# APPLICATION OF DYNAMIC PRESSURE MEASUREMENT FOR EMPENNAGE BUFFET

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## Abstract

*The paper describes the Dynamic Pressure Measurement System (DPMS) and its use for the concurrent measurement of unsteady buffet pressures arising on a generic delta wing and twin vertical-tail configuration. An original Acoustic Calibration System has been developed and used for experimental validation of DPMS measurement accuracy. The use of DPMS system will allow for investigation of the most significant features of empennage dynamic loading and for characterisation of aircraft buffet environments.*

## 1 Introduction

Aircraft empennage buffet is a complex aerodynamic phenomenon where highly turbulent vortical flow created over an aircraft during high angle of attack flight, impinges the empennage surfaces. Vortex-induced dynamic loading of the empennage surfaces can result in severe vibration and may lead to structural fatigue failures.

History has shown that many fighter aircraft capable of high angle of attack maneuvering have experienced some airframe buffet issues [1]. In fact, this problem is inherent in any aircraft design that relies on the generation of additional vortex lift for high angle of attack capabilities. However, empennage buffet is of particular concern for a twin-tail fighter aircraft where the vertical and horizontal tails are placed in the direct path of the highly turbulent vortical flow generated at the upstream separation areas. As future military aircraft are also expected to operate at high angles of attack in maneuvering flight, better understanding of aircraft empennage buffet is required in order to alleviate the inherent problems associated with this complex flow phenomenon.

## 2 Research Objectives

The work described in this paper is part of a research project which aims to develop tools and methods for characterisation of vortex induced buffet loading on aircraft empennage structure. This project evaluates the use of both experimental and numerical solutions to the problem and is initially concerned with the generation of a database of experimental results that can be used for the development and validation of buffet prediction tools. This stage of the project focuses on the development of the capability to produce such a database of results, derived from the wind tunnel testing on a simplified generic delta wing and twin vertical-tail configuration.

One of the major requirements when collating such a database for a range of different models is that the unsteady pressure can be accurately and reliably measured upon the relevant surfaces of the model. This necessitates the evaluation of a system to measure the dynamic pressures, in particular differential pressures across the surfaces of a vertical tail. It would be also beneficial if all components of the pressure measurement system could be interchangeable between various wind tunnel models, hence ensuring a consistent and cost effective method of measuring dynamic pressures.

## 3 Generic Buffet Model

It was demonstrated in [3, 4] that the vertical tail buffet problem can be simulated efficiently using a generic delta wing and twin vertical-tail configuration, shown in Fig. 1. This simple configuration contains all the pertinent flow physics involved in the development and breakdown of leading-edge vortices as well as interaction of their highly turbulent, swirling wakes with the vertical tails. This configuration is called the Generic Buffet Model (GBM). Using a simple geometry helps to facilitate development and initial validation of Computational Fluid Dynamics (CFD) codes by avoiding the long computational times that are encountered with more complex aircraft geometries.

Fig. 1. View of the Generic Buffet Model in DSTO Low Speed Wind Tunnel.

The GBM consists of a sharp edged, 76-degree leading edge sweep delta wing and swept back twin vertical tails. The delta wing has a main chord of 800 mm, the span of 400 mm and the tail separation distance of 160 mm. The tails are cantilevered on the upper surface of a trailing edge extension of the delta wing. Details of GBM design, development and wind tunnel testing can be found in [2, 5].

The GBM has one instrumented vertical tail that has been designed for the measurement of differential pressures across the surface. The port vertical tail has 32 pressure ports, with a pair of pressure ports on opposing positions of each surface of the fin, thus providing a grid of 16 ports on the surface. These ports are precisely aligned so that they can provide the differential pressure at the 16 points of interest. Each pressure port is formed from a 25 mm long steel tube of 1.2 mm Internal Diameter (ID) which is bent at a 90 degrees angle to the surface of the vertical tail and installed flush with the surface of the tail to avoid disturbance to the local flow. Each pressure port is then joined by 1000 mm long section of Scanivalve VINL-040 flexible plastic tubing to the corresponding input port of the pressure measurement module. Fig. 2 shows the arrangement of the pressure input ports upon the surface of the instrumented vertical tail.

