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AN ABSTRACT GROUND VIBRATION TEST SYSTEM
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Abstract: The requirements for modal testing of manned aircraft are not demanding in terms of frequency range, size or weight of sensors, or power required to perform the tests. Yet typical GVT systems used for this purpose are expensive and the inner workings are often obscured from the user. This paper presents a concept for an affordable and relatively easy to construct GVT system. The system makes use of distributed computing and the CAN bus.

1 INTRODUCTION

Ground vibration testing of aircraft is commonly required for two reasons: for new aircraft that need to be certified, and for military aircraft that need to carry a new combination of external stores. The results of a ground vibration test consist of the full set of natural modes within a prescribed frequency range. There are two predominant means of performing the test: phase resonance (sine dwell) or phase separation (sweep or random) [1]. In the case of sine dwell testing it is required to let the airframe oscillate in each of its natural modes in turn. Once this is achieved the mode shape and modal parameters are measured. The process is time consuming, but no further processing is required. In the case of sweep or random testing the aircraft is excited from a number of positions. The selection of these positions is not trivial, but is not discussed here. The excitation consists of either a swept sine or random input covering the frequency range. Transfer functions are measured between the input forces and the responses at a relatively large number of measurement points. The test itself is quick, but post-processing is required to extract the mode shapes and modal parameters.

The CSIR has been providing a GVT service since 1978, initially using commercial GVT systems but building its own systems since 1990 [2]. The systems typically consisted of large, fixed, sine dwell type systems and small (i.e., few channels), portable, phase separation systems. The capability to perform sine dwell testing on a portable system was developed in the 2000s. This involved developing a user interface, signal generation and signal processing routines that run on a data acquisition processor (DAP) card. Along with this capability low-cost MEMS sensors were introduced. Integrated Electronics Piezo-Electric (IEPE) impedance heads are still used to measure driving point transfer functions. The result was a portable system capable of sine dwell and sweep or random testing with a high channel count.

The use of different types of sensors necessitated that sensor calibration is represented by rational polynomials and not by single calibration factors.

The next innovation was that the DAP card was replaced by distributed computing. Signal generator nodes, voltage input nodes and accelerometer nodes were developed by Bronberg Dynamics. The nodes are connected to each other and to a host computer via a CAN bus. The CAN bus has been around for about 30 years, is robust and serves the needs of the GVT system well [3]. The signal generator node's outputs are connected to the exciter amplifiers' inputs, the voltage input nodes' inputs are connected to the output of an IEPE signal conditioner, and the accelerometer nodes are each connected to 8, analogue output, MEMS accelerometers. This system does not have a sweep testing capability, although it can measure transfer functions in a stepped sine fashion.

The CSIR is presently busy with the development of the second generation CAN bus GVT system. In this system MEMS accelerometers with built-in scaling, filtering and digitization are used. Microcontrollers are used liberally. The system will have a sine dwell testing capability as well as a sweep testing capability. The system allows for simultaneous excitation using multiple exciters well as measuring air support dynamic loads. The air supports can also be used as exciters. The specifications of the system are presented. A hardware design is also presented, although the choice of hardware architecture is by no means prescribed or fixed. The purpose of the sweep testing performed using the system is merely to measure FRFs. The processing of FRFs to obtain modes is performed using other software. The procedure for sine dwell testing is also presented as it is the most interesting, even though not the most popular, method.

2 DESIGN PHILOSOPHY

The present paper deals mainly with the data acquisition part of a GVT system. Components that are not discussed include exciters and their amplifiers, and force transducers or impedance heads and their signal conditioner(s). It is assumed that force transducer or impedance head outputs are converted to voltage signals that are connected to the data acquisition system. Signal generation is discussed for both sweep testing and sine-dwell testing although a separate signal generator can be used for sweep testing.

Each accelerometer in the system has a unique number. The user needs to make a list of which accelerometer is mounted at which physical node, and in which orientation. It is immaterial how (i.e., to which accelerometer node) the accelerometer is connected to the system.

One convenient feature of CAN interfaces is that they can filter messages according to the message ID. This used to indicate whether a node needs to respond to a message. A node needs to respond to a message with an ID corresponding to the node's number, and ID equal to zero or an ID equal to 1024. An ID of 1024 is used to address all nodes, a number of zero is used for a trigger signal and an ID equal to a particular node number is used to send a message to that node. The message ID is also used to prioritise messages in case of a conflict – the message with the lowest ID number has priority. Conflict resolution happens without a time penalty – the node trying to send the lower priority message detects the conflict and stops transmitting. The other node simply carries on transmitting. Each node in the system sends messages with an ID equal to 1024 plus the node's number. The host PC uses IDs from zero to 1024 and always has priority. The only exception is during sweep testing when one of the other nodes sends the trigger signal.

