Virtual Instruments
The Future for Vibration Measurement and Analysis

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Introduction: Virtual instrumentation has become a common topic of discussion at various technical seminars and between test equipment users. The recent buzz has created quite a bit of interest from different user groups ranging from traditional instrumentation manufacturers to test and measurement professionals trying to perform common measurement tasks.

Virtual instruments (VI's) provide a maturing technology for general test and measurement functions that rely heavily on leveraging computing capabilities of commercially available computer hardware such as personal computers. These devices are rapidly replacing traditional dedicated test equipment by providing identical function with added flexibility using various programming tools that are becoming more practical for common users to successfully implement.

The capability of virtual instruments can now provide relatively quick development of user solutions for both instrumentation developers as well as end users.

Benefits: There are some certain benefits to using VI that are the primary draw including:

- Lower cost data acquisition systems (due to using relatively "cheap" PC's and laptops)
- Capability of quickly building or modifying basic measurement or analysis applications
- Significantly improved portability of hardware
- Flexibility of common data acquisition hardware to perform vastly different measurement tasks
- Tremendous analysis capability of data using on-line or off-line methods

Properly designed applications using virtual instrument tools can replace the following hardware in use today:

- FFT analyzers
- Oscilloscopes
- Volt meters
- Tape recorders (with much higher channel counts and frequency range compared to FM recorders)
- Transient monitoring tools
    - Order tracking devices
    - Bode, Polar, Shaft Centerline plots
    - Waterfall plots
    - Trending
- Modal analysis
- Operating deflection shape data gathering
- Sound levels meters
- Seismic surveys
- Field and shop balancing
- Vibration monitoring and protection systems
- Process controls
- And almost any other instrument involving measurement of signals (voltage, digital inputs, RTD's, thermocouples, 4-20 mA current loops, etc.) and processing of results

History: Before a discussion can be started regarding the current status of VI as it relates to vibration and machinery health monitoring, it would be helpful to review the history of measurement technology. Since VI advancements are quickly replacing traditional instruments, the example below is used to help describe the technology and why this trend is likely to accelerate.

One of the major technology tools used in vibration analysis is the Fast Fourier Transform (FFT). Since the first instrument was developed for calculating and displaying FFT's, the "box" has included four common elements: analog signal processing, data acquisition (digitizing waveforms), calculations (FFT's), and user display.

The application of FFT technology is likely very familiar (to the >40 year old crowd) on devices like the HP 3582a as shown below that was sold in the mid/late 1970's. This was one of the work horse FFT analyzers available 30 years ago for use in the sound and vibration areas.

This instrument does some analog filtering of input signals (anti-alias filtering), digitizes waveforms, performs various FFT calculations, and then displays either time waveforms or FFT plots on the very large for the day cathode ray tube (CRT). This instrument was very dependable, could tolerate tremendous abuse and weighed a mere 28 lb. A single data block could be stored at the push of a button (hold) and easily plotted on a 25 lb flat bed pen plotter. These weights are excluding cables and shipping cases, or auxiliary equipment we all used like accelerometer power racks, oscilloscopes, etc. A typical "simple" test would often require hauling about 200 lb of test equipment with at best two channel analysis. Simultaneous analysis of more channels required the use of FM tape recorders (my TEAC 21 channel recorder weighted 68 lb in the shipping case).

This instrument is typical of traditional special purpose test equipment. The hardware and internal software are highly tailored to performing a specific task, and cannot be modified by the end user. Such a device will normally start (power up) rather quickly and, after going through some sort of self test on the hardware and software, function as described in the owner's manual. Due to the specific functional design and focused purpose, these instruments are very dependable, accurate, and well understood because every unit of similar model will function exactly the same. Calibration can be easily done to known standards and well published specifications.

