ICAS-90-1.8.3

A SOFTWARE-BASED GROUND VIBRATION TESTING SYSTEM

R. J. McKinnell* and D. M. Wilson*
Division of Aeronautical Systems Technology, CSIR
Pretoria, South Africa

Abstract

A modal test system implemented in software running on general-purpose digital hardware is described. While a limited capability for broad band testing has been included in the system, the emphasis is on the software implementation of the functions required for tuned, multiple exciter sine dwell testing for modal parameter and mode shape measurement. Through the use of an effective graphics interface between operator and test system, it was possible to continuously present response information from 376 transducers in a simple form, allowing near real time evaluation of the response of the entire test structure to a particular force distribution. This feature, combined with easy control of up to 8 excitation channels, increases the efficiency of sine dwell testing. The system also generates and controls excitation signals by software: use of improved algorithms ensured that no loss of measurement accuracy occurs in the system.

1. Introduction

Flutter clearance and other aeroelastic investigations require detailed knowledge of the vibration modes of the airframe or aerospace structure involved. The ground vibration tests (GVTs) in which these modes are measured typically involve a few hundred transducer channels measuring response, and a smaller number (1-8) of excitation channels driving electromagnetic or other shakers to excite the modes.

The traditional sine dwell test method[1] is a well tried and trusted procedure for determining the modes of vibration of large complex structures. In a sine dwell test, shakers are distributed over a structure and driven to excite just one real mode, while suppressing the response of all other modes. Measurement of the amplitudes of response to this excitation then gives the mode shape directly. The accuracy of the modal parameters (frequency, modal mass, modal damping and modeshape) then depends on the accuracy with which the particular mode has been isolated. The force appropriation required (that is, the process of choosing an excitation distribution to optimally isolate a mode) is labour-intensive and tedious. Algorithms to assist the test operator with appropriation have been proposed (for example by Anderson[2] and Hunt et al.[3]). Both manual and automated tuning procedures have the disadvantage that the results depend on the exciter locations and particular response channels used by the test operator to evaluate the quality of appropriation or as input to the tuning algorithm; a poor choice of initial exciter locations, or of response channels monitored in the appropriation, leads to a poorly isolated mode. This disadvantage, and the requirement for dedicated hardware (such as analogue oscillators or co-quad analyzers), which lacks the flexibilty of modern digital data acquisition and analysis systems, have caused a decline in the popularity of sine dwell testing in favour of broad band modal parameter estimation methods[4]. These methods also have their disadvantages: to mention but a few, the amount of data to be handled for a large structure is often unmanageable, signal-to-noise ratios can be low, numerical manipulation of acquired data may introduce significant error, and it is often extremely difficult to separate close modes. The multiple-exciter tuned sine dwell test therefore still has an important place in modal testing.

The purpose of this paper is to describe the development of a digital vibration test system, capable of both broad band and sine dwell testing, in which only general-purpose hardware has been used. In implementing sine dwell testing, many of the disadvantages of the method have been addressed. The system will give significantly reduced testing times compared with existing sine dwell systems, with the potential for greater accuracy in results than broad band FFT or time domain based methods. The system is user friendly in the extreme, while making allowance for the fact that the computer cannot make all of the engineering decisions required in a modal test. For example, separation of close modes using broad band techniques may prove impossible if the excitation used, and data acquired, was not appropriate. Sine dwell methods may be used to separate such modes; isolation of each mode would require an understanding of the structural behaviour before a useful force distribution for each mode could be set up. This understanding can be gained by interpretation of a global view of the structural response. The measurement system's role is thus to present the response information from all instrumentation channels in a clear format, making interpretation easy and making the choice of a new force distribution obvious. The paper describes how the new system achieves this role.

