PARAMETER ESTIMATION TECHNIQUES FOR FLIGHT FLUTTER TEST ANALYSIS

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ABSTRACT

Flutter flight tests are both time consuming and costly as result of the large number of flight tests performed. This involves a careful increase in flight speeds at different flight levels to open up and establish a flutter–free flight envelope. The introduction of powerful 386 and 486 personal computers enabled the development of algorithms for parameter identification techniques in a user friendly environment. This paper mainly describes the implementation of the half power bandwidth method in the on–line modal analysis system to provide rapid estimates of structural damping and frequency trends. Other parameter estimation methods are available to assist the flight test engineer but are not utilised in the on–line system. The performance of the different evaluation methods is illustrated from flight flutter test data.

INTRODUCTION

To safely conduct flutter tests, proper preparation, instrumentation and flutter monitoring techniques are required. This must be linked to an accurate parameter identification algorithm to verify that aeroelastic instabilities are not present during flight. In the past this required heavy user interaction and tedious hand calculations before being able to establish frequency and damping trends.

In this context it was necessary to develop a cost effective flutter test facility. To achieve this algorithms were implemented in the MATLAB^{TM} mathematical analysis workspace. This allowed the use of flexible analysis tools with no memory restrictions.

In subsequent sections, flutter testing will be analysed in view of excitation, signal condensation and parameter estimation. Broadband frequency domain methods are utilised to provide estimated frequency and damping estimates from random aileron excitation.

DATA PREPROCESSING AND DATA ANALYSIS

The nature of the testing procedure requires the use of particular signal and analysis functions which may differ from those used in standard modal testing. Although an aircraft in principal has a large number of degrees of freedom, there are usually only a limited number that contribute significantly to flutter behaviour and, consequently, only these modes need to be tracked as functions of flight conditions.

The extraction of the excitation response from a noisy environment is an important task since atmospheric turbulence is present even when the structure is artificially excited. This is the reason why averaging and data smoothing procedures are applied. The data processing depends on the testing approach which is followed as well as the capabilities of the system identification algorithms available.

In case the forcing signal is measurable, both excitation and response signals can be transformed into the frequency domain by taking the Discrete Fourier Transform. The autopower and crosspower functions can then be obtained by an overlap averaging scheme. Once these functions are available, a system identification technique can be applied to the transfer function or power spectral density.

The flutter software package provides a variety of identification algorithms which include :

1 : Orthogonal Polynomial Curve Fitting,
2 : Half Power Method (DFT or MEM based),
3 : Approach of Eliminating Lobe Effects (AELE),
4 : Laplace Analysis and the
5 : Complex Exponential Curve Fit.

Methods 1 and 5 are well known and need no further explanation [1],[2]. A brief explanation of the remaining techniques is provided here.

The half power technique is related to the bandwidth of the mode at half the peak power as illustrated in figure 1 [3]. The natural frequency is associated with the resonant peak while damping is obtained from :

$$\xi = \text{bandwidth}/(2f_n)$$

where f_n = natural frequency

The AELE method was originally developed for the identification of heavily damped, strongly coupled and higher order dynamic structures [4]. Nevertheless, it was implemented to check its performance against other well-known techniques. The principal of this method is very simple and only algebraic calculation is needed for the identification process. For each mode only three sampling points around each resonance are required. The parameters are then extracted while eliminating the effects of the modes already known as calculation proceeds. Finally an iterative procedure is used until the deviation in modal parameters are all within certain criteria.

The Laplace transform procedure consists of differentiating the transfer function twice which tends to sharpen the peaks. The resulting function is then scanned for peaks. The modes with the lower energy values are then discarded while frequency and damping values for the remaining locations are computed. The ratio between the first and second derivative is used to estimate damping [5]. In this implementation the method is applied locally to peaks chosen from the transfer function, thus avoiding computational modes to a large extent.

So far, the estimation of signal spectra assumed to take place by means of Discrete Fourier Transform, but this is not the only way to estimate the power spectrum. Signal modeling approaches such as the Maximum Entropy Method (MEM) can be used to reproduce the most prominent features of the spectrum [6]. The method makes no assumption regarding data outside the time interval specified and is thus least affected by unavailable data. In addition, short data samples can be used without compromising spectral resolution.

Basically the method consists of estimating the order and coefficients to a finite order autoregressive prediction filter which, when applied to the response signal, renders the prediction error time history as random as possible. This corresponds to maximizing the entropy. If no excitation signal is available, the Hilbert transform can be employed to generate an equivalent minimum phase and consequently the complex transfer function [7].