In comparison to dedicated analyzer products in use today with the same basic function, FFT's can be produced by a variety of devices known today as virtual instruments. These devices have the same general function as the custom instruments from days of old, but accomplish most of what they do by leveraging the capabilities of currently available computer technologies. Since the function of these tools are generally designed to fit a broader marketplace than just FFT display for sound and vibration testing, the potential for these products is rapidly changing the nature of test and measurement processes by increasing channel counts, measurement resolution, sample rates, and greatly reducing the cost of data acquisition hardware.

Hardware: The most basic hardware included in virtual instrumentation that is used for vibration and noise measurements includes time waveform digitizing devices that are connected to computers using a variety of commercial interfaces: ISA, PCI, compact PCI, PXI, USB, Serial Port, Parallel Port (EPP), ethernet, etc. These interfaces have been common "handoff" points from the manufacturer of the actual digitizing hardware and the software tools on the computer.

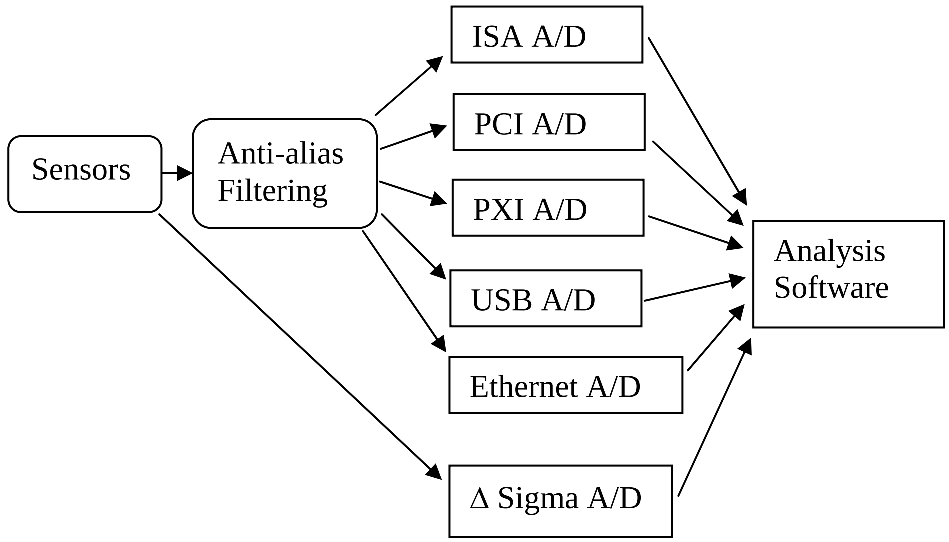
Since the hardware is designed using common computer platforms, general purpose drivers are provided along with the measurement hardware to distance the user from having to have any special hardware knowledge about the digitizing device. Using this method, the following series of activities are required to build VI hardware:

1. Specialized companies develop data acquisition devices using currently available hardware
    a. The hardware can use a variety of different capabilities, 12 bit, 16 bit, 24 bit, etc depending on the needs for the measurement
    b. Chip improvements by electronics suppliers can be incorporated in device upgrades or new products
2. These same specialized companies provide hardware drivers normally written in a very low level computer code (assembler, ANSI c, C++, etc.) that is specially tailored to the function of the specific hardware.
    a. These drivers provide hardware independent data acquisition methods that look the same from the programmer's view even though the actual hardware may be significantly different
3. Graphical programming tools (Labview, MatLab, etc.) provide relatively user friendly methods to gather raw data from the hardware data acquisition devices with the user having no interest in or need to know the details of how the acquisition hardware functions.
    a. Simple read commands/blocks provide data blocks of required formats for downstream processing
    b. These tools provide some "canned" routines for common analysis functions
        i. FFT's
        ii. FRF's
        iii. Order processing
        iv. Triggering
    c. These graphical programming tools are making sound and vibration measurements possible for non-programmers

Some of the key features of this type of instrument design process are that common analysis processes can be implemented for a variety of different hardware devices in a way that keeps the hardware details isolated from the programmer. The description below may be a better way to understand the process:

Almost any hardware platform can be used for the actual data acquisition including any computer interface or bus type and still allow the programmer to interface with basic measurements without any detail knowledge of how the device actually works. Many data acquisition programs or user solutions can be used to perform similar measurements using multiple hardware types.