The system design is modular; the intention is that the hardware is as far as possible interchangeable, and may be chosen to suit individual requirements and preferences. The emphasis has been on the avoidance of dedicated hardware - such as the co-quad analyser - which can be unnecessarily expensive and requires specialised knowlege to maintain. To achieve these objectives, the functions traditionally performed by hardware in the sine-dwell test method were replaced by software equivalents running on general-purpose microprocessors. The necessity for the presentation of response information in an interactive, near real time environment demands considerable computing power and speed - this has probably been one limiting factor in the development of software alternatives thus far. By the combined use of batch processing and distributed processing a modern workstation and modern microprocessors are more than capable of coping with the load in a near real time data acquisition system. The limitations of the system (in terms of frequency capability, for example) are imposed only by the performance of the digital hardware. As future hardware

---

* Engineer, Aeroelasticity Facility

development occurs, the software making up the test system will run faster without any need for modification, and so improvement and expandability of the test system is assured.

In addition to merely replacing analogue hardware functions with software modules, it was possible to take advantage of the flexibility of the general-purpose microprocessor to improve on some of these functions, so enhancing the quality of measurement results produced by the system. Examples include the new algorithms incorporated to enable very fine frequency control in sinusoidal excitation, and precise control of impulsive excitation, both of which required the use of specially developed function generators in the past. Problems with the digital implementation of these functions have been overcome.

2. Global Description of the System

We have already mentioned that the basis of the system is a modular design. Each function within the test system was designed as a separate piece of software, independently tested and with the capability for independent improvement or replacement. When requirements for the implementation of alternative test techniques arise, they may be added to the test system by writing a new module and adding it to the system. Also, because many modules have been written in a high-level language (FORTRAN or PASCAL), it should be relatively easy to modify the system to run on alternative hardware.

Two modes of operation of the test system have been implemented: a broad band testing mode, in which impulsive excitation is digitally generated, and response records are acquired and analysed; and a sine dwell testing mode, in which single-frequency excitation is digitally generated and coincident and quadrature responses are monitored in near real time. The hardware used by the system in each mode is the same: excitation hardware consists of 8 electrodynamic shakers with amplifiers, driven through digital-to-analogue (D-A) converters under microprocessor control; response measurement is by means of 368 accelerometers and 8 force transducers, routed through programmable signal conditioning equipment containing filters and amplifiers to analogue-to-digital (A-D) converters, also under microprocessor control.

The core of the system is a graphics workstation, running software for the interface between the operator and the test system, and controlling test excitation and data acquisition. Figure 1 presents a schematic of the system, showing the four main tasks undertaken on the workstation.

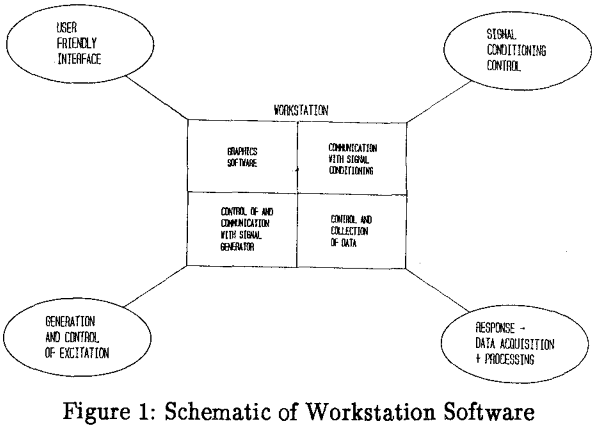

Figure 1: Schematic of Workstation Software

Firstly, the operator/system interface provides presentation of structural response information, and interpretation of the operator's commands. The interface makes use of graphical representation of a maximum amount of relevant information concerning the test set-up and structural response to excitation in a simple, easily interpreted format. This interface also gives the operator control of measurement set-up and execution by means of menus, with menu selection driven by a mouse. In this way, the operator is freed from having to learn and enter tedious command sequences.