Every component of the system is defined in terms of how it should react to a set of CAN messages. How the component is put together is immaterial. An example of a hardware implementation is presented, but the essence of the paper is the definition of the set of messages required to build a system. The number of messages is kept to a minimum but allows for some useful, non-essential, functions.

The present hardware implementation is based on the ADXL363 accelerometer which has built-in digitization, programmable gain and programmable anti-alias filters. The measurements are transmitted digitally for further processing which eliminates the errors introduced by poor contacts, long cables and interference. The challenge that is introduced is to trigger all the sensors simultaneously. This is done via the CAN bus and the use of dedicated (i.e., not multi-tasking) microcontrollers.

The use of a relatively slow data bus gives rise to the question of how scalable a system would be. The system uses many data buses – the primary one linking the host PC, signal generator, voltage input nodes and all accelerometer nodes, and the secondary buses linking the accelerometer nodes to the accelerometers. In sweep testing the time critical communication is between the accelerometer nodes the accelerometers. There will be a limit to the number of accelerometers that can be connected to a single accelerometer node, depending on sampling rate. This limit is in the order of 16 three-axis accelerometers. The amount of data that needs to be sent to the host PC over the primary CAN bus will be proportional to the number of accelerometers used and will affect the time taken to transfer the data to the host PC after a sweep. Sending a 512 line FRF should take in the order of one second.

In sine dwell testing much less data, the real and imaginary parts of the signals determined over each measurement cycle, needs to be sent to the host PC over the primary bus. The time required for sending of this data may exceed the length of the measurement cycle when many accelerometers are used, however, it is not necessary to send all the data for each measurement cycle. Since the data is only sent on request from the host PC, it is a matter of changing the host PC software to request a subset of the data. The only instance where all data is required is at the end of the mode extraction procedure.

3 IMPLEMENTATION

3.1 Sweep testing

The second generation CAN bus GVT system has sufficient memory on the nodes to allow the storage of time histories and the calculation of FRFs on the nodes. For sweep testing a common sampling clock is required due to the potentially long sampling times. This is achieved by letting the node measuring the reference input force, transmit the measurement over the CAN bus. This serves as a sampling trigger and also distributes the reference signal for calculating FRFs to all the nodes. The procedure for calculating FRFs is not discussed here. The analyst can specify the number of samples in the sweep, sampling rate, type of FRF, type of window and overlap factor. The signal generator can either be separate from the data acquisition system, or it can be a CAN node. In the latter case the signal generator needs to know the start and end frequencies, duration and force amplitudes.

3.1.1 CAN messages

The CAN messages used in the system can be divided into three groups: those sent by the host computer to all nodes at once, those sent by the host computer to a single node, and the messages sent by the nodes. Table 1 lists the messages sent to all nodes at once,

Table 2 lists the messages sent to a specific node, and Table 3 lists the messages sent from the nodes.

- Message 1 is the trigger signal for the nodes to start measuring.
- Message 2 resets all nodes. This is similar to cycling power. Each node will then start transmitting its own ID (message 14) until acknowledged by message 6.
- Message 3 sets the sampling rate and number of samples to take.
- Message 4 is used to inform the nodes of the window type and overlap, and FRF type.
- Message 5 arms the nodes for a sweep test. The nodes will then wait for message 1.
- Message 6 is used to inform a node that its ID has been detected. The node will then stop transmitting it.
- Message 7 is used to request the current value of an input channel. The node will respond with message 16. This is not used during testing, mainly for fault tracing.
- Message 8 is used to set the gain for a specific channel.
- Message 9 requests the node to send its current gains to the host computer (message 15). This is also not essential but used to confirm the gain of a channel.
- Message 10 transmits the sweep parameters to the signal generator mode, if a CAN bus signal generator is used.
- Message 11 tells the node the that measures the reference force to start a sweep by transmitting a trigger message at the desired sampling rate, along with the reference force readings.
- Message 12 requests a node to send an FRF to the host computer. The node will respond with multiple message 17s. Each message 17 transmits one value of the FRF.
- Message 13 requests a node to send a time history to the host computer. The node will respond with multiple message 18s. Each message 18 transmits two values of the time history. This function is also not generally used, but is available for troubleshooting.