The tremendous benefits of this sort of approach is that software tools can be developed to accomplish certain measurement tasks without having to design the program specifically for a particular piece of data acquisition hardware. Upgrades of hardware or software elements can often be done with only minor changes to programs.



Building Virtual Instrument Tools: Building VI tools to replace traditional instruments must be done carefully to make sure that key technical elements aren't bypassed. If care is not used to design and implement the VI, serious technical shortfalls can occur. Items to carefully consider:

- Signal sources must be compatible with the data acquisition hardware
  - Voltage range on the device must not be exceeded
  - Are signals truly single ended, double ended, or floating
  - Ground loop prevention
  - Possible impedance mismatching
  - AC/DC sampling type
  - Frequency range of the card (max sample rate)
  - Is the resolution adequate for the measurement (12 bit, 16 bit, 24 bit)
- Is analog signal processing included in the device, or does it need to be provided externally
  - Anti-alias filtering is not included in most data acquisition devices
  - Signals with large DC voltages (such as IEPE accelerometers) can exceed the range of the device, and certainly provide much lower signal resolution if the DC signals aren't removed prior to sampling
  - Is it necessary to attenuate signals to maintain voltage ratings on the device
  - Are all the common leads for each signal source at the same potential (different voltage potential on the negative lead for some devices can damage the device)
    - Some cards internally connect the negative inputs, providing a great source for a ground loop (can produce signal noise)
  - Is it necessary to power sensors
    - IEPE power to accelerometers
- Software must be tested and validated
  - Since all signal scaling, digital conditioning, etc. is done within software, there is much less control of the results unless there is good control on the software
  - Testing of the application must be exhaustive to verify that some conditions will not produce erroneous results
- Error trapping and self-testing is mandatory
  - Conditions that can produce invalid measurements or improper calculations need to be trapped in the software to notify the user

    - Hardware interface errors (USB devices not connected, remote device not powered, etc) need to be handled in code to prevent system crashes
- Backups and compiled code
    - Appropriate backups need to be maintained for all program elements
    - Compiled versions of all programs should be used for final applications to help prevent them from not working if some computer feature is upgraded or changed
        - Compiled versions are less sensitive to system changes, programming toolkit upgrades, etc.

Selecting an A/D Device: There are many different analog to digital (A/D) devices to choose from. The differences range from performance specifications ("high" frequency and "low" frequency), computer interface methods, signal connection methods, device packaging, etc. With all this variation, there is certainly no single device that is preferred for all measurements.

Some of the key differences between performance specifications include:

- Simultaneous sampling vs. multiplexing
- Sample rate
- Single ended inputs vs. differential
- Resolution (12, 16, 24 bit)
- AC/DC coupled inputs
- Full scale voltage range
- Channel count limits
- Bus speed

Simultaneous sampling refers to a multichannel device that is capable of sampling all the channels at the same time. When this occurs, each sample point on the waveform plots for each channel were captured from the A/D device at the same time. Multiplexed devices can function in two forms, either sampling many values from each channel then progressing to the next channel, or sampling one sample from each channel sequentially. The more common method with multiplexed devices is to sample one point from each active channel sequentially, resulting in a slight phase delay between measurements.

Simultaneous sampling devices tend to be a bit more expensive due to the higher count of actual A/D circuits required, but produce very nice phase accurate data right off the device.

Multiplexed devices can be used to produce "synchronized" data by sampling the active channels sequentially and correcting in software to remove the phase offset by using down-sampling and re-alignment algorithms. When properly implemented, this method can produce multi-channel streams that are phase accurate and are similar to simultaneously sampled data.