The major difficulty however, is the selection of the optimum order of the filter. If the number of poles or number of data points is too large, roundoff error can be a problem, even in double precision. If the order is too small, resonances cannot be resolved; if too high, spurious peaks may occur. Order estimation procedures, such as the Akaike Information criteria [6] can be used for this purpose. A drawback of this method is the considerable computing power required compared to FFT based methods. Sample spectra produced by the MEM is shown in figure 2 and depicts the behaviour of the method for different filter order settings.

Synthesized Test Case

A simple theoretical example was synthesized to establish the validity of a few parameter estimation methods. To simulate a test case a transfer function was generated for a one-degree-of-freedom system with natural frequency of 20Hz and damping coefficient of 0.04. The results in Table 1 are as expected with only a scatter of 0.21% in frequency and 2.0% in the damping coefficient.

To validate the performance of the available methods in the presence of noise, a disturbance was added to the signal. Figure 3 shows the real and imaginary parts of the disturbed transfer function, while table 1 lists the frequency and damping solutions.

For the Orthogonal Polynomial Curve Fitting technique it is clear that addition of disturbed values over a wider frequency band reduces the accuracy of results when comparing figures 4a and 4b.

The sensitivity of the time domain Complex Exponential Curve Fit to noise can be observed from figure 5 where the singular values of the Toeplitz matrix are compared at different noise levels. The algorithm requires a priori information concerning the number of modes. Since the singular values are an indication of the expected number of roots in the signal it becomes difficult to specify the model order.

FLIGHT FLUTTER TEST PROCEDURE

Before flight flutter tests are conducted an aeroelastic analysis must be undertaken to determine the flutter characteristics of the structure.

Flutter flight tests are conducted at different points of the flight envelope in an air-speed build up approach. Therefore testing starts at high altitude/low air-speed and proceeds to low altitude/high air-speed.

The flight test procedure consists of stabilizing flight conditions followed by forced aileron excitation to induce symmetrical and anti-symmetrical excitation at each point within the flight envelope. The forcing signals consist of square waves with random pulse width produced by a random pulse generator. Responses from force and accelerometer stations are transmitted via telemetry to the ground station and displayed on strip charts. A direct interface between the front-end and a 386-PC stores 35 channels of data on virtual disk.

Typically about 4 stations are analysed during flight, initially selected on the basis of flutter analysis predictions. Each flight contains about 4 to 5 envelope points, depending on the position in the flight envelope, for both symmetric and anti-symmetric excitation.

The frequency and damping values are then plotted as a function of indicated air speed. Clearance to the next test condition in the flight envelope is given once damping coefficients and trends are determined to be satisfactory.

REDUCTION OF FLIGHT TEST DATA

A menu driven manager was developed which streamlines the manipulation of data from acquisition to the point where damping and frequency versus air–speed trends are displayed. The flutter engineer can configure the system with different filter options, decimation procedures and Welch power spectrum estimations.

Flight data are acquired at a rate of 240 samples per second for a duration of 40 seconds. In our case a sampling rate of 240Hz is too high given a baseband of interest of 30Hz. The time traces are then undersampled with the final rate being 60 samples per second.

The frequency content of the signal is captured by performing FFT analysis to obtain the power spectrum. The power spectrum is obtained by first removing any linear trend from the time record. Successive sections are Hanning windowed, transformed and accumulated with 67 percent overlap processing [8]. From literature it is known that the Hanning window is the best choice for system analysis using a true random signal [9]. The filter shape of this weighting function is characterised by a relatively narrow mainlobe and low sidelobes and gives the lowest possible leakage.

During the flutter missions only key parameters are analysed for decreasing damping and instabilities. Because testing needs to proceed as quickly as possible only PSD frequency and damping solutions are taken.

The frequency and damping values are picked off the power spectral density functions with the mouse cursor using the half power bandwidth method. The only problem is that the definition of some PSD functions degenerates in the higher range of the flight envelope. This called for a method where damping values could still be obtained in a realistic manner without the inconvenience of hand calculations. In cases where the peaks are not well defined as result of a low signal to noise ratio or closely coupled modes a relative confidence limit is placed on the damping value. The manner in which this is accomplished is by basically keeping record of the slope changes on both sides of the peak value until half power point is reached. To illustrate, an autospectrum with two modes at 20Hz and 21.5Hz and damping ratios of .04 and .025 respectively was generated. The result is shown in figure 6. This method obviously becomes invalid when modes are too closely coupled and is only used if the mode is not present in signals from other pick–up locations.

