Dynamic measurement of differential buffet pressure

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Abstract

A technique for measuring the unsteady differential pressure acting across two closely spaced surfaces is successfully demonstrated. The results show that conventional single-surface pressure measurements are likely to provide misleading information about the buffet pressures responsible for unsteady structural loading on fighter aircraft.

Introduction

Modern high performance aircraft, such as the F/A-18 fighter, are designed to rely on the high lift generated by a vortex system to enhance their manoeuvrability. The behaviour of the vortex system is complex and not well understood. Breakdown of F/A-18 LEX vortices is responsible for severe buffeting, which has resulted in premature fatigue failures of the aircraft frame. The buffet loads are responsible for increased maintenance costs and downtime.

Given that a major DSTO (Defence Science and Technology Organisation) objective is more accurate prediction of aircraft life, and given that the buffeting associated with vortex breakdown is a major contributor to fatigue loading, it is surprising, but true, that only limited and incomplete information exists concerning the buffet pressures responsible for the loads.

Research Objectives

The long term objective is to create a database from wind tunnel tests that will provide detailed information about the buffet pressures acting on tail fins and other critical components of fighter aircraft at flight Reynolds numbers. Pressure fluctuations that act in common on opposing surfaces will not contribute to the structural loading. On the other hand, pressure fluctuations that are out of phase will result in larger pressure differences than indicated by individual fluctuations experienced on each side. The fluctuating pressure difference across a component will provide a more accurate indication of the structural loads than the pressure fluctuations acting on a single surface.

Creation of the database will not be a trivial task since measurement of the unsteady differential pressure acting across two surfaces will be required. Furthermore, measurements obtained at a single point may not be fully representative. Therefore a useful database will need to consist of multiple unsteady differential pressure measurements at each of a large number of operating points that are representative of the multiple parameters that define the flight of the aircraft.

Dynamic Pressure Measurement System (DPMS)

At the outset it was recognized that it would be unfeasible to mount multiple dynamic pressure transducers within the components of interest of an aircraft model, which are usually very thin, e.g. the tail fins. A viable alternative is the Dynamic Pressure Measurement System (DPMS) offered by Turbulent Flow Instrumentation Pty Ltd (TFI).

The advantage of the DPMS system is that only relatively minor additional modifications need to be made to a model for dynamic measurement compared to the conventional arrangement where only static pressures are measured. A typical DPMS module consists of 16 or more pressure transducers, with a pressure port for each transducer and a common reference pressure port. The same form of hypodermic tubing could be used to route pressures from taps on a fin to a position outside where flexible tubing would complete the connection to the DPMS module ports. The DPMS module could be mounted in the fuselage of the model to minimize the total length of tubing.

The total length and diameter of the pressure tubing is an important consideration since it introduces frequency dependent amplitude and phase distortion of the pressure fluctuations. The TFI software compensates for the distortion introduced by the external tube and components within the module by using a transfer function to represent the transmission of pressure fluctuations from the tap to the transducer. The theoretical basis for the compensation is a linearized theory first proposed by Iberall [3]. Details of the derivation are provided by Bergh and Tijdeman [1] and they also derived a general recursion relation for the propagation of small amplitude harmonic disturbances through a system consisting of an idealized series of volumes interconnected by thin straight round tubes. They found the predicted response to agree very well with observation. Validation of the predicted transfer functions has also been demonstrated more recently by Hooper & Musgrove [2] and Mousley, Watkins & Hooper [4]. The theory is strictly valid only for simple geometries, but it has been shown that curvature of the pressure tubing has an almost insignificant effect on the transfer function provided that the tubes are not kinked.

In practice, installation of an external tube from the module port to a pressure tap will modify the system transfer function. Acoustic tests could be used to evaluate the modified response of the entire system, including the external tubing and the pressure port, internal tubing between the port and the transducer, and the physical (and electronic) characteristics of transducer. However, in most situations the external tube conforms well to the idealized geometry assumed by the Bergh & Tijdeman model. Hence the TFI software can use the recursion relation to accurately estimate the modified transfer function once the length and internal diameter of the external tubing are known. The tube diameter is a particularly important parameter since it is raised to 6th power. In a conventional application the accuracy of the modified transfer function is almost solely dependent on the accuracy of the measurements of the tube diameter and length.