Sample rates continue to increase as microprocessors are improved and new A/D chips are developed. Sample rates in the megahertz and gigahertz range are now available in a variety of different interfaces. Most vibration and noise measurements can be limited to a maximum sample rate of about 50 kHz, since the highest audible frequency is about 20 khz.

Devices with simultaneous sampling will have a rating on the A/D that will define the maximum sample rate. This rate will be the same maximum for one active channel, or all channels active. Cards that multiplex will have a maximum sample rate for the A/D circuit that has to be shared by the number of active channels. For instance, a multiplexing card with a 200k sample/second maximum rate will only sample 16 channels at 12,500 Hz. This would provide a useful frequency range (FFT's) of 4,880 Hz.

Low cost A/D devices are most commonly single ended input type cards. This means that all the signals are assumed to have the same ground (common or – lead) potential. This may or may not be the case, depending on the signal sources. Multiple signal sources (different instrument racks or type of sensors) pose the greatest problem since grounds could be different from one instrument to the other.

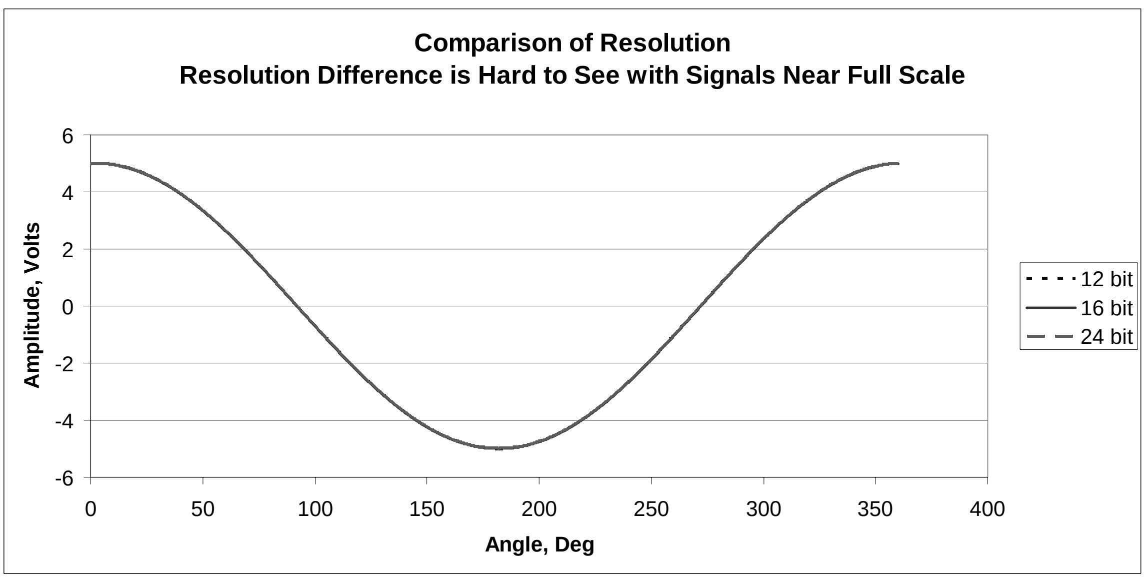
Differential input devices are equipped to have the + and – leads fed through separate A/D circuits so that both signals are measured and the difference reported to the software. Since the differential configuration requires twice the A/D circuits, many cards will have 50% the channel count when in differential mode compared to single ended mode. Specialized analog input hardware can be used to assure that all incoming signals are sent to the A/D board as a true differential signal, while still using the cost value of single ended A/D technology.