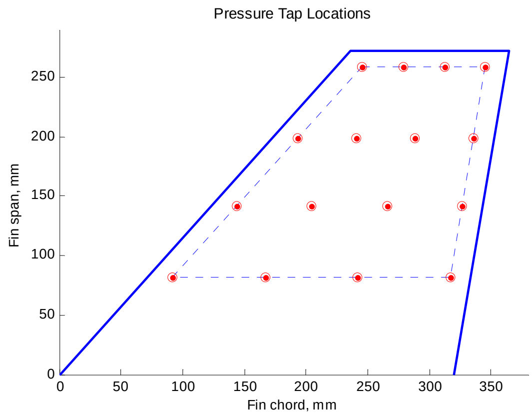


Fig. 2. Location of pressure taps on port vertical tail.

The design of the vertical tail allows for the pressure port flexible plastic tubing to be installed internally to carry the pressures through the inside of the tail to its root, where they can be discretely routed to the pressure measurement modules of DPMS system.

The GBM model is mounted on a sting-column support rig with a cranked sting, which allows the model to be set to angles of attack of up to 50 degrees while avoiding wind tunnel wall interference, see Fig. 1. The model can also be yawed to produce non symmetrical flow conditions. The DPMS modules are located at the rear of the sting and provided with aerodynamic fairings to reduce their influence on upstream flow conditions.

## 4 Wind Tunnel Test Facility

The Defence Science and Technology Organisation (DSTO) Low Speed Wind Tunnel (LSWT) located in Melbourne, Australia is a closed-circuit, single-return wind tunnel with an irregular octagonal test section measuring 2.74 m high by 2.13 m wide by 4.12 m long. The LSWT has a contraction ratio of 4:1 giving nominal turbulence intensity of 0.4%. The tunnel is powered by a 660 kW electric motor generating a maximum air speed of 100 m/s. However, due to the model's design load limits, the maximum test velocity during most of the test runs was limited to 50 m/s, giving a test Reynolds number of $1.8 \times 10^6$ based on the mean aerodynamic chord of the wing and a Mach number of approximately 0.15. The GBM was tested at various angles of attack up to 45 degrees, at zero sideslip and at wind speeds ranging from 10 m/s up to 50 m/s in order to investigate the effect of Reynolds number on buffet pressure characteristics.

## 5 Dynamic Pressure Measurement System

The measurement of unsteady buffet pressures on the empennage surfaces of sub-scale models places restrictions on the size of pressure measurement equipment that can be incorporated into the model. The ability to measure unsteady differential pressure across the aircraft empennage surfaces is of particular importance as it is critical to the understanding of the aircraft buffet environment. However it is particularly difficult to incorporate pressure sensors on both sides of a thin vertical tail so that they are placed directly opposite each other without obstructing the flow.

The Dynamic Pressure Measurement System (DPMS), designed and manufactured for the buffet test program by Turbulent Flow Instrumentation Pty Ltd (TFI), is particularly suitable for such tasks as it allows the unsteady differential pressure to be inferred across fairly thin lifting surfaces. The DPMS is a 64-channel pressure measurement system that provides time-accurate quasi-simultaneous measurement of both time-averaged (mean) and time-varying (fluctuating) pressure measurements and allows processing of the results in real-time [6]. The distinctive feature of the DPMS is its ability to infer dynamic pressure at a port located on the model surface using a system of tubes connected to the remotely located pressure transducers and signal conditioning hardware in the Dynamic Pressure (DP) modules.

### 5.1 Tube Response Linearisation

Accurate measurements of time-varying (fluctuating) pressure require 'linearisation' of the signals for amplitude and phase distortions that occur in the tubing used to connect the measurement points (pressure taps) on the vertical tail to the DP measurement modules. The amplitude and phase distortion of the dynamic pressure fluctuations travelling through the tubing is compensated for by using theoretically derived Frequency Response Functions (FRFs) that can be generated for the system of tubes of known geometry (diameter and length) [6].

A linearised theory for the amplitude and phase compensation was first proposed by Iberall [7]. Details of the derivation are provided by Bergh and Tidjeman [8] and they also derived a general recursion relationship for the propagation of small amplitude harmonic disturbances through a system consisting of an idealized series of volumes interconnected by thin straight round tubes. A good agreement between the predicted and measured response was reported by the authors.

Validity of the analytically derived FRF's has also been demonstrated by Hooper and Musgrave [9] and Mousley, Watkins and Hooper [10]. The relationship that the frequency response function is based upon considers simple idealized geometries, but it has been shown that the curvature of tubing does not affect the accuracy of the response function [9, 10]. However, kinking and/or changes in diameter of the tubing may have a significant effect on the measurement accuracy. Therefore, special care was taken during manufacturing of the pressure tapped vertical tail as well as during wind tunnel testing to avoid such issues.