The remaining three workstation tasks involve control of excitation, signal conditioning and response acquisition. The aim of these functions is to translate commands given by the operator into the formats required by the particular subsystem involved, and to translate response data or subsystem status information into the form required by the graphical interface. These functions are implemented as background processes in a multi-tasking environment, to ensure optimum usage of the workstation's resources and to make the intricacies of the test system transparent to the user. Communication with each subsystem is by means of a standard interface (GPIB or Ethernet). Such interfaces have been used to reduce the cost of the system, and to maintain flexibility: should any subsystem require replacement, a new subsystem may be incorporated without modification to any other subsystem, and only the software specifically dealing with that subsystem need be modified. Data flow over the interfaces was minimised by making use of the processing power available in each subsystem, so that only relevant data need be transmitted.

3. Interface Between Operator and Test System

Any test system is no more than a tool used by the modal analyst to measure the dynamic characteristics of a structure. While it is of course essential for the system operator to understand the principles of operation of his test system, it is also essential that test time is not needlessly spent on setting up details of operation: wherever possible, this setup has been automated. The graphics interface then presents only the important choices available to the operator during particular phases of testing: internal setup parameters for test system components can then be derived automatically. For example, when the operator selects a particular frequency, the system can automatically derive and set up optimum D-A and A-D conversion rates, filter cut-off frequencies and amplifier gains required by the various subsystems to ensure that maximum measurement accuracy is maintained. At the same time, the system ensures that the test parameters chosen lie within the capabilities of the test system, so avoiding overloads and other distortions.

In this way, the potential for operator error can be removed from testing. Also, by making use of the system straightforward (by means of menus and mouse-driven selection of options, and easily interpreted, uncluttered presentation of essential information only) the test tool becomes easy to operate, increasing efficiency and accuracy in testing. In the next sub-sections, we describe features of the graphics interface and show how these enhance testing.

3.1 Hardware Setup and Instrumentation

The first step in the ground vibration test is the set up and instrumentation of the test structure. Typically for a large structure there may be several hundred accelerometers and up to eight exciters and force transducers, all of which must be calibrated. The calibration function is easily facilitated by software since each channel can be individually accessed. The approach taken in this system is not to use calibration factors for each component in the signal path (transducer, amplifier, A-D convertor) but instead to calibrate each channel as a whole. This is achieved by putting a known input on each individual channel. Software then relates the signal returned by the instrumentation to that input, and records a calibration factor for subsequent use with that channel. The operator's contribution in this process is simply to apply the known input to each channel in turn. The system can detect which channel is being calibrated, and derives the calibration factor.

3.2 Response Measurement in Broadband Testing

The first stage of the ground vibration test is to get a feel for the response of the structure by performing broadband frequency scans and monitoring response.

Several key channels, where modal response can be most easily detected, are chosen. The number of channels selected is not limited, and on a complex configuration 16 or more may be required. Exciters are attached at convenient points to excite the structure. Once the initial set up phase is complete, the rest of the frequency scan process is conducted via the keyboard and mouse. By use of graphical data entry techniques exciter forces can be set, and incremented up or down in a manner similar to the thumbwheel switch.

Response channels are selected and labels assigned, exciter forces and sense are set, and the frequency range of interest is entered. On instruction from the operator the exciters are triggered to impart a programmed impulse to the structure, the frequency content of which relates to the frequency range initially selected by the operator. The response is recorded and the time history for four channels at a time is displayed on the screen. The user may select to proceed or to reject the samples. If he proceeds the frequency response is displayed.

This data could be used for any of the modal parameter estimation techniques, and software could be implemented to do this if desired.

In the current implementation, the operator decides how many peaks of significance are displayed for each response channel, and these peaks are marked with the cursor. This need not be done too precisely as the software will select the nearest peak to the cursor position. The frequency and amplitude of the response at each point are listed to the screen and simultaneously stored in a file for future reference. This information identifies all modal frequencies of interest, and can then be used as a starting point for excitation setup in sine dwell testing.

While being easy to operate the method is not over automated. It is a combination of engineering decisions made by the operator, and automation of routine procedures. The peak-picking technique used here is the simplest form of modal parameter estimation. However, the only information extracted at this stage is frequency and relative amplitude. Unlike most broad band techniques which would use FFT information as a data base, the sine dwell technique is preferred in the interests of accuracy.

