the three response curves in Figure 5, shows that: (i) the finite element code can sucessfully predict acoustic fatigue response, if the correlation of loads is accurately provided as an input; (ii) the correlation of acoustic pressures measured by microphones can be replaced, with comparable response, by the analytical formula (in the appendix), with semi-empirical parameters (in §7). These two conclusions are important, because they show that, although acoustic fatigue has been treated almost exclusively by empirical methods in the past, in fact: (i) it is not a 'new' structural phenomenon, but 'merely' a matter of specification of loads; (ii) the most 'difficult' feature of the loads, viz. that they are random but definitely correlated, can be modelled theoretically. Going further, and comparing directly the loads, it is clear from Figure 4 that the agreement of measured and theoretical correlations of acoustic pressures, is much less satisfactory than for panel responses (figure 5). We note that the values semi-empirical parameters in the analytical formula in (Appendix), were 'guessed' as indicated in §7, and with little adjustment gave satisfactory panel responses, thus there was little incentive in 'optimizing'the 8 parameters, to improve the agreement in figure 4, e.g. multiple scattering was not considered at all. Nevertheless, the fact remains that the good agreement of panel response was not undermined by the poorer fit of loads; one explanation may be that the analytical prediction and experimental measurement are in better agreement over the range of frequencies where are concentrated the panel responses, and that is what matters.

§10 - Comparison of tests in PWTs and AWTs

It is also worth noting that the panel response depends on many pairs of correlation of loads, and thus may not be much affected by a local discrepancy, and depend more on having the right order-of-magnitude in most combinations. One could conceivably stretch the last argument, in a skeptical way, to argue that the implication might be that panel response is relatively insensitive to the correlation of loads. This conjecture is quite false,as can be shown both by using experimental data or results of finite element code. The rather strong sensivity of the panel response to the correlation of loads is demonstrated in figure 6, where the finite element calculation (center) is compared with measurements at a progressive wave tubes (PWTs). The data refer to the same gauge 1, and show that: (i) the results of the finite element code, which had modelled well the AWT (Aerocoustic Wind Tunnel) experiments, disagree with PWT tests; (ii) the test results are the two distinct PWTs are also in disagreement, but less so. The explanation may be: (i) the correlation of loads is dominated by distributed sources and propagating waves in AWTs, and thus is quite different from PWTs, where the source is concentrated and there are standing modes; (ii) since the eigenvalues and eigenfunctions of the standing modes, depend on the geometry of the PWT, the results in PWT with different geometries may be distinct. In Figure 6, the response in PWTs differs from that in AWTs, in the number of peaks, their absolute and relative magnitude in dB, and frequency at which they accur. All this may be a consequence just of one effect, namely, a different correlation of loads. This can be confirmed by calculating response, for four values of the correlation of loads (from 0.2 to 0.8 in jumps 0.2), each assumed uniform over the panel; as the correlation increases, different modes become dominant, e.g. a high (low) correlation is more effective at exciting symmetric (skew-symmetric) modes.

§11 - Conclusion

The acoustic fatigue is traditionally addressed by purely empirical methods, based on testing in PWTs. The present work has reported on research on acoustic fatigue using both PWTs and AWTs. The latter are less practical as a test facility, but more representative of real flight conditions. Thus our conclusions should address three points, namely, the results of acoustic fatigue tests in AWTs and PWTs and how to possibly bridge the gap between the two. Acoustic fatigue test in an AWT are an excellent approach to improving our understanding of the phenomenon. The first tests of this kind, have led to two important sets of conclusions. The first is that finite-element code, of the kind used for a wide variety of aeroelastic problems, can also sucessfully model acoustic fatigue; this shows that acoustic fatigue is not a physically 'new' structural phenomenon, but rather the effect of a complex ensemble of random, correlated loads. The determination of these loads by wind tunnel tests is a powerfull research tool, but also a costly and complex one; the ability of an analitical formula to do just as well, for panel response calculations, is a welcome alternative; it also shows that acoustic fatigue is not beyond the reach of mathematical modelling, even in a relatively complex case. The remaining limitation is that the parameters in the theoretical formula still need to be adjusted by comparison with wind tunnel experiments; an alternative, would be to used 'a priori' estimates of the parameters, and to fit them by comparing computed and measured panel responses.