The accuracy requirements of overall system transfer functions used for the compensation are more stringent for differential pressure measurements. Small errors in the amplitude response of each signal could result in a relatively large error after the signals are subtracted, especially if the difference between the two signals is small. Additionally, errors in the phase response will not significantly affect the accuracy of a single point

measurement. However, small errors in the individual phase response of two time records could result in a much larger error after they are subtracted. Furthermore, configurations with sharp corners and other significant departures from the idealized geometry could introduce considerable deviations from the calculated transfer function that can only be fully accounted for by direct calibration. These are important issues that need to be resolved before embarking on the proposed investigation.

One method being considered for creating carefully aligned pairs of taps on either side of a fin is to braze the sidewall of a hypodermic tube onto the inside of each surface. The hole for each tap would then be drilled from outside through the fin surface and the sidewall of the tubing. The minimum thickness of the fin is then only limited to be at least double the thickness of the surface material plus the outside diameter of both tubes. This non-standard tap geometry is likely to significantly depart from the idealized geometry used in the recursive model since the pressure fluctuations will have to negotiate a sharp corner. Another objective of these preliminary tests is to examine the influence of this non-standard form of pressure tap.
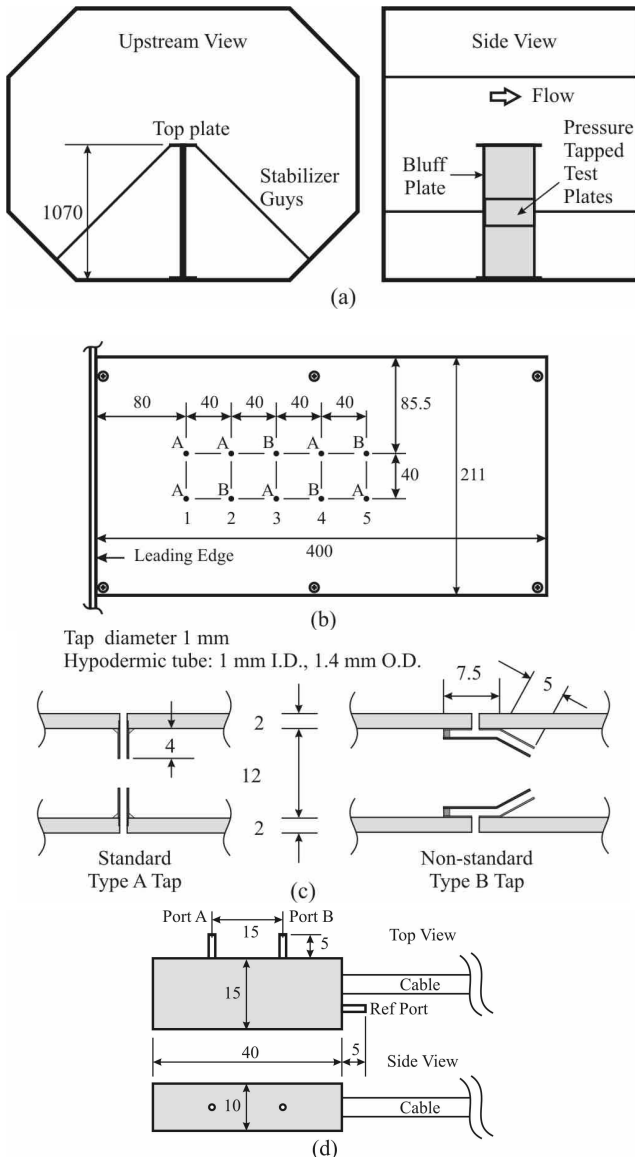

(a)

(b)

Tap diameter 1 mm
Hypodermic tube: 1 mm I.D., 1.4 mm O.D.

(c)

(d)

Figure 1. Experimental configuration. (a) Model in DSTO 9×7 ft low speed wind tunnel (b) Definition of pressure taps (LH test plate shown) (c) Details of pressure taps (d) DPMS module. Dimensions in mm.

Test Model and custom miniature DPMS module

A simple test model has been constructed to investigate the accuracy of the DPMS system for unsteady differential buffet pressure measurements with significant energy up to a frequency of 300 Hz using the non-standard form of pressure taps described in the previous section. This frequency range corresponds to the buffet pressures anticipated on the tail fins of a 1/9th scale model of the F/A-18 fighter that is part of future tests being considered in the DSTO 9×7 ft low speed wind tunnel. The model consists of a 32 mm wide bluff plate attached to a 16mm thick splitter plate. Figure 1(a) is a schematic of the model located in the working section of the DSTO 9×7 ft tunnel used for the tests.