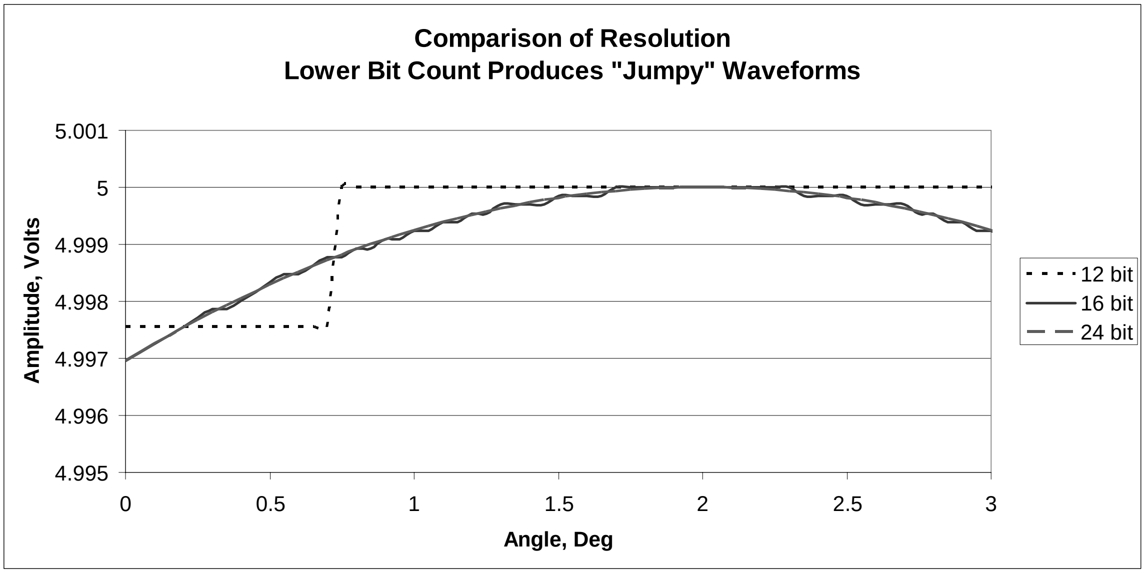
All A/D cards are rated with a resolution or bit count. The common cards available are 12, 16, and 24 bit resolution. What this means is how many different values define the full scale range. The A/D function works like this:

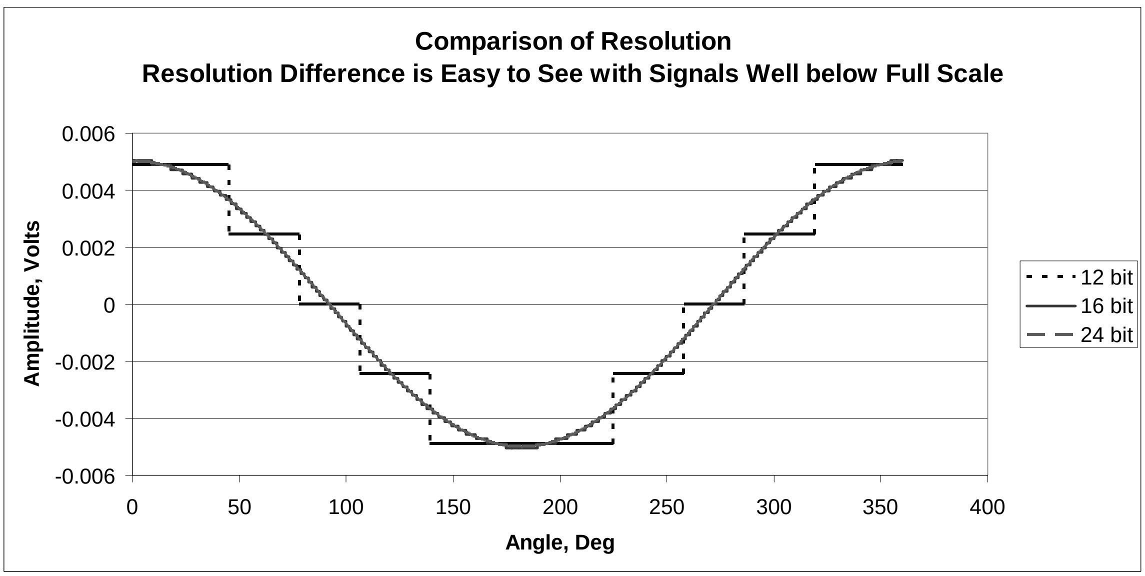
- A list of integer values are available to represent the actual value of the analog value at each instant it is digitized
- The bit count will define how many different values are available as shown below indicating the smallest voltage detected for the different resolutions:

Type	Counts	Step @ +/-5
12 bit	4096	0.0024414
16 bit	65536	0.0001526
24 bit	16777216	0.0000006

- Once the integer value is identified, it is converted in software to a floating point value (decimal value instead of an integer) that represents the full scale range







Some cards will have software selectable options for either AC or DC coupling on the signal inputs, and others will provide one or the other. Many vibration related signals such as proximity probes require measurement of both AC and DC voltage levels. In contrast, and accelerometer signal that is not AC coupled to remove the bias voltage is almost useless due to the rather low voltage values in comparison to the bias voltage. The most flexible devices would then have the capability of measuring in either an AC or DC coupled method.

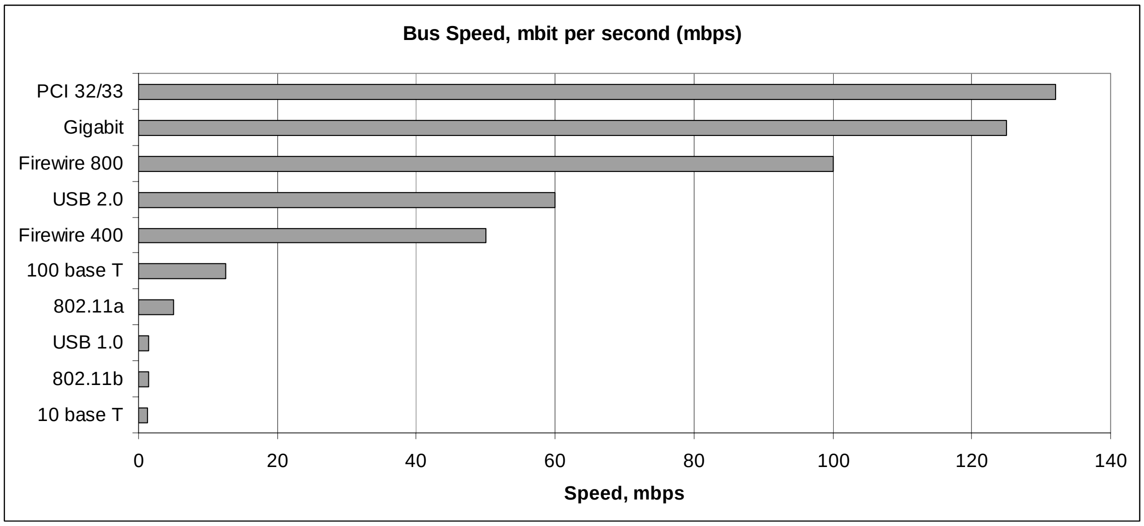
Full scale voltage ranges will fall into several categories due to available common A/D chips. The most common input ranges are +/- 10, +/-5, and 0-5 volts. Few A/D devices operate higher than 10 volts due to common available microchips. To exceed this rating, input analog circuits are used to either attenuate or amplify the signals to properly fit the range of interest.