## 5.2 Data Acquisition and Processing

TFI's software is an integral part of the DPMS system that controls and processes the pressure data. The software includes all functions required to operate the DPMS and to provide data acquisition, real-time processing and storage [6]. Frequency Response Functions for data linearisation are calculated by the Device Control software using the prescribed diameter and length of each section of the tubing that is used to connect the pressure taps (measurement points) to the DP modules. The software applies these analytical FRFs to correct the raw pressure data for the tubing response during real-time data processing.

A sampling rate of 2.5 kHz per channel was used during the wind tunnel test program while a scanning rate of 10 kHz per channel was used to decrease a phase lag between channels in an attempt to provide quasi-simultaneous acquisition of pressure data. Software correction of the phase lag between channels was also applied during real-time processing and linearisation of raw pressure signals. This allowed for accurate measurement of fluctuating buffet pressures within the frequency range of up to 1 kHz. This frequency range was found to be more than sufficient to cover all the frequencies of interest for the current buffet study.

## 5.3 Dynamic Pressure Measurement Module

Pressure taps on the vertical tail were connected via a system of flexible tubes to pressure transducers located in the DP measurement modules. A photo of a DP module is presented in Fig. 3. Each module contains pressure transducers, filters, pre-amplifiers as well as other signal conditioning hardware. The DP modules are provided with thermal regulation that maintains a constant optimal temperature within the module, thus reducing drift in the transducer signals due to wind tunnel internal temperature variation.

Fig. 3. Dynamic Pressure (DP) measurement module.

## 6 DPMS Acoustic Calibration

A full static calibration check of the DPMS was performed by the author prior to commencement of wind tunnel testing. The accuracy of the static calibration was found to be within ±0.3% of the full range, in line with manufacturer's specifications. However, the accuracy of DPMS unsteady pressure measurement depends on geometry of the pressure tubing and the known accuracy of its dimensions, such as length and internal diameter (ID). The accuracy of the predicted FRF used for pressure linearisation is even more critical for differential pressure measurements, where small errors in the amplitude response of each pressure signal could result in a relatively large error after two signals of similar magnitudes are subtracted. Also, small errors in the phase response of two signals will not significantly affect the accuracy of a single point measurement but could result in a much larger error of the corresponding differential signal. Therefore, considerable efforts have been spent on the development of apparatus and techniques to apply acoustically generated pressure waves to the pressure taps and DPMS tubing to allow for direct and accurate determination of the compensation FRF [11, 12].

## 6.1 Use of an Unconfined Acoustic Source

One acoustic method investigated for DPMS calibration was to allow acoustic waves to openly radiate from an unconfined source (loudspeaker). This method is simple and could be used for simultaneous calibration of multiple tubes or pressure taps, provided acoustic signal of the same intensity is applied to each pressure tap. However, the main limitation of the use of an unconfined source is the low intensity of the generated acoustic signals in comparison with pressure fluctuations produced by a typical wind tunnel buffeting flow. Here, the peak acoustic pressure fluctuation levels are two-orders of magnitude smaller than the dynamic range of the DPMS, insufficient for reliable and accurate calibration. Another problem is the complexity introduced by frequency dependent reflections from boundaries and other surfaces. Although the reflections could be minimized by placing absorbent material on the surrounding surfaces, the acoustic environment would still have a priori unknown, spatially complex, varying and frequency dependent sound pressure distribution [11, 12].

## 6.2 Enclosed Acoustic System

In order to avoid the issues associated with the spatially varying acoustic environment, several other approaches using an enclosed speaker system have been developed and tested. The initial enclosed design consisted of a loudspeaker attached to a flat plate and a long tube mounted in the middle of the plate and opposite the centre of the loudspeaker [12]. The advantage of using the enclosed speaker design is that the acoustic excitation produced at the end of the tube is very repeatable and independent of the external environment. However, it was found that the intensity of the generated acoustic pressure fluctuations was still too low compared to the DPMS dynamic pressure range. Additionally, it was found that the measured characteristics of the compensation FRFs were very inconsistent. This was likely due to the partial flow blockage and acoustic interference introduced by the presence of the reference microphone and/or pressure ports near the tube opening.