3.3 Sine Dwell Testing

Traditionally in sine dwell testing a limited number of channels may be chosen to monitor the response of the whole structure. These would typically be selected at key positions on the structure and patched in individually. The mode is then 'tuned' in by adjusting the positions of the exciters, their sense, amplitude and frequency of excitation, until the response to excitation appears to be that of a real mode for the channels monitored. Then the amplitude and phase of all channels is extracted. It may become obvious at this stage that some exciters are not optimally positioned as there are non-real mode responses on some parts of the structure not monitored in the initial selection of channels. The exciters would then have to be moved and the whole process would have to be repeated for the new set-up. It is primarily this repetition which has led to the unpopularity of the sine dwell method.

The ideal situation would be monitor all of the channels on the structure simultaneously in terms of amplitude of response and phase angle (the coincident and quadrature components of the response with respect to excitation). With up to several hundred channels required on a complex structure this sounds like a daunting proposition, but using modern graphics techniques it is achievable. The emphasis must be on simplicity, and care must be taken that the operator is not confused by a screen full of information which is not required at that time.

The important information is the magnitude of the coincident and quadrature responses; the aim of the test being to maximise the quadrature component (real mode response) and minimise the coincident. Since the exciter settings are the means by which this optimisation process is achieved, their current settings must also be displayed; and the means to control or change the settings should be via the keyboard/mouse. Figure 2 illustrates how a 19" monitor has been used to display the above- mentioned information.

The main panel of the display is given over to the display of the (up to) 376 channels of response and excitation data. Three rows of data are shown; depending on the number of accelerometers on the structure, the display will be arranged to give an optimal format. For each row the bar chart above the central line represents the quadrature component of the accelerometer response, and the bars below the line represent the coincident component. For a properly isolated mode these would of course be zero. The acclerometers are displayed in numerical order, which, depending on the accelerometer layout on the structure, would automatically mean that all the accelerometers on a particular component of the structure would be displayed consecutively. Thus the centre line can be used to display labels for the components so the operator can see at a glance where the accelerometers are placed, and so relate the response displayed directly to motion on the structure. The use of different colours enables differentiation between the sense of the movement of the structure, for example between symmetric or antisymmetric movement. The operator would also like to know the current positions of the exciters; this is displayed in the exciter control box, and also each exciter is marked with a small box above the accelerometer bar corresponding to the nearest location.

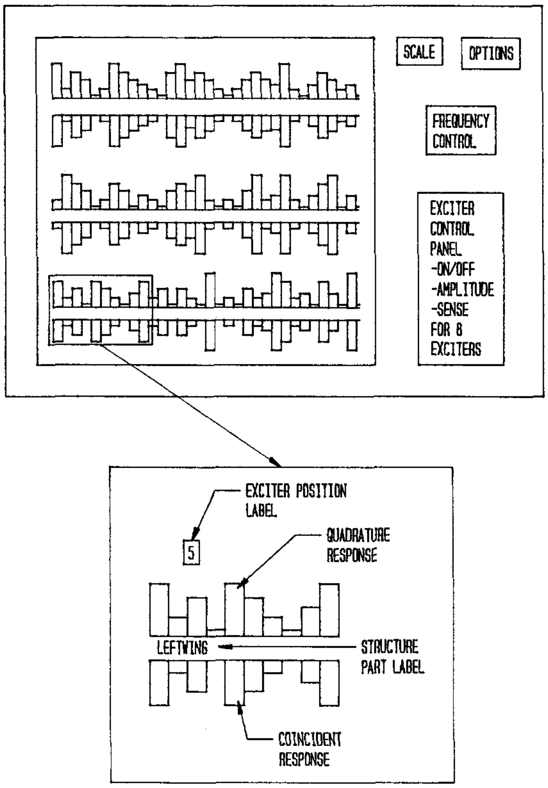

Figure 2: Schematic of graphics interface, showing response display and excitation control.