The biggest problem found was that panel responses measured in PWTs did not have acceptable agreement with tests in AWTs. It should be borne in mind that here we are concerned with a particular type of acoustic excitation, viz. due to a turbulent wake; it may be that the PWT is an accurate testing tool for other types of acoustic fatigue, which were not considered here. Even for the type of aeroacoustic fatigue considered here, it is clear that the PWT is the practical testing medium, and the AWT may be restricted to in-depth research rather than routine testing. The circumstance that there is not much alternative to the PWT, and that it does not give reliable results in at least some cases, makes it more important to be aware of its limitations: (i) it is difficult in PWT to exceed 150-160 dB, whereas in some aerospace applications noise levels are higher; (ii) the excitation mechanism in PWTs may represent poorly the real flight conditions; (iii) results of testing in PWTs are configuration-dependent, and do not quite coincide in different facilities. Of these problems the most serious is (ii), because it means that PWT does not necessarily excite the same modes as are exited in flight; (i) is also of some concern, since failure modes in a PWT may not replicate those at higher noise levels. Although (iii) is comparatively a lesser problem, together with (ii) it falls under the scope of the present paper, and both could be adressed by entending to PWTs the methods which have been used successfully for AWTs.

Accepting the PWT as the main test facility for acoustic fatigue, and being aware of its limitations, can have three aims: (i) not to rely too heavily on PWT test unsubstantiated by other means; (i) developing new test methods for PWTs, which reproduce better aeroacoustic excitation mechanisms of real flight; (iii) using models of acoustic loads, together with finite element structural codes, to bridge the gap between PWTs and AWTs. The attitude (i) is prudent, in view of the results obtained so far, but is not an acceptable long-term solution. The search for improved test methods (ii) is worthwile, but it should not be overlooked that there is a fundamental physical difference between a localized source in an enclosure (PWT), which produces also standing waves, and distributed sources in a turbulent shear layer in the presence of a scattering panel (in real flight). Thus a basic issue may remain, of comparing the correlation of pressure loads in a PWT and AWT. The ideal solution would be: (i) to do fatigue tests in the most practical facility, viz. the PWT; (ii) to use FE-codes to compare panel response, and refine parameters of correlation of loads; (iii) to 'translate' the parameters of the correlation of 'loads' in a PWT, to those of a correlation of loads in an AWT; (iv) to use the latter, together with the FE-code, to calculate the modified panel response in an AWT, which should be representative of real flight. The part of this program which has been initiated is the correlation of acoustic loads in an AWT; the part still left open is the corresponding work for a PWT.

Appendix - Correlation of Acoustic Pressure Loads

The correlation (Khinchin 1948, von Mises 1960) of acoustic pressure loads, for two points with relative coordinates (x, y), and excitation frequency ω_0 and wavenumbers (K_0, k_0) is given (Campos 1992, 1994) by:

$$P(x,y;\omega) \equiv \left[F(x,y;\omega)/F(0,0;\omega)\right]\exp\left\{i(K_0 x + k_0 y)\right\},$$

$$F(x,y;\omega) \equiv$$

$$\equiv e^{-\sigma^2}\left\{2\pi\,\delta(\omega-\omega_0) + T\sqrt{\pi}\left\{\sum_{n=1}^{\infty}\left(\sigma^{2n}/\sqrt{n}\right)\right.\right.$$

$$\left\{E(x/L)E(y/\ell)\right\}^n$$

$$\sum_{p=0}^{n}\left\{(-)^p (n/2)^{-p}/p!(n-p)!\right\}e^{-\eta^2}H_{2p}(\eta)\},$$

$$\eta \equiv (\omega-\omega_0)\,L/2\sqrt{n},$$

where E is the correlation coefficient for phase shifts (Ho & Kovasznay 1976a,b; Campos 1978a,b):

$$E(x/L) = \left(1-\frac{1}{2}x^2/L^2\right)\, e^{-x^2/L^2},$$

and L, ℓ the longitudinal, transversal correlation scales (Campos 1984, 1986).