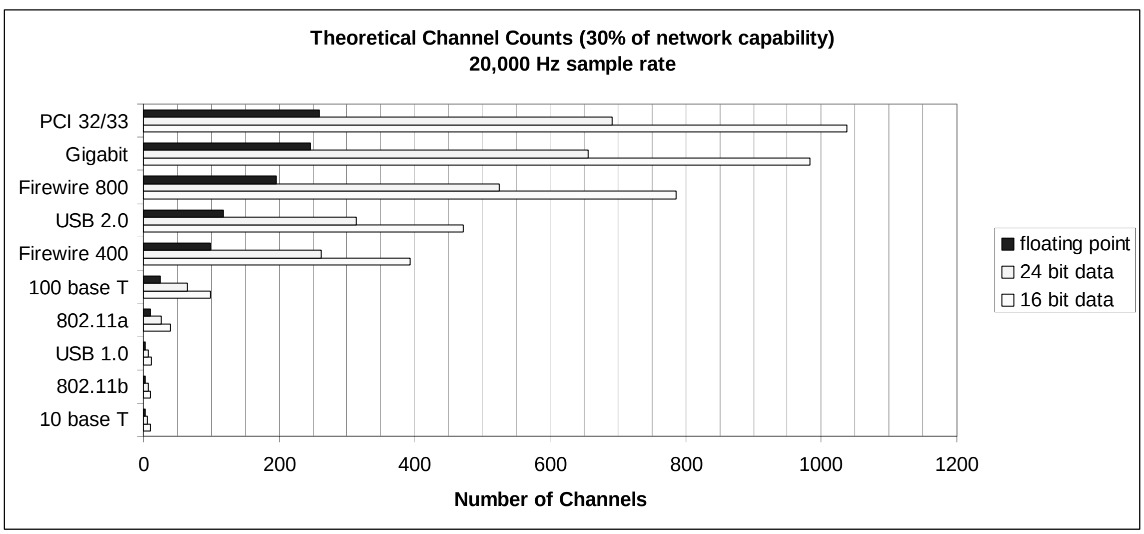
One common method to attenuate the signals is to use voltage divider type passive devices. These are available with various dB attenuation ratings, with the most common 10 dB (3.16:1) and 20 dB (10:1). A 10 dB attenuator will change a +/-10 volt card function like a +/-31.6 volt card. The effect of the attenuator is compensated for in software to produce the proper scaled values. Attenuator circuits must be properly impedance matched to the input of the A/D card, and will usually have some passive filtering built in along with the voltage divider network.

Attenuators cannot be used for devices that provide IEPE power to accelerometers since the power output from the device would have to get through the attenuator, which won't happen.

Channel count limits are governed by the A/D circuits, multiplexing configurations, and inter-device synchronization capabilities. Some hardware devices can be synchronized so that multiple devices are all sampling at the same time. This will produce negligible inter-channel phase delays even between multiple devices. In extreme cases, multiple racks of devices can be synchronized together using special timing interfaces.

Current computer bus capabilities will limit the throughput of some devices. The total throughput of various computer interfaces is shown below:





Analog Signal Processing: Most data acquisition devices do not include antialias filtering. This is one of the most basic requirements for signal measurement and processing. If aliased data is not prevented prior to digitizing the signal, the results can be complete fraudulent.

Aliased data is a real problem for many vibration measurements. For example, an accelerometer that is attached to a pump housing with a magnet will have a mounted resonance of about 3kHz. There will be a rather broad range of medium to high frequency floor noise if the pump has a damaged bearing or if it is cavitating. If this is the case, the accelerometer will produce high amplitudes near 3kHz due to the sensor resonance.

If an FFT is desired up to 1,000 Hz, the sampling would be performed at 2.56 x 1000 = 2560 Hz. According to the Nyquist criterion, the signal cannot contain amplitudes above 50% of the sampling rate to prevent aliased sampling. Unless the 3kHz signals are removed prior to sampling, alias peaks will occur in the FFT that are not real.

Some of the newer devices include 24 bit delta-sigma analog to digital (A/D) sampling. These devices in practice don't require external analog antialias filters since the actual sample rate is generally significantly higher than requested in the software. The frequency range that is requested is digitally filtered to throw away the high stuff, with the final digitized data down sampled to the frequency of interest. Provided that any stray signal levels don't exceed 50% of the actual delta-sigma over-sampling rate, aliased data is not possible.