A crude appropriation criterion is also implemented in the graphics display: for example, it may be considered acceptable that the coincident component of the response should be less than say 10% of the quadrature; if this factor is exceeded then the coincident component would be displayed in red to immediately identify a problem area on the structure. A global appropriation indicator function[5] is also continuously displayed.

Control of the exciters is achieved using the panel on the right which accomodates up to eight exciters. The frequency is set on the smaller panel above. Forces and frequencies can be changed in either of two ways. The cursor is placed in the box and the value typed in, or the value may be incremented in steps of 1, 10 or 100N again by placing the cursor in the relevant box and pressing the enter button. In the same manner exciters can be switched on or off and the sense can be changed. When the operator switches an exciter off the screen indicates that it is no longer active. However, there is no need to remove it from the structure since constant feedback from the force transducer located on the end of the sting ensures that an effective zero force is seen by the structure. In addition any sudden changes to the force, such as turning it on or off are transmitted to the amplifier in a controlled manner so that no sudden changes occur, and software protection of the structure ensures that no excessive forces may be set.

The information on the screen is displayed in near real time, ie the screen is refreshed every second (this time varies depending on the number of channels involved) so that the effects of changes in the excitation are visible as they occur.

Once the mode has been isolated to the satisfaction of the operator, fine-tuning algorithms may be invoked to optimise the force appropriation and derive modal parameters. At this stage only the method of Complex Power[6] has been implemented, but software modules can be incorporated at any stage to include other methods.

Through the interface described above the isolation of each mode over the entire structure can be ensured to the degree of accuracy demanded by the operator without the need for repetition. The appropriation process is performed by the engineer, but the display of all channels enables him to identify problem areas immediately, both in terms of exciter position and force settings. The appropriation is thus made more efficient, eliminating a major disadvantage of the sine dwell method of modal testing.

4. Interface Between Test System and Structure

Transducers for excitation and response measurement form the interface between the test system and the structure being tested. The test system must generate input signals to excitation transducers, and must process the output signals from response transducers to form meaningful measurements. As already described, the interface is also an interface between sampled, digital data and continuous, analogue signals. In this part of the paper, some of the algorithms implemented in software to form this interface are described. It is shown that the software implementation of the functions required may be used to improve the measurements produced.

4.1 Impulse Generation

The impulse test requires that the shakers selected for the test be driven to produce an impulsive force acting on the structure. This is achieved by downloading a table of values describing the shape of the impulse from the workstation to the D-A controller microprocessor. When the D-A subsystem is triggered, this microprocessor merely outputs this table of values through the D-A converter and smoothing filters to the shaker amplifiers, so generating the impulsive force required.

This method has the advantage that the shape of the impulse can be tailored to suit the frequency range of interest to the test, so only the modes sought are excited. The table of values downloaded can be viewed simply as the impulse response of a non-recursive digital filter: a wealth of algorithms exist for the design of such filters with specific frequency characteristics[7]. For example, if a test required that a frequency range of 0-20 Hz be excited, then a finite impulse response $h(t_k)$ is derived with a frequency response $H(\omega_k)$ that is flat in the range 0-20 Hz, with a sharp cut-off above 20 Hz. The advantage of this approach is that the bandwidth of the impulse is not determined by the bandwidth of an analogue filter, so that the full range of the D-A converter can be used in the frequency range required. Also, anti-aliasing filtering of response data is less critical - for a linear structure there will be no corruption of the data of interest by high frequency modes. This is similar to tests using impulsive sine excitation[8] in which a truncated impulsive sine series was used as an excitation signal. The use of finite impulse response filter design methods guarantees that no truncation is necessary and so the frequency response is closer to that required, particularly at frequencies close to maximum.

4.2 Digital Realisation of the Sine Wave Generator

In sine dwell testing, the excitation forces required from each shaker are pure sine waves of tightly controlled amplitude and relative phase. The task of the D-A subsystem controlling excitation is thus to produce sequences of sine values which, when output through D-A converters and smoothing filters, drive the shakers to produce these forces.