The number of messages required is small and the associated functions are relatively easy to program. The calculation of the FRFs on the nodes is not discussed here (to keep it easy).

Table 1: Messages sent to all nodes for sweep testing.

Message number	**Message**
1	Trigger
2	Reset
3	Sampling rate and number of samples
4	Window and FRF parameters
5	Arm (for sweep)

Table 2: Messages sent to specific nodes for sweep testing.

Message number	Message
6	Acknowledge
7	Send channel data
8	Set channel gain
9	Send current gain settings
10	Signal generator sweep parameters
11	Start sweep
12	Send FRF
13	Send time series

Table 3: Messages sent by nodes for sweep testing.

Message number	Message
14	ID
15	Gain settings
16	Channel data
17	FRF data
18	Time series data

3.1.2 Data processing

Upon receiving a trigger signal on the primary CAN bus the accelerometer node triggers all the accelerometers connected to it on the secondary buses, then reads the data from them and stores it in memory. It also saves the reference force reading received along with the trigger message. After the last data point has been read, the node calculates the transfer function from the reference force signal to each of the acceleration signals. This transfer function is from one series of 12-bit numbers to another. Each transfer function is transmitted to the host PC when requested. The host PC keeps track of sensor gains and transfer functions to arrive at the transfer function in engineering units.

The voltage input nodes measuring force inputs and impedance head accelerations (if used) perform the same actions. It is possible to use simultaneous force inputs (and when an aircraft is supported on air supports, the dynamic support forces are measured) and the transfer functions from the reference force to all the other forces are calculated.

3.1.3 User interface

An interface is provided for the analyst to set up the sweep parameters and monitor the sweep. Monitoring is through time histories transmitted on the CAN bus between signals. The number of time histories that can be plotted is limited by the sampling rate. The signal generator start and end frequencies, sweep duration and force amplitudes can be set. The sweep interface, with the signal generator setup window in the foreground, is shown in Figure 1. During the sweep time traces can be displayed in the graph areas.

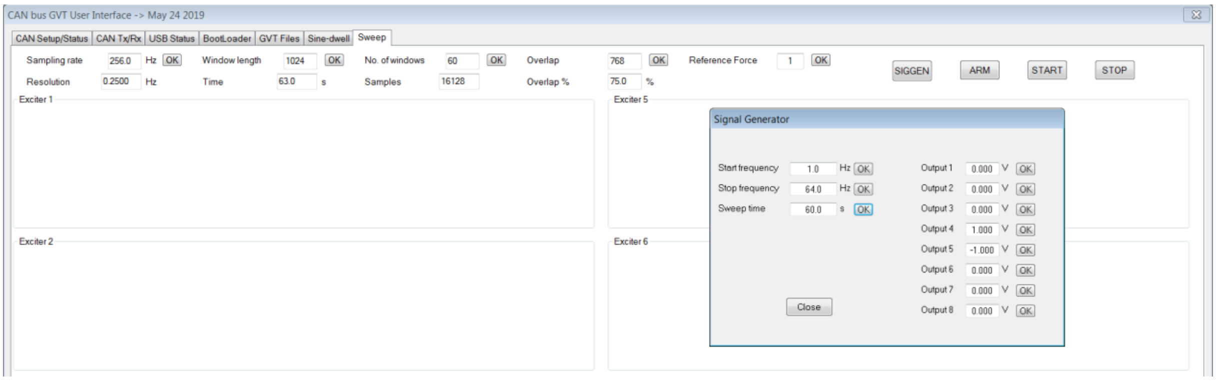

Figure 1: User interface for sweep testing.

3.2 Sine dwell testing

Although less popular than sweep testing, sine dwell testing offers some advantages in terms of control over the power input, which is relevant for non-linear structures. As far as the GVT system is concerned it is more complicated as the excitation needs to be accurately controlled by the system. The response of the structure is measured over periods of a small number of complete cycles of the excitation frequency. The sampling period is usually between 0.5 s and 2 s. Each node uses its own clock to perform the sampling, but they all start measuring when they receive a trigger signal from the host computer.

3.2.1 Basic requirement

The basic requirement is to force the aircraft to vibrate in each of its natural modes in turn. The implications are that the vibration of each point on the aircraft should be perfectly in phase or perfectly out of phase with all other points. The applied forces should likewise be in phase or out phase with each other, and also with the responses. The analyst has at his disposal a number of exciters that can be attached to different points on the aircraft, he has control over the frequency and over the force amplitudes. The requirement can usually not be perfectly met. A measure of the phase difference between the responses is usually used as indicator, typically appropriation or a mode indicator function. It is a challenge to most humans to achieve good modal isolation. The present software has some automated features for frequency control and for force control.