After extensive experimentation with various test designs and discussions with the DPMS developer (TFI) it was concluded that the most efficient acoustic test configuration consists of a loudspeaker attached to a cone with a small diameter tube fixed at the end of the cone, see Fig. 4. The cone helps to focus the acoustic energy produced by a loudspeaker and the long tube aims to produce the one-dimensional acoustic pressure waves which are undistorted by reflections. It was also found that in order to significantly increase the magnitude of the output acoustic pressure fluctuations and to provide accuracy and consistency of the FRF measurements, the tube opening needed be sealed with an end cap where the reference microphone and the test pressure ports can be installed. The final configuration of the acoustic calibration system is presented in Fig. 4.

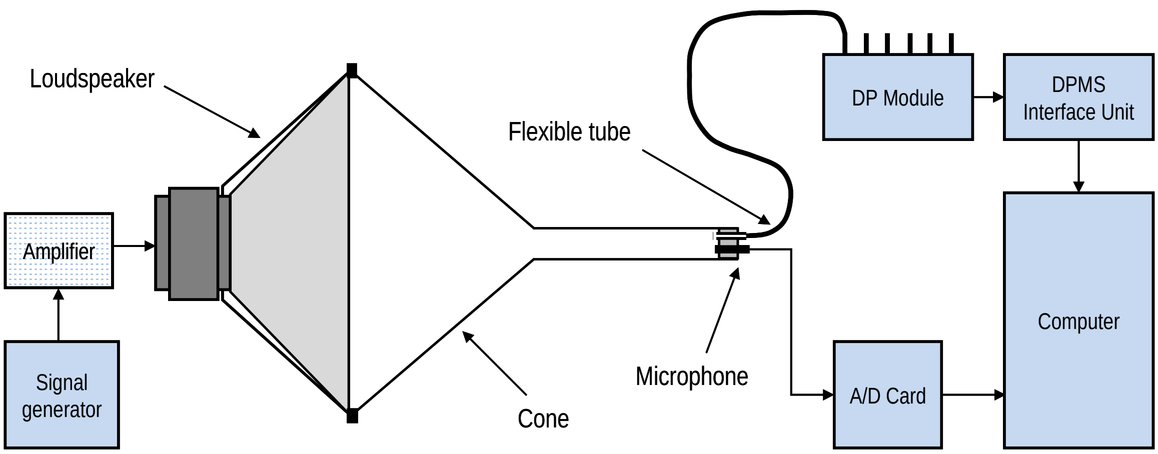


Fig. 4. DSTO Acoustic Calibration System

### 6.3 Validation of Analytical Frequency Response Functions

During the wind tunnel testing of the GBM [2, 5], 'linearisation' of unsteady buffet pressures was carried out using analytical FRFs based on measured geometry of the pressure tubing system. The tail's tubing system consists of several sections of tubes of various lengths and IDs including a 1000 mm long section of Scanivalve VINL-040 flexible plastic tubing. This tube is the longest component of the whole tubing system and therefore any error in the estimation of its frequency response is likely to significantly affect the overall accuracy of pressure measurement.

According to manufacturer's specification, the Scanivalve VINL-040 tube's nominal ID is 0.86 mm. To confirm this estimate for the actual tube used in the experiment, ID measurements were taken by visual inspection of the tube at several cross-sections using a microscope. The results revealed a noticeable variation of the tube's ID along its length and deviation from its nominal value. Based on a number of measurements at various cross-sections of a sample tube it was found that the average value of the tube's ID was 0.91 mm so this value was used to define the tube geometry. However, it was recognised that simple averaging may not be adequate to determine the 'effective' tube ID as the relationship between the variation of tube's diameter and its effect on the compensation FRF is highly non-linear.

In order to validate the accuracy of the analytically derived FRFs, the acoustic calibration system was utilised to estimate the overall frequency response of the complete DPMS, including its entire tubing system as well as the pressure ports installed on the vertical tail. During the acoustic calibration, one of the DP pressure ports, acting as a reference microphone, was used to directly measure the acoustic calibration input, see Fig. 4. Acoustic excitation applied to the tubing system consisted of three sine sweeps of 60 seconds duration, covering a frequency range from 0.1 Hz up to 1250 Hz.

Predicted and measured amplitude response of the DPMS estimated for all of the pressure ports is presented in Fig. 5. Here, the measured tube's ID of 0.91 mm was used in the calculation of the analytical compensation FRFs.