Software Development: Software tools are rapidly advancing to improve the ease of use and making it more practical for non-programmers to build simple or complex virtual instruments. The available software varies from C++ for professional programmers to completely graphical programming tools that allow the user to build instruments with well developed libraries with packaged elements for many standard analysis types. The standard tools available can include:

- Streaming of waveform data to disk (similar to tape recorder)
- Filtering
  - AC/DC coupling in software
  - Integration
  - Band pass
  - High pass/Low pass
- Resampling
  - Downsampling to specified frequency range
  - Alignment of multiplexed waveforms
- FFT and zoom FFT processing
  - Various windows
  - Averaging
- Inverse FFT's
  - Recreate waveforms from modified FFT coefficients
- Order tracking
  - Calculated Amplitude and Phase
  - Resolution of data is as fine as one measurement per shaft rotation
- Transient analysis
  - STFT's
  - Wavelets
  - Gabor analysis
  - Waterfall (plots of traditional FFT's)
- Graphical display
  - Standard waveform and FFT plots
  - Customizable XY plots
  - Polar plots

In short, the tools are available for almost any type of data acquisition and analysis task used in common vibration and noise analysis.

The A/D card will provide measured voltage values to the software, and are often transferred in blocks of a certain number of waveform samples or of a specified time. Since the voltage values are transmitted by the software drivers to the test software, all of the control of the data is performed in user software. Any mistakes ("bugs") in the user software, improper application of the provided libraries of tools, or problems with the hardware interface with the computer can produce unexpected results.

In addition to these general concerns, the software toolkits and programming environments are also subject to upgrades, patches, etc. that can also produce unpredictable results. After all this is said, it should be obvious that the developer or user of the virtual instrument must either thoroughly test the operation of the system, or depend heavily on others to provide enough validation to produce high confidence in the measurement system.

Error Management: Once you get started building virtual instruments using the available software tools, you will find that it is necessary to provide methods to handle hardware and software errors, bugs, and glitches. It is very easy to quickly build simple data acquisition and analysis routines. However, adding proper error handling can be rather complicated.

Hardware errors are normally the first thing to handle. These concerns involve the software not being able to find or attach to the hardware (most commonly a software setup problem), lack of power to a remote DAQ device, or loss of bus connection (USB or ethernet unplugged, etc.). Some of these can be handled gracefully, and some can produce "blue screen" crashes.

Software bugs are the more difficult ones to properly trap out, and can best be done with good programming practices and crash prevention concepts (don't divide by zero, etc.).

One of the more frustrating parts of developing virtual instruments is managing the upgrades to programming software and purchased tool kits. Much like problems upgrading operating systems on PC's, upgrading of software tools can create tremendous errors and bugs that can be difficult to resolve.

The best way to minimize the problems with software upgrades, is to generate compiled (*.exe) versions of all virtual instrumentation applications. In addition, it would be helpful to clearly define the dependant toolkit versions that were used to build and/or operate the program so that problems can be more easily resolved in the future.

Conclusion: Virtual instruments are likely to continue to rapidly capture more and more of the test and measurement market. The hardware will continue to be driven to be smaller and more portable, and at the same time to include higher channel counts, higher sample rates, and better resolution.

Most A/D devices used for vibration measurement will be 24 bit delta-sigma type systems with additional flexibility to incorporate IEPE sensor power, AC/DC coupling, etc. making the hardware more flexible to accomplish many more tasks with even more general specifications.

Software will continue to improved, including more canned toolkits to provide additional high end measurements without the user/programmer having to get involved in any of the details used to produce the data. Additional plug-in modules will tremendously push the ability to perform complex data measurement and analysis tasks to less specialized users, producing lower cost methods of accomplishing some very high level tasks.

Although building computer programs and applications using virtual instruments may seem like a daunting task for most of the 40+ year old crowd, most of the younger crowd will be significantly more willing and equipped to embrace this technology. Since the tools and methods depend so highly on leveraging commercially available computer tools, there is a much greater general comfort level with the concepts and tools used. I suspect that in 20 years, there will be very few special purpose instruments sold that are not developed using virtual instrumentation.