3.2.2 Excitation control

The excitation is usually applied to the aircraft by electro-magnetic exciters through impedance heads. The impedance head is a high quality sensor and is used to calculate the complex power input. The current or voltage is supplied to the exciter by an amplifier. Amplifiers can either be current amplifiers, where the output current is proportional to the input voltage, or voltage amplifiers, where the output voltage is proportional to the input voltage. It should be appreciated that exciters generate a significant back emf as soon as they move - they are actually powerful dampers. If a voltage is applied to the exciter, part of the voltage is resisted by the back emf and the remaining part induces a current through the exciter. The excitation force is proportional to the current.

Current amplifiers are attractive because the force varies very little with the response of the structure. Voltage amplifiers require adjustment of the input voltage in order to achieve the required force. Because of the damping introduced by voltage amplifiers, the settling time after a change is reduced. Another advantage of voltage amplifiers is that they allow for testing very light structures in a response control mode. The approach taken in the present work is to use voltage amplifiers and software feedback to adjust the input voltage to the amplifier in order to obtain the desired force. If current amplifiers are available they could be used without any change to the GVT system, although response control testing would not work.

Determining the output voltages required to be sent to the amplifiers is not trivial. When using electro-mechanical exciters placed so that they do not have a strong mutual influence, it is sufficient to control each exciter individually. The error is known from each measurement cycle. The error is divided by the exciter transfer function (either force or velocity) and the result is added to the output voltage.

When exciting through the pneumatic supports the mutual influence is so great that individual control cannot be used. A matrix control algorithm is implemented in which the influence of a voltage change in each output, on the force at each exciter, is measured. The error is regarded as a vector and is multiplied by the inverse of this influence matrix. This procedure can be used under all circumstances, but may be slower than the simpler method.

3.2.3 Frequency control

When using several excitation forces, it is not obvious how to construct a phase reference. This is where the concept of complex power is useful. The real part of the complex power is the power that flows only into the structure. It is dissipated by the structural damping. The imaginary part of the complex power flows into and out of the structure. It is temporarily stored as elastic potential or kinetic energy in the structure. At the natural frequency the imaginary part of the complex power is zero. The complex power is calculated from the force and response at each exciter, it is the sum of the products of force and the conjugate of velocity at each exciter. In the vicinity of a mode there is a simple rule that relates the phase of the complex power to the frequency. This rule is implemented in the software to relieve the analyst of continually having to make frequency adjustments.

3.2.4 Appropriation

Assuming one has a system that can apply specified forces at the modal frequency, the next step is to adjust the forces in order to get the structure to vibrate in phase. For a small number of exciters a human can perform this task well, but not for more than two or three. The software incorporates a procedure for doing this automatically. The force adjustments will get the force and velocity at each exciter exactly in phase, but this may not be sufficient. Exciters may need to be moved around, or removed, or added. The software does not do this, nor does it prescribe where to add or remove exciters. The analyst needs to make a judgement from the phase errors in the mode shape displays.

3.2.5 Modal extraction

Once the structure is vibrating in phase, it is a simple matter to measure the mode shape. The modal frequency is also known exactly. There are, however, two modal parameters that are not obvious: the modal mass (how much mass is moving) and the modal damping. To measure these parameters requires the frequency has to be varied by a small amount around the modal frequency. The modal mass and damping is estimated from the value of the real part of the complex power and the slope of the imaginary part with respect to frequency.

3.2.6 Signal generation

The signal generator node contains a number for D to A converters, one for each output channel. The D to A converters are clocked at a fixed rate. The reference signal is calculated as a sine and a cosine wave. Over each output clock cycle it is advanced by an amount that corresponds to the clock rate and the set frequency. The host computer calculates the numbers $\sin(\omega dt)$ and $\cos(\omega dt)$ and sends it to the signal generator mode via the CAN bus. Each force's complex number representation is multiplied by the phase signal and the real part of the result is applied to the relevant D to A converter. A band pass filter is applied to the output signals for smoothness and for protection against over-voltage.