The advantage of the model is that both standard and non-standard taps can be used in the same test. Construction details of standard (termed Type A) and non-standard (termed Type B) pairs of pressure taps are shown in figure 1(c). The layout and nomenclature for referencing the tap locations are shown in figure 1(b). It is not possible to conduct tests by swapping between different types of taps at the same location. However, the taps are staggered about the centreline of the 1070 mm tall model and one of the design objectives is to ensure that the flow is acceptably two-dimensional.
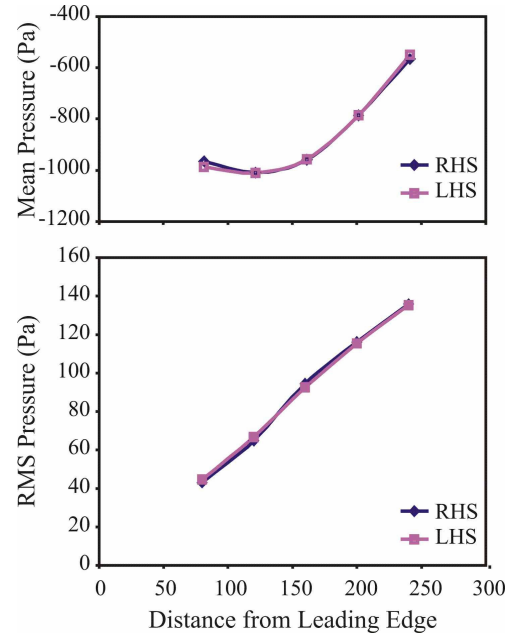

Figure 2. Streamwise development of mean and rms pressure. Upper pressure taps, 600 mm long tubes, 16 channel DPMS module, U=50 ms^{-1}.

Large amplitude pressure fluctuations are generated on each side of the splitter plate by turbulent eddies that are shed from a pair of separation bubbles forming behind the bluff plate. The internal gap between the test plates forming the surfaces on either side of the splitter plate allows a custom-built miniature dual channel DPMS module to be located inside the model. The DPMS module is shown in figure 1(d) and it uses the same pressure transducers and it is functionally equivalent to standard DPMS modules manufactured by TFI.

The configuration allows a range of flexible tubing lengths to be used between the DPMS pressure ports and the hypodermic tubes of the taps. The shortest pair of flexible tubes is limited by the requirement to reinstall the test plates after the installation of the tubing and the minimal length was found to be 30 mm. The other pairs of tubing used in the tests are 140, 300 and 600 mm long. All tests were conducted using nominally the same length tubes on each port.

Results

Experiments were conducted in the DSTO 9×7 ft wind tunnel located at Fishermens Bend using the two test section velocities of $U = 50$ ms^{-1} and $U = 70$ ms^{-1}. Streamwise development of the mean pressure and rms pressure fluctuations for $U = 50$ ms^{-1} is shown in figure 2. These results were obtained using all the upper row of pressure taps on both sides of the model and 600 mm long flexible tubes were used so that a larger 16 channel DPMS module could be located in the test section but outside the model.

The symmetry of the distributions shown in figure 2 demonstrates that the model is properly aligned with the freestream. One end of a long tube was connected to the reference pressure port and the other open end was located in a still region outside the test section. This was considered more desirable than connecting the reference port to a static pressure source in the test section with the risk of introducing additional pressure fluctuations. The test section is vented to atmosphere so that the minimum pressure coefficient has been estimated to be $C_{Pmin} \approx -0.67$. The largest rms amplitudes are observed at station 5 corresponding to a distance of 240 mm (30 step heights) from the leading edge. The rms pressure fluctuations at this location are about 10% of the dynamic pressure. The taps at this location have been used for all the subsequent pressure fluctuation measurements with the miniature dual channel DPMS module.
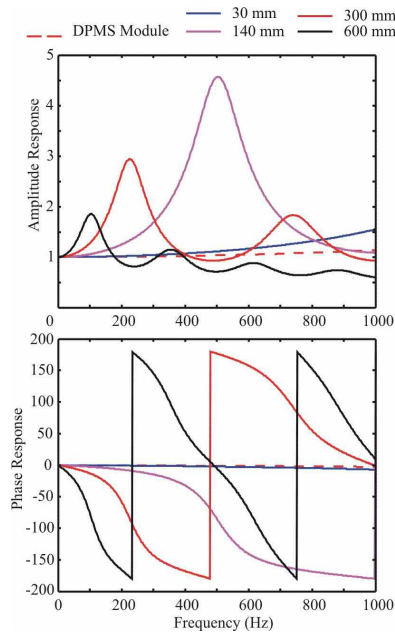
Figure 3. Amplitude and phase response of transfer function of DPMS module alone and the responses with added lengths of pressure tubing.