The advantage of this approach is that it is consistent and that no measurement errors are possible. The effectiveness of this approach is reflected in the better definition of the damping trends.

Once frequency and damping values are available they are arranged to correlate with predicted structural modes. Placing of modes are weighted with a correlation between the predicted mode and the position of the accelerometer station on the structure. The operator still retains the highest authority in the final placing or suppression of measured modes. This allows the flutter engineer to devote his time to analysis and interpretation of results.

Finally the frequency and damping trends are displayed before clearance to the next test point can be given. Either true damping values are shown or they can be mapped as a moving average to place more emphasis on the trend rather than the damping value itself.

ANALYSIS OF FLUTTER TEST DATA

Aileron Excitation System

The Random Pulse Generator (RPG) on the aircraft produces a random square-wave as forcing signal. Since the raw data needs to be undersampled it was necessary to consider the spectral implications of decimation on the excitation record.

The Fourier series of a square-wave can be written as a sum of odd cosine harmonics. The resulting series is a complete description of the frequency content if each cosine component is plotted against time and the waveforms added to approximate the original square wave. The original waveform can never be regained exactly unless all of the terms for its Fourier series are included. Even at that waveforms with instantaneous transitions (discontinuities) cannot be regained exactly. [10]

When discontinuities exist in the original waveform, addition of its Fourier terms does provide the exact original at every point except at the discontinuities. At every discontinuity there will always be an overshoot (Gibb's phenomenon).

A sample record of the raw RPG signal is presented in figure 7. As shown in Figure 8, the FFT of such a square wave will contain frequency components that are harmonically related to the basic frequency band where the harmonics of the 30Hz frequency band are visible up to the Nyquist frequency. To remove the harmonics, the forcing signal was decimated by a lowpass digital filter to prevent higher frequency components being aliased into the basic frequency band of interest. Figures 9 and 10 compare a portion of the original RPG signal and the decimated signal. The time trace for figure 9 was obtained by using a FIR lowpass filter while figure 10 employed a Chebyshev filter with cutoff at 30Hz [11]. The appearance of the decimated signals is caused by the removal of the higher frequency terms by the filters and characterise the Gibb's phenomenon. The ringing appearance for the Chebyshev filter is visible and reflects the loss of data removed to avoid aliasing. In both cases filter overshoot clearly appeared after the signals were bandlimited by lowpass filters.

Figures 11a and 11b compare the power spectrum of the RPG signal without pre–filtering with the undersampled signals using Chebyshev and FIR lowpass filters. A comparison between the transfer functions did not show a significant difference between the bandpass limits with and without pre–filtering.

Influence of Pick–up location

Analyses on transfer functions and autospectra were performed for several response stations on the wing tips and outboard weapon stations. The half power method together with single– and multi–mode polynomial curve fits were used to determine the influence of different pick–up locations on results. The frequency and damping values are summarized for comparison in tables 2 to 4. The locations presented in the table can be described as:

- W – Wing
- P,S – Port, Starboard
- LE,TE – Leading and Trailing Edge
- F,R – Front and Rear
- V,H – Vertical and Horizontal

Results resemble flight conditions at an altitude of 8000m and flight speed of 260 KIAS. The first three modes are tabled with rows corresponding to the mode numbers. Most of the modes were found at more than one location, as was to be expected. Flutter analysis predicted low damping for mode 3 within the flight envelope and was confirmed during the flutter tests. The measured damping solutions were lower than the predicted values, but it is known that, in general, random data yield lower damping values.

Due to different locations the scatter of the analyzed data reached 18% in damping for the half power method while 15% and 23% were reached for SDOF and MDOF polynomial fitting respectively. The scatter in frequency reached 2% for the half power method and 1% for both single– and multi–mode curve fitting. In addition, the damping values for MDOF fits tend to decrease when the number of modes in the analysis are increased.

The effect of higher turbulence levels with increasing flight speeds is visible in the higher scatter values of table 5, which were obtained at 370 KIAS.

The polynomial curve fitting algorithms are not restricted to equal frequency spacing and therefore function values which do not satisfy a certain coherence level can be neglected. However, this approach didn't improve the scatter margin. Table 6 compares the percentage scatter below and above mean value for frequency and damping at coherence levels of 0.5, 0.6 and 0.8 obtained from MDOF polynomial fitting.