3.2.7 Response measurement

The fact that the excitation is applied at a fixed frequency implies that the real and imaginary parts of the signal can be calculated as a linear combination of a number of response measurements. This is done in the form of a matrix multiplication. The host computer calculates the matrix, which has two rows, and sends it to every node in the system (except for the signal generation node). The matrix is the biggest block of data that needs to be sent over the CAN bus, fortunately it is sent to all nodes at the same time. Each node calculates the cumulative sum of the matrix and sends it back to the host computer to verify proper reception. Upon receiving a trigger signal, each node starts sampling a pre-determined number of samples of the inputs connected to it and multiplies each measurement array by the matrix. The result is the real and imaginary parts of the signal. These are sent to the host computer via the CAN bus.

3.2.8 Command set

The additional commands that need to be sent over the CAN bus to implement a sine dwell GVT system are presented. Some of the messages defined for sweep testing are also used in sine dwell testing.

Table 4 lists the messages sent to all nodes at once, Table 5 lists the messages sent to a specific node, and Table 6 lists the messages sent from the nodes.

- Message 19 is used to transmit the matrix for calculating real and imaginary parts.
- Message 20 arms the nodes. They will then wait for message 1.
- Message 21 sets the amplitude and phase of an output channel on the signal generator node.
- Message 22 sets the output frequency on the signal generator node.
- Message 23 requests the node to send the cumulative sum of the matrix that it had received. The node will respond with message 25. If it is not correct a warning is generated.
- Message 24 requests the node to send the results of a measurement for a specific channel. The node will respond with message 26.

The number of messages needed to add a sine dwell GVT capability to the system is not prohibitive. Most of the complicated work is internal to the user interface.

Table 4: Messages sent to all nodes for sine dwell testing.

Message number	Message
19	Parameter data for sine dwell
20	Arm (for sine dwell)

Table 5: Messages sent to specific nodes for sine dwell testing.

Message number	Message
21	Signal generator amplitude
22	Signal generator frequency
23	Send cumulative sum
24	Send result

Table 6: Messages sent by nodes for sine dwell testing.

Message number	Message
25	Channel result
26	Cumulative sum

3.2.9 Data processing

The host computer continuously receives the response data from the system in the form of real and imaginary parts of the measured signals. Real and imaginary is with respect to the trigger signal and has no physical meaning. The data is processed as follows:

- The transfer functions of all the sensors are applied to obtain data in engineering units.
- A phase reference is calculated from the forces, or from the velocities at the exciters in response control mode.
- The phase reference is applied to all channels.
- All accelerations are converted to velocities.
- Complex power is calculated
- Structural settling, excitation control and appropriation parameters are calculated.
- All data is displayed on the user interface.

Depending on what the analyst requested a number of excitation control tasks are performed during each measurement cycle:

- Excitation control.
- Frequency control

A number of higher order functions can also be performed:

- Appropriation, i.e., setting the excitation amplitudes to minimize the appropriation criterion.
- Stepped sine transfer function measurement
- Modal extraction

3.2.10 User interface

The user interface should allow the analyst to control the testing and get an impression of the structural behavior. The general layout of the user interface is shown in Figure 2. The interface has a number of “pages”, the one shown is the sine dwell testing page. The others include a CAN bus status page, a file handling page and a sweep testing page. The overall controls are arranged at the top of the screen. The exciter controls are on the left and the responses on the right. A stepped sine test window is open in the foreground.