Digital function generators typically generate a sine wave simply by periodically outputting a sine table through D-A convertors. One of the stumbling blocks in the use of this approach for the generation of sinusoidal signals for sine-dwell testing has been the frequency resolution problem. For the accurate appropriation of a mode, for the separation of close modes, or for the accurate measurement of modal mass and damping, it is often necessary to make extremely small changes in excitation frequency. The frequency of the sine wave so generated is determined by the number of points describing the sine wave (i.e. the number of points in the sine table) and the rate at which the D-A conversions take place. This rate must be an integer submultiple of the microprocessor's clock rate. It is this constraint that limits the frequency resolution available from a digital system. For example, the use of a 4 MHz clock with a 32 point sine table to produce a 100 Hz output signal would require a clock divider of 1250 to achieve the correct sine wave frequency. To reduce the frequency we would increase the divider to 1251, yielding a sine wave frequency of 99.92 Hz. When investigating the properties of a lightly damped mode, this resolution may prove inadequate.

An alternative approach, implemented in the test system described in this paper, is to replace the sine table approach with a software implementation of an oscillator. This was achieved using a recursive digital filter with the Z-domain response function

$$H(z) = \frac{z^{-1} \sin \omega_e T}{1 - 2\cos \omega_e T \, z^{-1} + z^{-2}}$$

where ω_e is the excitation frequency and T is the D-A sampling interval.

The impulse response of this filter is given by

$$h(t_k) = \sin \omega_e T$$

The output of this digital filter, after D-A conversion and filtering, gives the excitation signal desired. The frequency of excitation is now determined by the coefficients of the digital filter; the frequency precision, and thus the frequency resolution, is determined by the accuracy with which the arithmetic involved in the digital filter is implemented. 32-bit arithmetic yields a frequency resolution of 1 in 2^{31} at all frequencies - obviously a great improvement on the sine-table approach.

4.3 Control of Excitation

The mechanical impedance of the test structure with respect to excitation force changes with frequency and the modal characteristics of the structure itself. These impedance changes have the effect of modifying the amplitude and phase of the actual force generated by an electromagnetic shaker, relative to its input signal. It is therefore not sufficient to merely output a sine wave of desired amplitude and phase in the multi-shaker modal test; a test system must also ensure that these signals are converted by the shakers into a force of desired amplitude and phase. This is typically achieved by using current-controlled shaker amplifiers. An alternative, also advocated by Hunt et al.[9] is to monitor the actual forces imposed on the structure by means of force transducers mounted between the shaker and the structure. The responses of these transducers are then controlled to the desired amplitude and phase. The digital control system implemented to perform this task is illustrated in Figure 3. The feedback controller calculates the error between the desired and measured force response, then uses this error to change the values of the coefficients of sine and cosine components in the excitation signal. In this way, the system ensures that the phase and amplitude of each shaker channel corresponds to that set by the operator.