In general the half power method provided results with a smaller scatter margin. This may partly be attributed to the fact that the algorithm uses only the response spectra while, with transfer function fitting techniques both turbulence and the RPG signal contribute to the response.

Some scatter may be caused by accelerometers which are not optimally placed with respect to maximum modal deformation. Therefore it becomes a trade–off between the value obtained from the optimum placing and the mean value obtained from different locations.

Influence of Different Estimation Methods

The same methods were used to evaluate the modal characteristics with data obtained from a flutter flight test. All the results presented were obtained with symmetric excitation at a flight level of 8000m at speeds ranging from 260 KIAS to high in the transonic region.

The exact values are not known and therefore no direct evaluation of the different analysis methods can be done. However, it is possible to draw conclusions from the comparison between the methods using the same flutter data.

The Complex Exponential Curve Fit didn't reveal reliable results. As shown in figure 12, no clear indication of the model order can be deduced from the singular values. Employing a Least Squares fit did not improve the results either.

Several response locations were analysed and then averaged. The averaged values are shown in table 7. The scatter due to the different estimation methods reached values of 1.44% for the frequency, and even 21.4% for the damping coefficient.

It is apparent that no two methods employed yielded similar results for all the modes. This may be true, but each method is based on its own mathematical principals to reach a final result. Figure 13 shows the damping trends for the different methods at each velocity. It is clear that even though the tendencies are at different levels they resemble the same trend. The tendencies are even more accentuated in figure 14 if damping trend is weighted as a moving average.

CONCLUSIONS

The objective of flutter tests is successfully accomplished using the MATLAB based data manager and has proven to be an effective tool in flutter flight testing.

Since the forcing system excites the modes of interest, it is possible to determine the frequency and damping trends of critical modes at points within the flight envelope.

The results from the half power method correlate well with orthogonal polynomial fitting techniques. For transonic test points scatter was marginally lower compared to transfer function techniques. Although robust, it is effective and confidence is established in damping solutions.

Accuracy of damping and frequency differs using different estimation methods but nevertheless it is possible to establish similar tendencies from modal data. It is therefore fair to say that flutter testing can be conducted in a safe manner.

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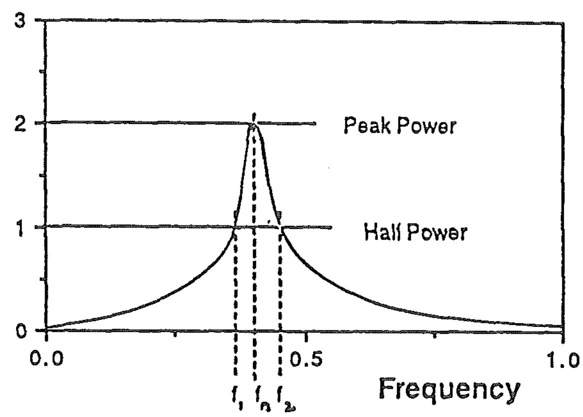


Figure 1. The Half Power Technique.

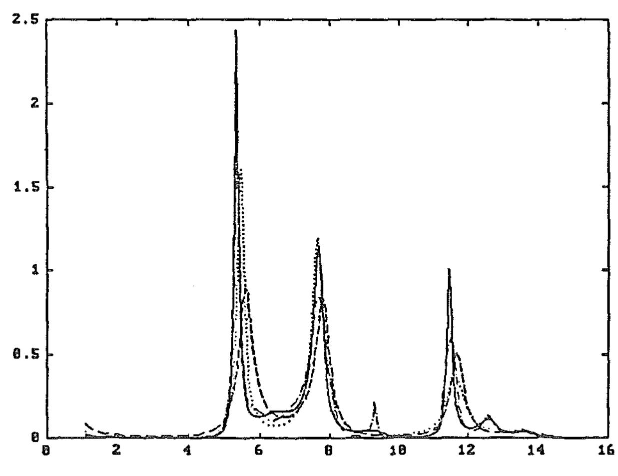


Figure 2. Sample spectra with MEM using filter coefficients 16, 20 and 40.