The transfer function of the dual channel DPMS module alone and with flexible tubing is shown in figure 3. The variations in the amplitude and phase response with the 30 mm long tubes are both very small over the frequency range 0-500 Hz. This configuration is therefore the least likely to be affected by any errors in the compensation so it will act as a baseline for comparing the results obtained with the longer tubes.

The transfer function for the next longest tube, $L=140$ mm, contains a resonant peak at 500 Hz with an amplitude ratio that is a factor of 4.5 times the response at 100 Hz. Smaller amplitude ratio peaks are also observed with the longer tubes, but these are more significant since they are closely centred in the frequency range to be experienced by the transducers. Note that for the 600 mm long tube, the gradient of the phase response is about 0.7 degrees per Hz in the region of interest.

(a)

L, Tap	P_L	P_R	P_{diff}	P_{diff}/P_L	P_{diff}/P_R	R
30, A	142.1	140.6	201.9	142%	144%	-0.0205
140, A	144.4	141.2	203.5	141%	144%	-0.0151
300, A	140.6	137.8	197.6	141%	143%	-0.0079
300, B	140.4	137.1	197.0	140%	144%	-0.0080
600, A	136.7	134.4	193.5	142%	144%	-0.0185

(b)

L, Tap	P_L	P_R	P_{diff}	P_{diff}/P_L	P_{diff}/P_R	R
30, A	256.1	256.9	366.8	143%	143%	-0.0226
140, A	267.1	261.5	376.1	141%	144%	-0.0122
300, A	251.4	246.3	353.6	141%	144%	-0.0094
300, B	256.6	253.0	362.1	141%	143%	-0.0095
600, A	253.5	249.4	361.2	143%	145%	-0.0319

Table 1. Rms pressures, Pa. (a) $U=50$ ms^{-1} (b) $U=70$ ms^{-1}. L(mm) Tap A/B, P_L: LHS; P_R: RHS; P_{diff}: difference; R: correlation coefficient.
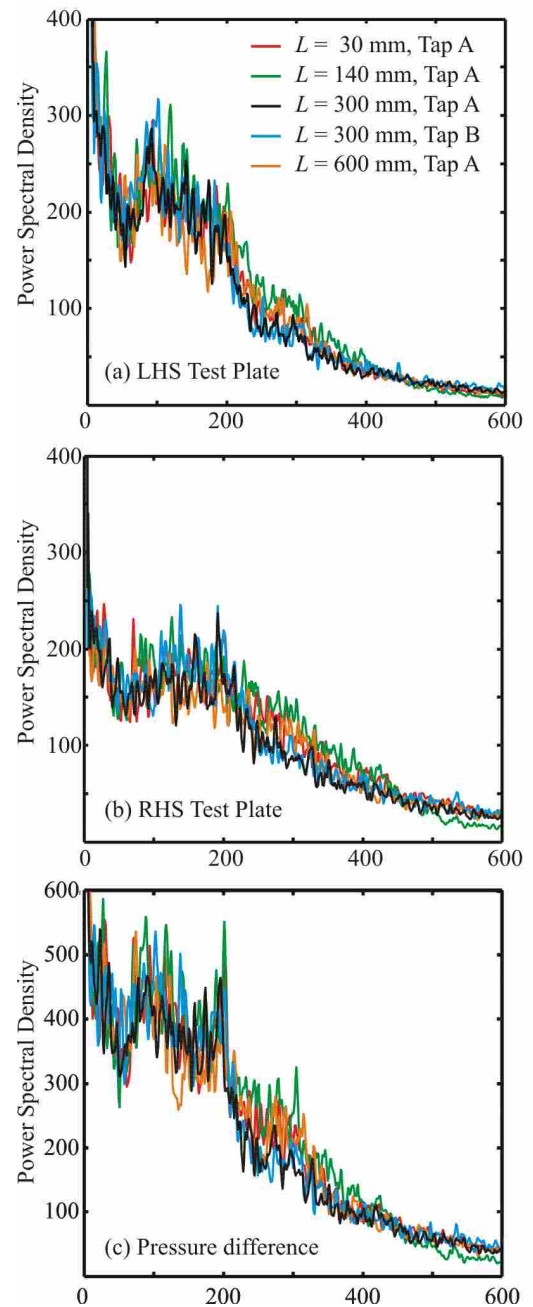
Figure 4. Power spectra corresponding to broadband results in Table 1(b).