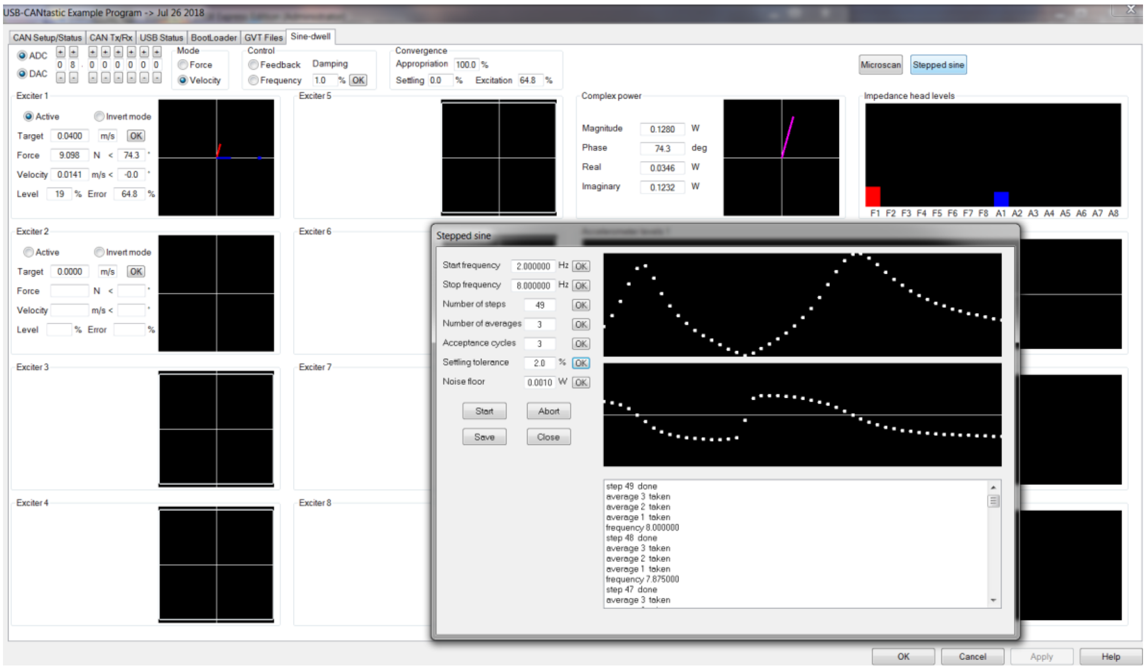

Figure 2: Sine dwell user interface

The details of the overall controls and an exciter control are shown in Figure 3. From left to right there are buttons for tuning input and output on and off, a window for setting the frequency manually, a selection of force control or response control modes, a button for activating the excitation control loop, and a button for activating automatic frequency control. The estimated damping value is used by the frequency control function.

In the exciter control the analyst mainly specifies the target force or response value. The actual force and velocity are shown as complex numbers and the force and velocity vectors are plotted on the right, blue representing velocity and red representing force. The target value is shown as a dot on the real axis. The fraction of the available output being used is displayed at the bottom, as well as the error between the specified and measured force level.

The complex power feedback is shown in Figure 4, both plotted as a complex vector and in numbers. This is the main indicator for frequency adjustment. The value of the real part of the complex power is also significant for modes that show non-linear behaviour. The modal parameters can be a function of the amplitude at which the mode is extracted, and the power is a convenient indicator of amplitude.

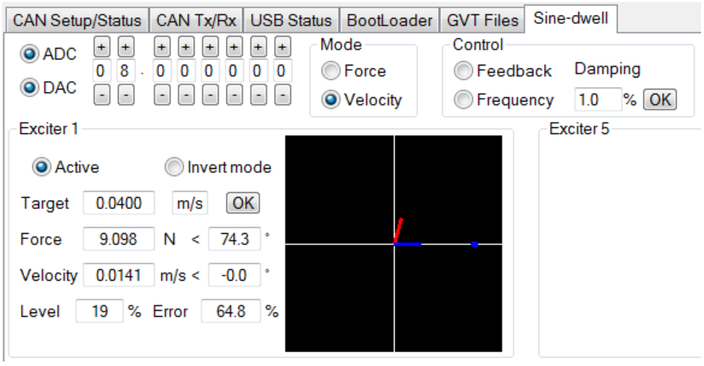

Figure 3: Detail view of the overall controls and exciter control

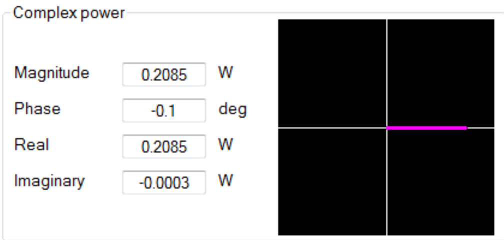

Figure 4: Detail view of the complex power feedback

The detail of the mode extraction interface is shown in Fig. 8. The frequency range, number of steps and convergence parameters are specified by the analyst. The complex power real and imaginary parts are plotted on the right, and the measured parameters displayed at the bottom. The mode shape is written to a .u55 file.