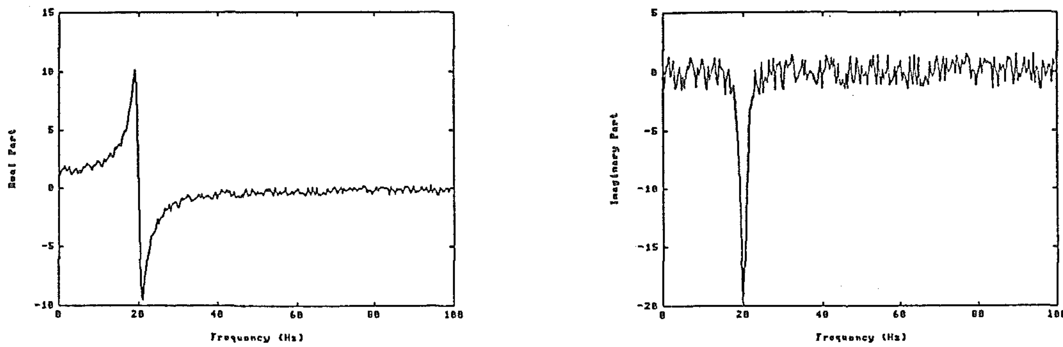
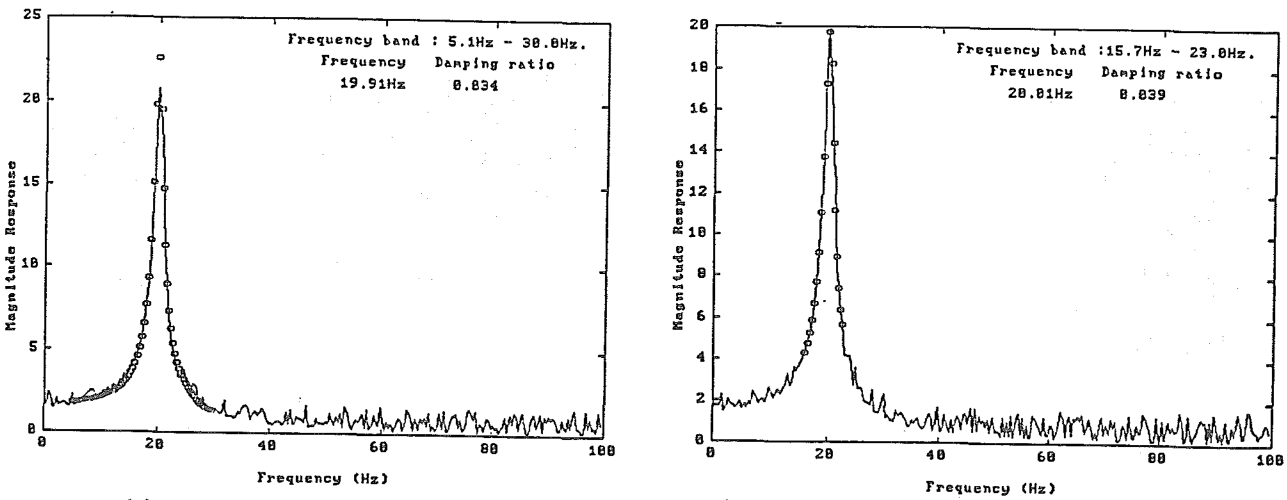


Figure 3. Real and imaginary part of disturbed transfer function.



(a) (b)

Figure 4. Check of polynomial fitting with varying frequency bands.

METHOD	No noise: Frequency (Hz)	No noise: Damping ratio	10% noise: Frequency (Hz)	10% noise: Damping ratio
Polynomial Curve Fit	20.00	.040	19.97	.040
AELE	19.96	.041	19.92	.037
Laplace Analysis	20.04	.040	20.27	.040
Complex Exponential Fit	20.02	.040	20.02	.042
Half Power method	19.99	.040	19.97	.041
	Scatter as % of mean Frequency : .21/.19 Damping : .50/2.0		Scatter as % of mean Frequency : .55/1.2 Damping : 7.5/5.0	

Table 1. Check of methods on generated data.

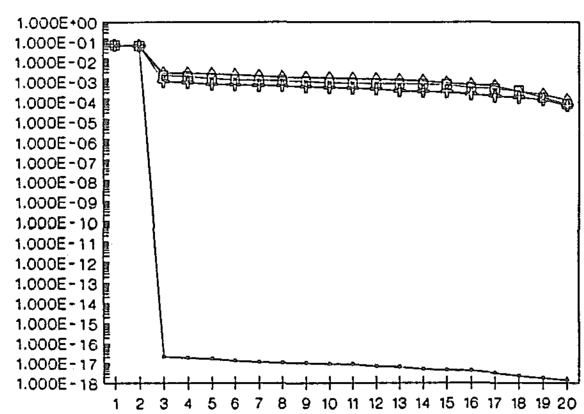


Figure 5. Singular values compared at 5, 10 and 15 percent noise levels.