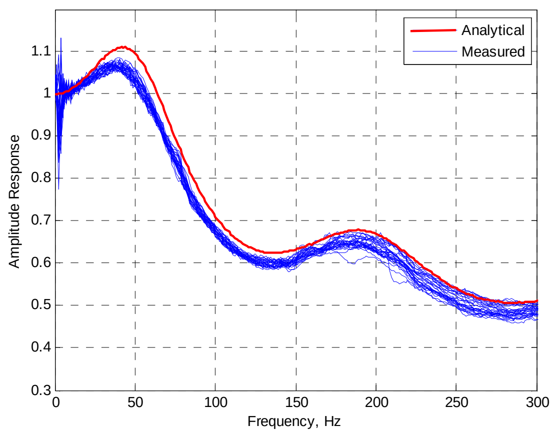


Fig. 5. Predicted and measured amplitude response of DPMS tubing system

The results presented in Fig. 5 demonstrate that the predicted amplitude response closely follows its measured values for frequencies up to 300 Hz, which is the most important frequency range for buffet studies. However, the analytically derived FRF tends to have higher magnitude of its amplitude response for the entire frequency range and this is likely to result in underestimation of the actual amplitude of pressure fluctuations.

## 7 Test Results

A substantial number of tests were carried out in the DSTO LSWT over a wide range of test conditions, thus providing a large amount of data for the required buffet database. Tests were conducted at freestream velocities of 10 m/s, 20 m/s, 30 m/s, 40 m/s and 50 m/s. The model was tested at zero sideslip and angles of attack ranging from 20 deg. to 45 deg. at increments of 1 deg.

### 7.1 Effect of Reynolds Number

One of the important fundamental features of vortex breakdown is that it is essentially an inviscid phenomenon and almost independent of Reynolds number. This assumption has been shown to be valid for many aircraft configurations tested previously by other investigators [1, 13, 14]. The data obtained using the GBM configuration in water and wind tunnels also demonstrated the Reynolds number independence of not only the vortex core trajectory but also the vortex breakdown location at various angles of attack. Fig. 6 presents non-dimensional Power Spectral Density (PSD) plots of differential buffet pressure measured at the same location on the tail and the same angle of attack of 30 deg. but at different flow velocities. Differential pressure was calculated by subtracting the inboard pressure value from the corresponding outboard pressure for each time step.

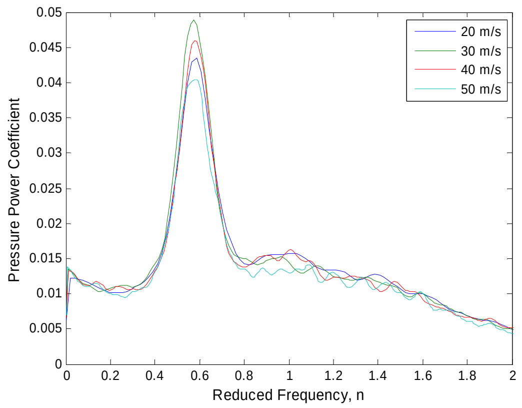


Fig. 6. Non-dimensional PSD plots of differential pressure measured at various flow velocities.

As can be seen from Fig. 6, the pressure power peaks all occur at the same reduced frequency and the shapes of PSD curves as well as non-dimensional values of peak pressure power are similar for different test conditions. This similarity of non-dimensional PSD plots measured at different flow velocities is an important indication of the Reynolds number independence of not only the statistical characteristics but also the spectral content of buffet pressures based on limited range tested so far. It also provides an indication of the health and integrity of the pressure measurement system.

## 7.2 Buffet Pressure Distribution

The distribution of Root Mean Square (RMS) values of differential pressures over the vertical tail calculated using analytical and measured compensation FRFs is shown in Fig. 7 and Fig. 8, respectively. The results are presented for the case of 30 deg. angle of attack. Comparison of the plots reveals that in both cases the pattern of RMS pressure contours remains the same but the values of differential pressure calculated using measured FRFs are noticeably higher over the entire tail surface. A similar trend was observed for all other attitudes investigated.