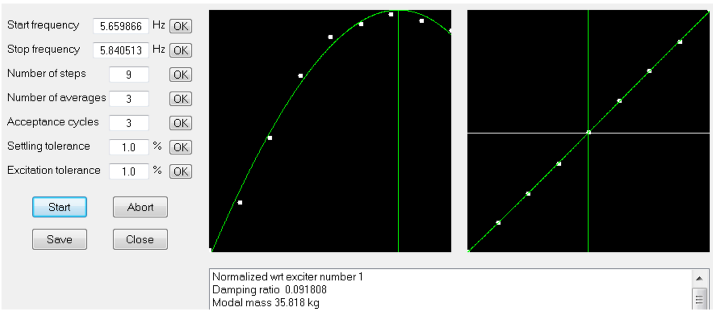

Figure 5: Detail view of the mode extraction interface

3.3 Hardware

There is generally no limitation on the hardware that can be used to build a GVT system – each component must simply respond to messages in the agreed manner. The host computer can be a standard desktop or laptop computer. It will most likely use a USB to CAN adapter to communicate with the system, and possibly a USB to RS232 adapter to control the IEPE signal conditioner. The host computer software is written in Visual C++ 2008, which is freely available.

It is convenient to use a Eurocard format for the signal generator and voltage input cards, and mount them in a 19 inch rack along with the necessary power supply to power the system. The present system is shown in Figure 6 during programming of a voltage input card. Signal generator and voltage input cards are shown in Figure 7 and Figure 8.