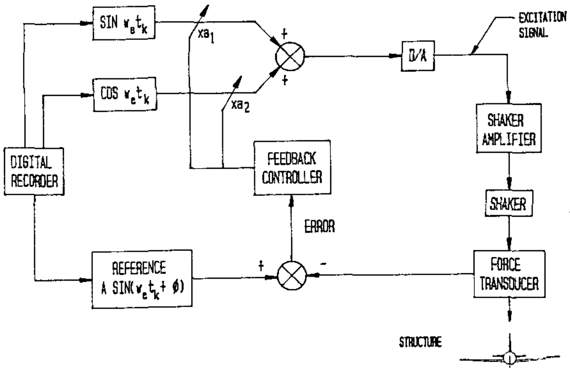

Figure 3. Diagram of Excitation Control

This system of force control has a number of advantages in ground vibration testing: firstly, by using the actual force transducer output as reference, rather than the excitation signal fed to the shaker amplifier we ensure that measured results reflect the behaviour of the structure without distortion by the presence of the shakers. It is well known that electrodynamic shakers add mass and damping to a structure; with force transducer reference, these effects are removed from the measurements. Secondly, because the controller can be set to maintain zero force at a particular transducer, it is unnecessary to disconnect the associated shaker from the structure when it is not in use. This eases the operator load during the test as he can begin by connecting all eight shakers to the structure at positions where they are likely to be required, and then need not waste time disconnecting and connecting shakers unnecessarily. Thirdly, logic may be included in the software implementation of the controller to ensure that neither the structure nor the test equipment is overloaded at any stage.

4.4 Implementation of Force Control in the GVT System

In keeping with the design philosophy of modularity and distributed processing, the excitation generation and control for eight force channels was implemented in software running on the general-purpose microprocessor controlling the D-A subsystem. This microprocessor performs calculations for sine-wave generation and control, and also controls the data flow for the eight D-A channels driving shaker amplifiers, and the eight A-D channels monitoring force transducer response. The test control software (and thus the operator) communicates with this subsystem over an Ethernet link, sending commands describing the excitation frequency, amplitude and phase for each of eight channels to the subsystem. This subsystem then generates the required forces independently.

4.5 Acquisition and Processing of Response Data

In broadband testing, the data required for analysis are a sampled time record for each response channel selected. In this mode, the A-D subsystem simply logs these records then transmits them to the workstation for analysis. These procedures are standard and will not be discussed in detail here.

The results required from sine testing of a linear structure are the amplitude and phase of the response, at the frequency of excitation, for a large number of transducers distributed over the structure. The testing is typically continuous, but its frequency characteristics do not change rapidly with time, unlike impact testing or other broadband methods. Unless a different approach is taken to the acquisition and processing of response data, the amount of data would be totally unmanageable. In the system described here, a combination of batch processing and the application of distributed computing power is used to provide the capability of presenting the amplitude and phase of up to 376 channels of response data up to an excitation frequency of 200 Hz at one extreme, or of 16 channels at 2.5 kHz at the other, using three subsystems each comprising a microprocessor controlling 128 A-D channels.

As described in section 3.3, the graphical operator interface presents the coincident and quadrature components of the response with a refresh period of the order of a second. In a sine dwell test, only the steady-state response is of interest and transient effects are not important. Because excitation is typically varied slowly during force appropriation, and because the settling time associated with typical lightly-damped aerospace structures is long, new data is not required instantaneously: it is adequate that new response data is avaliable to this interface every time the refresh begins. This refresh period is used by each subsystem to acquire and process the data from the response channels under its control in a batch processing mode. The data required by the interface is then transmitted, ready for the next refresh. By ensuring that the algorithms implemented on each subsystem are simple (without sacrificing accuracy) we ensure that the computational burden on each subsystem, and on the workstation, is approximately the same.

During every refresh period, the following operations are carried out by each microprocessor: first, data is collected by scanning all of the active channels a number of times until the data record for each channel covers one complete cycle of the response. Next the coincident and quadrature components for each channel are computed. In order to keep these calculations simple, a low-order discrete Fourier transform (typically using a data record of only 3-6 points) is evaluated for the excitation frequency only.

The A-D converters used in this system do not sample all channels simultaneously. While A-D systems with simultaneous sampling are available, they are more expensive and the problem of compensating for the delay between channels is not a serious one, provided that each delay is known. The time taken for A-D conversion is not a constant, so it was necessary to use the microprocessor clock to trigger each conversion separately. The interval between samples of different channels is then known precisely. This time interval corresponds to a specific phase lag at the frequency of excitation. After the coincident and quadrature components of each channel have been derived, therefore, they must be corrected for this phase lag.

The results of these calculations are then transmitted to the workstation where they are first divided by the reference response (one of the force transducer channels) then included in a moving average. This process is continuous.