Acknowledgment

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Legends for the Figures

Figure 1- Finite-element discretization of one-half of the symmetric structural panel, with finer mesh in the central bay, where oscillation amplitudes may be larger.

Figure 2- Modes n = 1,6 with frequency of 393, 720 Hz of oscillation of panel, with symmetric respectivelly (top) and skew--symmetric (bottom) boundary conditions.

Figure 3 Sketch of recirculation bubble, and reattached flow, behind flap, and over the test panel.

Figure 4- Cross-correlation spectra for one pair of microphone positions, showing the real part (solid line) and imaginary part (dashed line). The experimental data (jagged) lines in easily distinguished from the smooth threoretical curves.

Figure 5 - Comparison of panel response at gauge 1: (top right) measured in wind tunnel; (top left) calculated by Elfini code, using correlation of loads measured in wind tunnel; (bottom) calculated by Elfini code, using analytical formula for correlation of loads.

Figure 6 - Comparison of response at same gauge 1 as for Figure 5, but measured in a progressive wave tube (top) versus prediction of Elfini code (bottom).

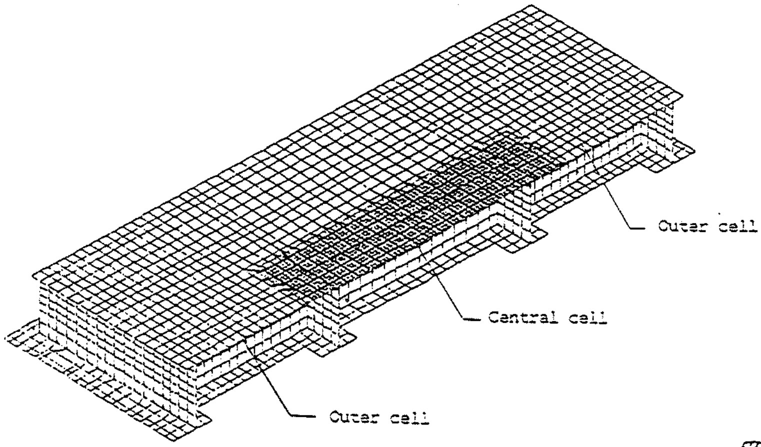


Figure 1

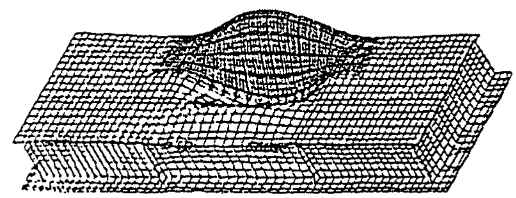
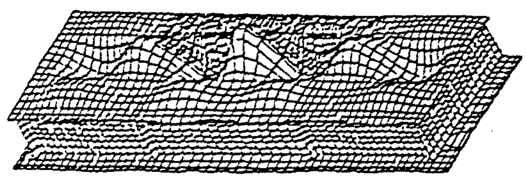