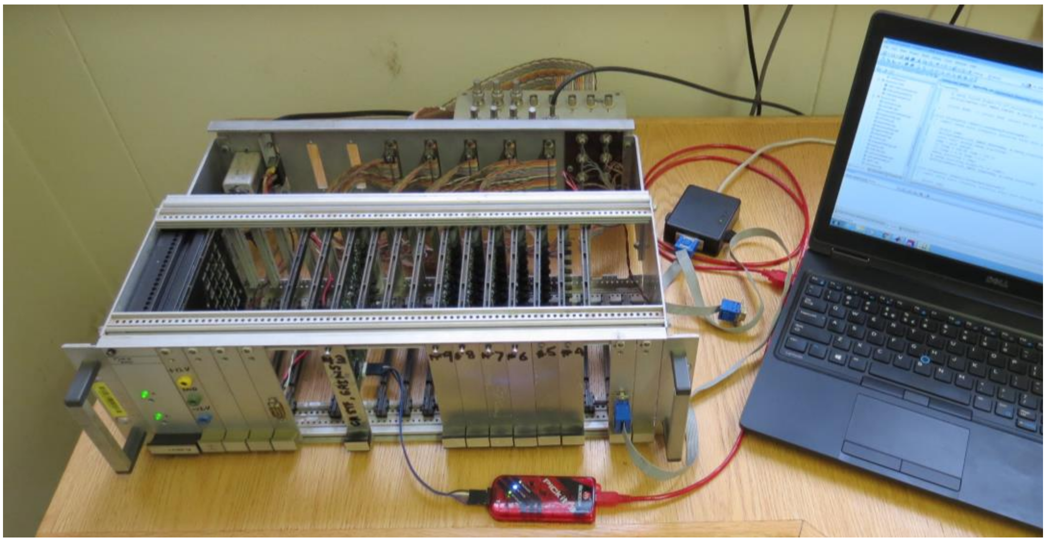

Figure 6: Eurocard rack with voltage input cards installed

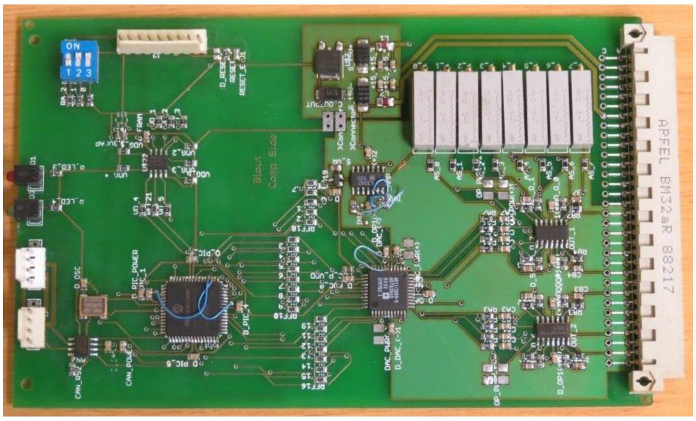

Figure 7: Signal generator node Eurocard

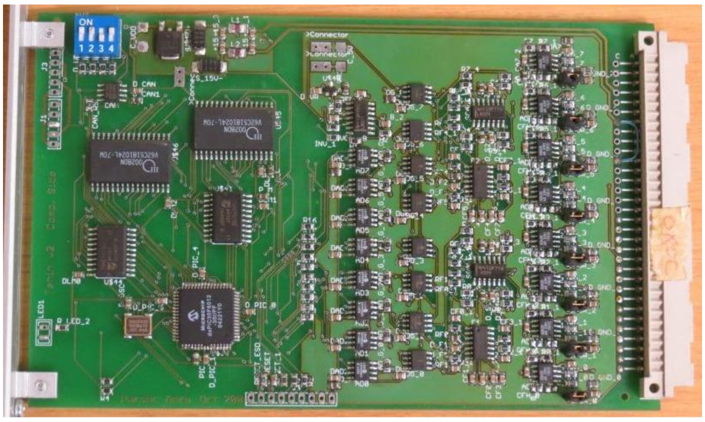

Figure 8: Voltage input node Eurocard

The second generation's accelerometer nodes have more than one CAN bus, the first to connect to the other nodes and the host computer and the rest for connecting to its accelerometers. A printed circuit board of 12 accelerometers and two accelerometer nodes with components installed is shown in Figure 9.

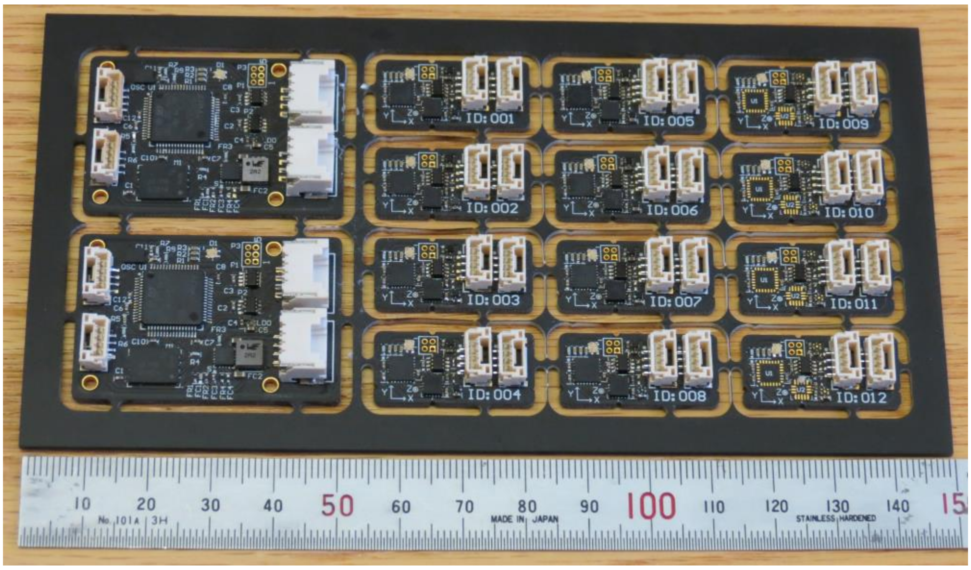

Figure 9: Accelerometer nodes and accelerometers

The accelerometer selected for the second generation CAN bus GVT system is the tri-axial ADXL363. This sensor has a programmable range of +/-2g, +/-4g and +/-8g. It also has built-in digitization and programmable anti-alias filters. The maximum sampling rate is 400 Hz, which should yield reliable GVT results up to 100 Hz. The digital interface of this sensor is ISP, they are therefore packaged with a micro-controller in order to connect to the CAN bus. The PCB with the accelerometer, microcontroller and CAN connector is no larger than the PCB with the analogue output accelerometers of the first generation system.

The CAN bus system simplifies the wiring of a GVT considerably. The accelerometer nodes are connected to the CAN bus in daisy-chain fashion. The accelerometers of the second generation system are also connected in daisy-chain fashion, typically 8 on a single bus. For example, a setup with 128 tri-axial accelerometers on the aircraft will require 8 accelerometer nodes. A single cable will run from the host computer to all of these nodes in a daisy chain. From each accelerometer node two CAN bus cables will run to eight accelerometers each, also in a daisy chain. Therefore a total of 16 cables will run to the aircraft. It is quite conceivable to fix the accelerometer nodes to the aircraft, which will mean one CAN cable running to the aircraft.

4 CONCLUSION

The design considerations of a GVT system capable of sweep and sine-dwell testing have been presented. The system is based on the concept of distributed computing power connected by a CAN bus. Apart from the host computer there needs to be a number of CAN nodes that perform certain functions and respond to messages in a specific way. How these nodes are realized is not limited. The system can be fully functional with a total of 26 CAN messages.

The system should be a viable alternative to more expensive commercial systems, at least as far as manned aircraft is concerned. It is hoped that this specification will bring the construction of GVT systems within the reach of more companies and people.

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