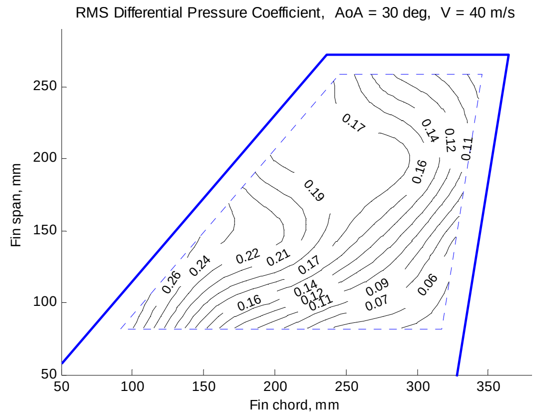


Fig. 7. RMS differential pressure contours calculated using analytical FRFs.

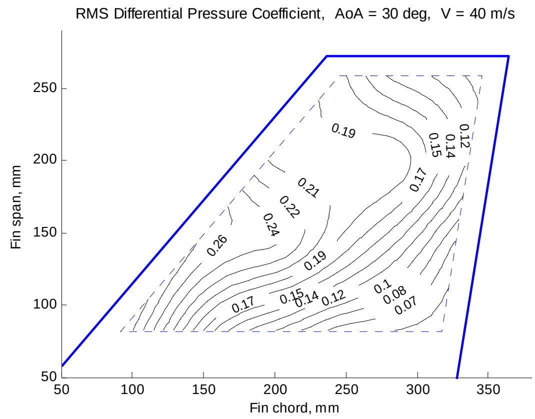


Fig. 8. RMS differential pressure contours calculated using measured FRFs.

## 7.3 Integrated Buffet Loads

One of the important measures of aircraft buffet loading is vertical tail root bending moment which can be obtained by integrating differential buffet pressures over the vertical tail surface. Fig. 9 presents the variation of broadband RMS root bending moment coefficient with angle of attack calculated using analytical and measured FRFs. In order to calculate the root bending moment caused by buffet pressures, the surface area of the vertical tail was divided into quadrilaterals surrounding each of the pressure port locations. The unsteady buffet pressures measured at the pressure port locations were multiplied by the area of the enclosing subsection and by the distance of the subsection centroid from the tail root. These values for all the subsections were then summed at each time step to obtain a time history for the bending moment imposed by the unsteady pressure field on the vertical tail.

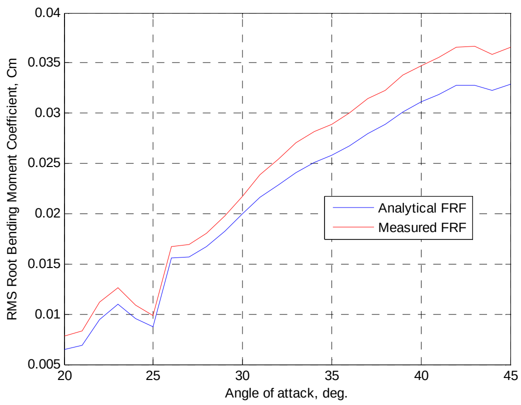


Fig. 9. Variation of RMS root bending moment coefficient calculated using analytical and measured FRF.

As can be seen from Fig. 9, the use of measured FRFs resulted in more than 10% higher values of RMS root bending moment coefficient for the whole range of angles of attack. However, it is known that any error in the evaluation of buffet loading gives rise to an exponential error in fatigue life estimation [15]. For example, an underestimation of the value of dynamic buffet loads by only 15% can lead to more than 50% underestimation of fatigue accrual. Therefore, the buffet pressures must be measured accurately as they define the associated structural dynamic loading which is crucial for the design of buffet-affected structures as well as for the reliable monitoring of aircraft's fatigue life.

## 8 Conclusions

The paper describes multi-channel Dynamic Pressure Measurement System (DPMS) and its use for the measurement of unsteady buffet pressures arising on the vertical tails of Generic Buffet Model.

An original Acoustic Calibration System has been developed and successfully used for verification of DPMS performance. It was demonstrated that considerable improvement of the DPMS measurement accuracy could be achieved by performing individual acoustic calibrations of all the measurement channels and using experimentally derived compensation FRFs for pressure linearisation.

The Generic Buffet Model and DPMS with calibrated FRFs will be used as a test bed for further development and validation of numerical and analytical buffet prediction methods. The DPMS will also be used for wind tunnel buffet testing of the current and future fighter configurations.

The use of Acoustic Calibration System and experimentally derived compensation FRFs will allow the use of DPMS for unsteady pressure measurements on wind tunnel models equipped with pressure ports and tubing which were originally designed for steady pressure measurement.

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