Figure 2



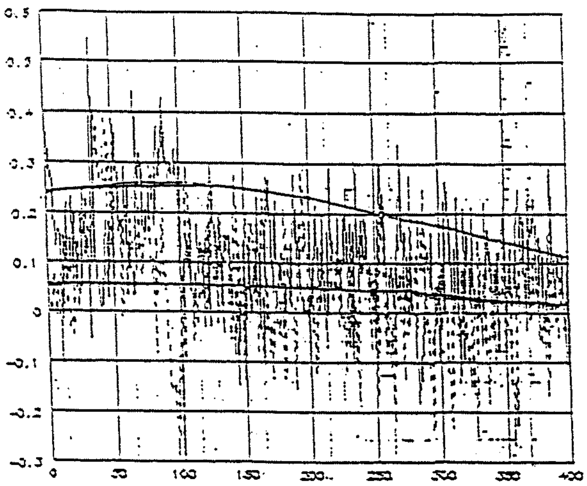


Figure 4

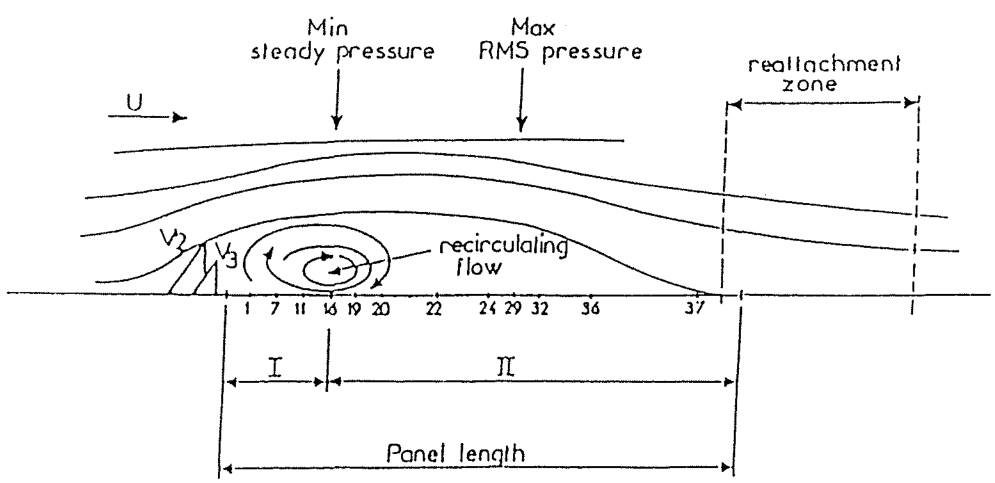


Figure 3

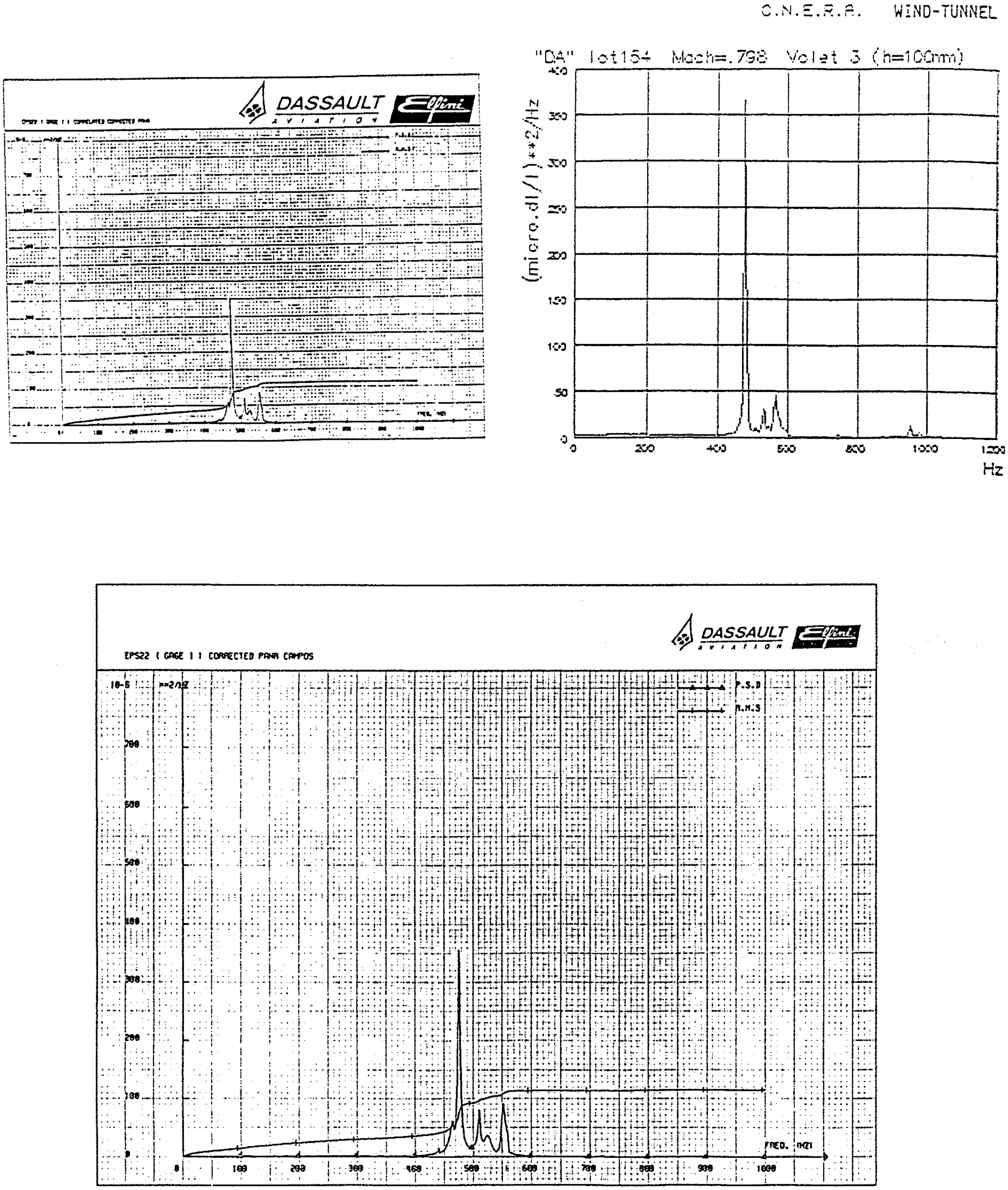

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