A summary of the rms pressures obtained with the miniature dual channel DPMS module is shown in table 1. The rms pressures were calculated using the same time records as those for calculating the spectra shown in figure 4. The agreement between results for different tube length and pressure tap combinations indicates that the transfer functions used to correct for the distortion introduced by the tubing have worked extremely well. In particular, the agreement between the rms values of the pressure difference across the splitter plate using the standard and non-standard taps is excellent, despite the factor of three variation in the correction factor used for the amplitude response for the 300 mm long tubes over this frequency range. The correlation coefficients are close to zero, which indicates that the pressure fluctuations on both sides of the splitter plate can be considered to be random and independent. For truly random fluctuations the ratio of the individual to pressure difference rms fluctuations would be $\sqrt{2}$, which is closely observed in the measurements. The most significant observation is that the magnitude of the rms pressure difference is 40% larger than the individual rms pressures on either side of the splitter plate.

The power spectra shown in figure 4 allow a more detailed evaluation of the measurements to be made and they are plotted on a linear scale to clearly distinguish differences between the results. The spectra were evaluated from time records consisting of 40,960 samples obtained at a frequency of 1250 Hz to avoid aliasing, leading to total sampling period of 32.8 s. The spectra are evaluated using 512 samples for the FFT so the rms values in each frequency bin were obtained from 80 realizations.
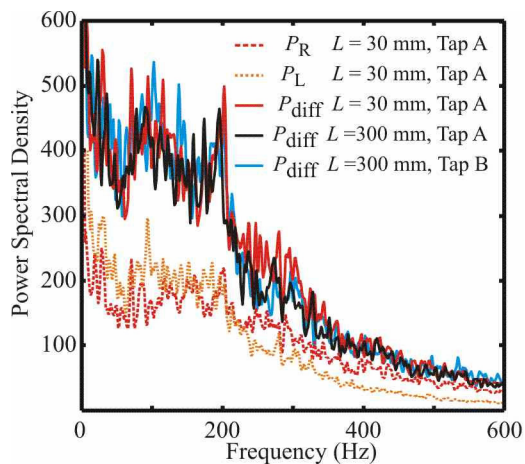

Figure 5. Individual spectra of P_L, P_R and spectra of P_{diff} for the baseline, and for L = 300mm tubes with both Type A & B pressure taps.

The spectra on each side of the plate are in reasonable overall agreement; within the scatter arising from incomplete convergence. However the amplitudes on the LHS test plate shown in figure 4(a) are consistently larger than those on the RHS at a frequency around 100 Hz. The differences are nullified in the spectrum of the pressure difference shown in figure 4(c). It appears there is some small differences in the vortex shedding characteristics on each side of the model. The origin of the differences is unknown. However, the most important observation is the consistency between the spectra obtained with standard and no-standard taps and with different length tubes

Spectra obtained on each test plate and spectra evaluated from the result of subtraction of the time records from each test plate are shown in figure 5. As explained previously, the results obtained with standard pressure taps and 30 mm long tubes will be the least in error and provide a baseline for comparison. The spectrum of the pressure difference for the 30 mm long tubes clearly demonstrates that it is the low frequency (long wavelength) fluctuations that are responsible for the larger rms

amplitudes of the pressure difference compared to the individual pressures on each side. The spectra of the pressure difference using standard and non-standard pressure taps with 300 mm long tubes are both in substantial agreement with the baseline result.

Conclusions

The rms value of the pressure difference acting across the splitter plate has been demonstrated to be about 40% larger than the rms pressure measured on each side of plate. The test model is not representative of an aircraft, and the rms pressure fluctuations are much less than those that can occur on the tail fin of the F/A-18 aircraft (peak values of up to 4 or 5 times the dynamic pressure). Nevertheless, the results demonstrate that standard single-surface pressure measurements are likely to provide misleading information about the buffet pressures responsible for unsteady structural loading on fighter aircraft. For the simple configuration used in these experiments, it is the lower frequency (longer wavelength) fluctuations that are responsible for the larger value of the pressure difference measurements. The DPMS system offered by TFI is capable of providing accurate results in the more demanding situation where dynamic measurement of pressure difference is required. The non-standard pressure taps that will be necessary for dynamic measurements of the pressure difference across the thin fin of an aircraft model do not appear to contaminate the measurements. Lingering doubts that remain about their effect on the transfer function used for the compensation can be removed by direct calibration.

Acknowledgments

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