A potential disadvantage of using short data records, combined with using a sampling frequency which is not necessarily an integer multiple of the excitation frequency, is that because exactly one cycle of the response data may not be covered by the time record, spectral leakage may result. Because the sampling rate can always be set to be extremely close to the ideal sampling rate, however, it is found that the errors introduced by this inaccuracy are not significant when compared to quantisation errors in the 12-bit A-D system and noise levels on the response signals.

4.6 Dynamic Range Considerations

The quantisation levels of D-A and A-D convertors are fixed. In dynamic tests, the dynamic range of measured responses is large. If signal levels are fixed before conversion, therefore, the resolution of low-level measurements will be extremely poor. It is essential to make use of the entire dynamic range of the convertors for all measurements, since accuracy at low-levels can be as important as that at high levels. To remove this problem, the test system uses the maximum possible gain setting of the programmable transducer amplifiers to ensure that all signals entering the A-D system are at sufficiently high levels. The gain set for each channel can then be read by software running on the workstation, and included in measured data as part of the calibration factor. In this way, potential resolution and dynamic range problems associated with the digitization of response data can be avoided.

5. Conclusions

The GVT system described has been designed for flexibility and adaptability. The modularity of the system ensures that future developments, including the incorporation of new analysis methods or new hardware, may easily be incorporated to enhance the quality of test results. Where possible, general-purpose hardware has been used to keep costs down. Shortfalls in testing introduced by such hardware have been compensated for in software. Potential disadvantages of the replacement of many of the functions previously requiring dedicated analogue hardware by software have been removed without any loss of system accuracy. This has resulted in a system capable of operating in both broad band and sine dwell testing modes.

At the same time, the introduction of a graphics interface between operator and test system has removed much of the difficulty associated with the force appropriation required in tuned sine dwell testing. By presenting response information from all the instrumentation channels in a clear format, the quality of isolation is made immediately obvious to the operator. In addition, problem areas on the structure can be immediately identified, so that required changes to exciter positions are also obvious. This information allows force appropriation to be completed quickly and efficiently, so removing a major disadvantage from the sine dwell testing method. Use of this system thus provides the accuracy and reliability of tuned sine testing, combined with an efficiency which, it is believed, will compete with that of broad band methods.

Future development of the system will involve the incorporation of automated methods of testing, including broad band parameter estimation methods and automation of force appropriation.

6. References

1. R.C. Lewis and D.L. Wrisley: "A System for the Excitation of Pure Natural Modes of Complex Structures"; Journal Of Aeronautical Sciences, vol 17, no 11, pp 705-722, 1950.

2. J.E. Anderson: "Another Look at Sine Dwell Testing"; Proc 22nd Structures, Structural Dynamics, and Materials Conference, pp 202-210, April 1981.

3. D.L. Hunt, H. Vold, E.L. Peterson and R. Williams: "Optimal Selection of Excitation Methods for Enhanced Modal Testing"; Proc 25th Structures, Structural Dynamics, and Materials Conference, pp 549-553, 1984.

4. R.C. Stroud: "Excitation, Measurement and Analysis Methods for Modal Testing"; Joint ASCE/ASME Mechanics Conference, Albuquerque, New Mexico, June 1985.

5. E.J. Breitbach: "Recent Developments in Multiple Input Modal Analysis"; Journal of Vibration, Stress and Relibility in Design, vol 110, pp 478-484, Oct 1988.

6. E. Bonneau: "Determination of the Vibration Characteristics of a Structure from the Expression of the Complex Power Supplied"; La Recherche Aerospatiale, No 130, pp 45-51, 1969.

7. L.R. Rabiner and B. Gold: "Theory and Application of Digital Signal Processing"; Prentice-Hall, 1975.

8. M.W. Kehoe and D.F. Voracek: "Ground Vibration Test Results of a Jetstar Airplane using Impulsive Sine Excitation"; NASA TM-100448, 1989.

9. D.L. Hunt, H. Vold and R. Williams: "Modal Testing Using Modern Sine Excitation"; Proc International Modal Analysis Conference, 1990.