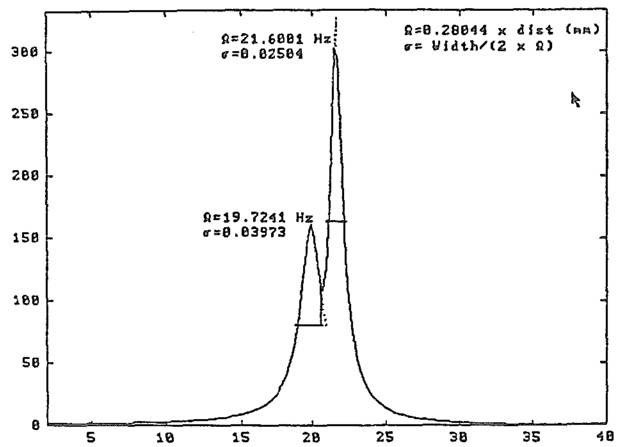


Figure 6. Check of half power method for coupled modes.

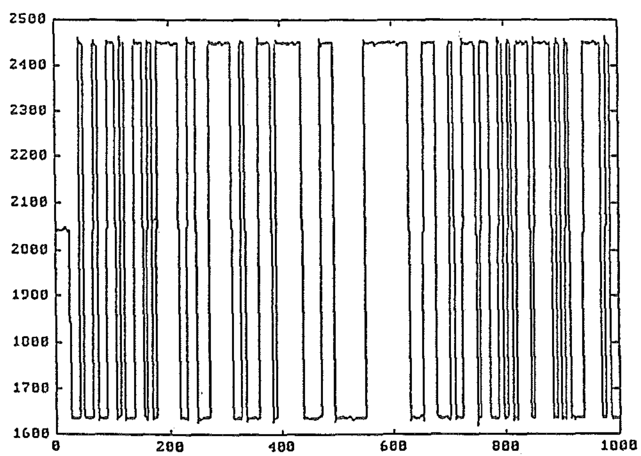


Figure 7. Sample record of raw RPG signal.

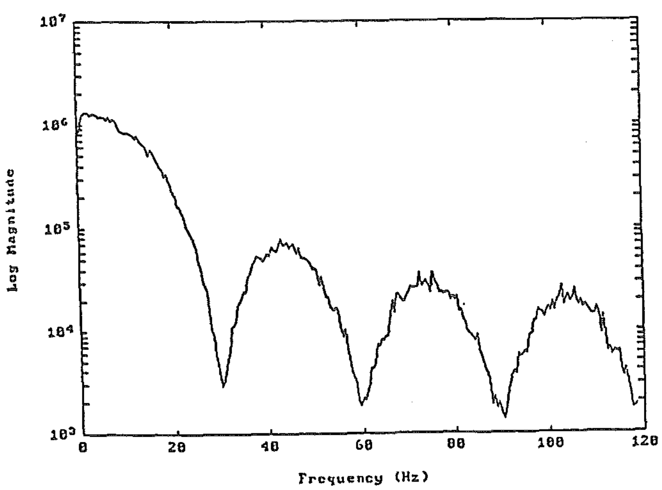


Figure 8. Autospectrum of original RPG signal.

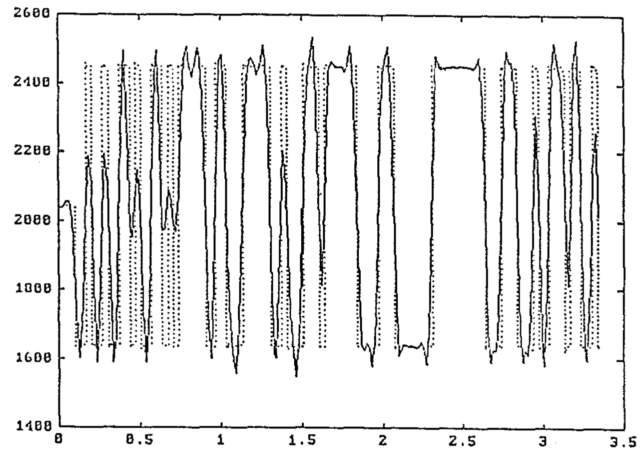


Figure 9. Time trace decimated with FIR lowpass filter.