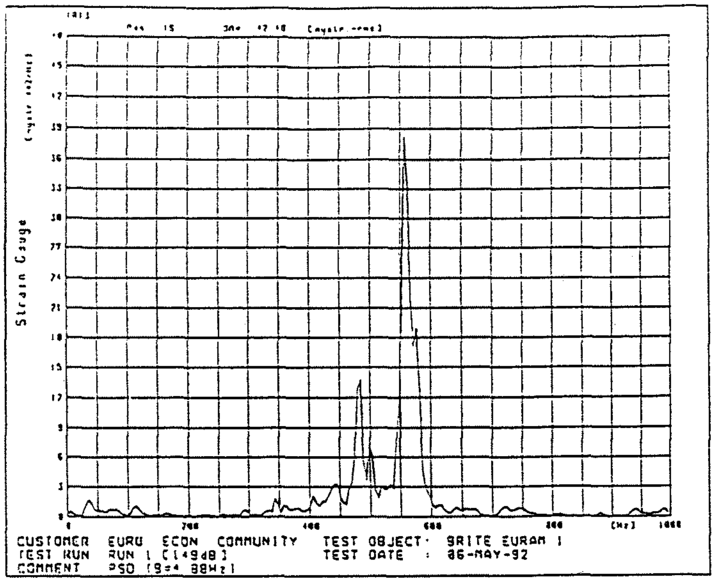
Figure 5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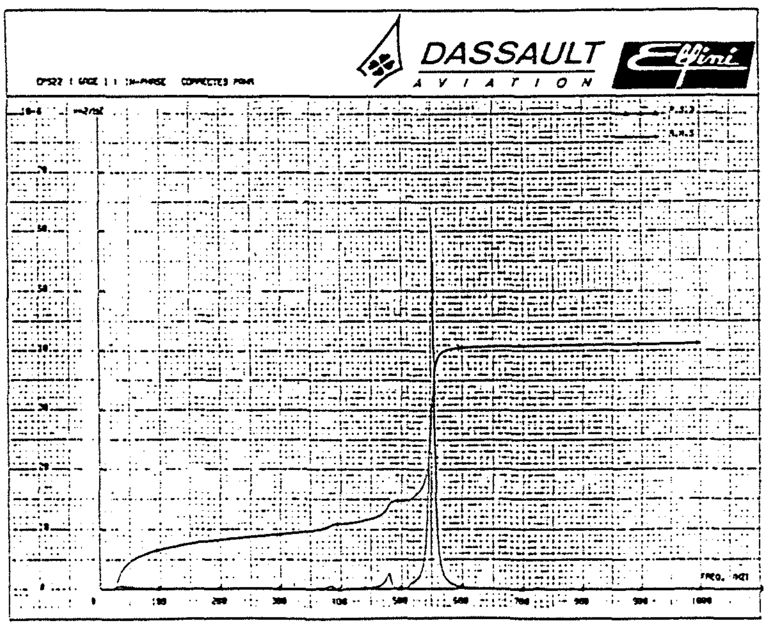
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AVIATION

Figure 6