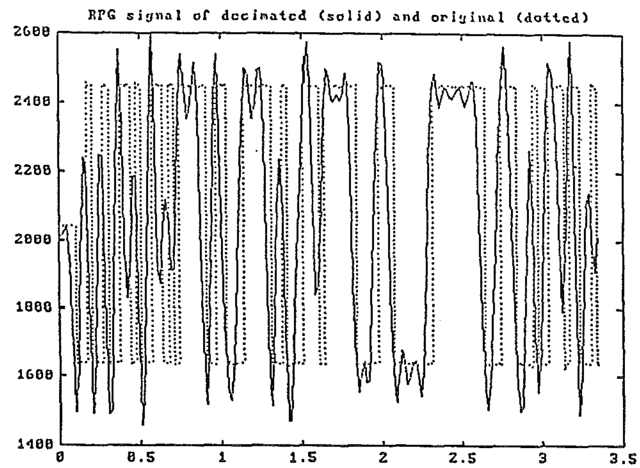


Figure 10. Time trace decimated with Chebyshev lowpass filter.

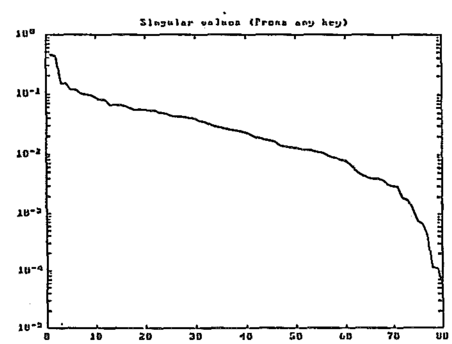
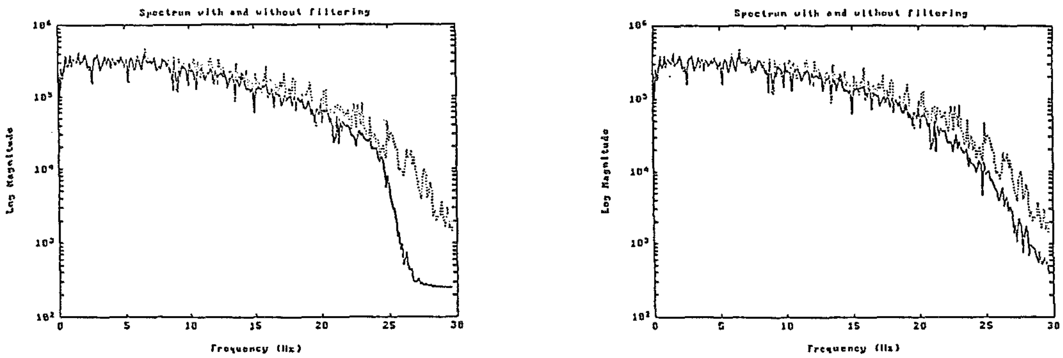


Figure 12. Singular values for Complex Exponential Curve fit.



(a) (b)

Figure 11. Autospectra of excitation signal with (a) Chebyshev and (b) FIR lowpass filters.

Wing Accelerations				Outboard station				MEAN	Perc. Scatt.
PWLE	PWTE	SWLE	SWTE	PFV	SFV	PRH	SRH		
5.35 .025	5.34 .025	5.34 .025	5.34 .026	5.37 .026	5.38 .027	5.35 .025	5.35 .025	5.353 .0255	0 /0 2 /6
7.64 .026	7.61 .024	7.61 .022	7.62 .022		7.70 .030	7.61 .024	7.70 .030	7.641 .0254	0 /1 13/18
					9.26 .014	9.47 .014	9.27 .014	9.33 .014	1 /2 0 /0
						Average Scatter Frequency Damping ratio			: 0 /1 : 5 /8

Table 2. Influence of accelerometer position using Half Power analysis.

Wing Accelerations				Outboard station				MEAN	Perc. Scatt.
PWLE	PWTE	SWLE	SWTE	PFV	SFV	PRH	SRH		
5.32 .026	5.31 .023	5.31 .026	5.32 .026	5.32 .028	5.32 .025	5.32 .026	5.32 .025	5.318 .0256	0 /0 10/9
7.54 .028	7.53 .028	7.61 .035	7.62 .034	7.51 .023	7.73 .036	7.67 .027	7.62 .030	7.60 .030	1 /2 23/20
						9.44 .009	9.27 .008	9.36 .0085	1 /2 6 /6
						Average Scatter Frequency Damping ratio			: 1 /1 : 13/12

Table 3. Influence of accelerometer position using multi–mode polynomial fitting.

Wing Accelerations				Outboard station				MEAN	Perc. Scatt.
PWLE	PWTE	SWLE	SWTE	PFV	SFV	PRH	SRH		
5.32 .028	5.32 .029	5.32 .029	5.29 .031	5.32 .028	5.34 .031	5.32 .030	5.31 .030	5.318 .0295	0 /0 5 /5
7.61 .027	7.57 .026	7.58 .034	7.60 .035	7.53 .028	7.66 .033	7.57 .028	7.59 .034	7.589 .0306	1 /1 15/11
						9.43 .013	9.28 .011	9.355 .012	1 /1 8 /8
						Average Scatter Frequency Damping ratio			: 1 /1 : 10/8

Table 4. Influence of accelerometer position using single–mode polynomial fitting.

Mode	% Scatter from mean PSD	SDOF fit	MDOF fit
1	0.2 /0.2 8.7 /5.8	0.8 /0.8 11.8 /18.6	1.1 /1.6 10.2 /6.1
2	0.6 /1.0 8.9 /17.6	0.7 /0.4 17.4 /20.5	1.9 /1.6 11.1 /22.2

Table 5. Percentage scatter in frequency and damping with different methods.

Mode	% Scatter as function of Coherence >0.5	>0.6	>0.8
1	0.9 /0.6 15.8 /13.3	0.8 /0.6 12.9 /19.4	0.2 /0.2 8.7 /9.5
2	1.8 /1.3 21.9 /19.5	1.8 /1.3 22.0 /18.5	1.0 /1.7 27.9 /27.9

Table 6. Percentage scatter at different coherence levels for MDOF curve fits.

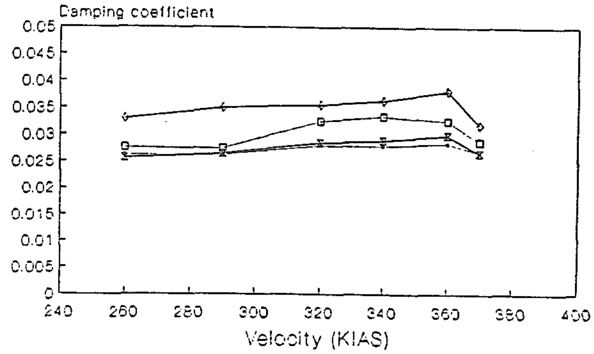


Figure 13. Damping trends for methods in table 7.

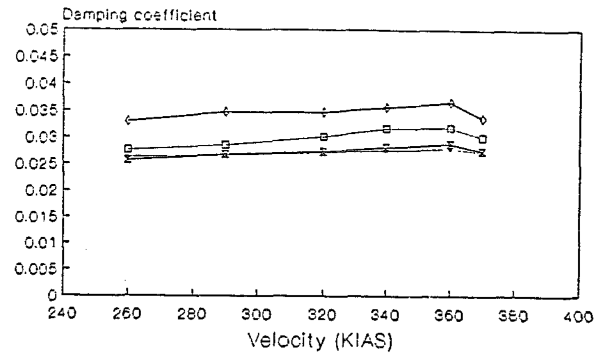


Figure 14. Damping trends displayed as moving average.

Speed (KIAS)	Estimation Method AELE	Lapl.	PSD	Poly	Mean	Std.dev	Scatter, % of mean
260	5.34 .033	5.43 .028	5.37 .026	5.32 .026	5.37 .028	.0465 .0033	.9 / 1.2 8.6 / 17.0
290	5.35 .035	5.45 .028	5.39 .026	5.32 .027	5.38 .029	.0562 .0042	1.1 / 1.3 8.8 / 21.4
320	5.35 .036	5.39 .033	5.39 .028	5.34 .029	5.37 .031	.0263 .0035	.5 / .4 10.0 / 14.5
340	5.35 .036	5.46 .034	5.38 .028	5.34 .029	5.38 .032	.0543 .0039	.8 / 1.4 11.7 / 14.7
360	5.35 .038	5.44 .033	5.39 .029	5.34 .030	5.38 .032	.0455 .0043	.7 / 1.2 11.9 / 18.1
370	5.35 .032	5.44 .029	5.35 .027	5.31 .027	5.36 .029	.0550 .0024	1 / 1.4 6.5 / 11.6

Table 7. Influence of different analysis methods on modal data.