Introduction to Filtering Mechanical Data[1]

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ABSTRACT

Raw measurements of mechanical data are rarely used to answer engineering questions. A long-standing practice has been high-pass and/or low-pass filtering to better show the desired content in a measurement, while decreasing extraneous information. These classic methods continue in widespread use, however in a digital world, the choice of specific filter type has become unlimited. Such flexibility can be especially confusing to the new measurement engineer and intended reader. This paper will present experience in filtering mechanical measurements and sometimes unintended consequences.

INTRODUCTION

Few mechanical assemblies perform as desired by their end users every time. When such performance doesn't "measure up" to expectations, an opportunity exists to improve the device involved. Furthermore, even those structures which currently seem perfect for the job are often the target of cost reduction activities, or are destined for a use that the original designer did not intend. Consequently, measurement engineers are called upon to produce useful information about one or more of the following:

- Extent and cause of undesired performance, and likely design improvements or retrofit
- Operating margins above potential failure, or performance margin relative to user-specified criteria
- Quantitative description of proposed application environment

Those who are unfamiliar with these tasks--obtaining raw mechanical data, and extracting useful business information from it--sometimes view this process as elementary. (After all, every mechanical engineer is taught the proportionality of acceleration to force, force to flexure, flexure to strain, strain to stress, and stress to damage.) Similarly, those with formal study in electronics were shown the same equations under different analogies. Therefore, crossing of engineering disciplines is often expected of measurement problem solvers. With experience, most measurement engineers become comfortable with such expectations. However, new engineers may find the design, installation, calibration, application, and interpretation of a measurement system and its data as far from trivial. This paper will attempt to help the beginner with one phase of this process: filtering data to improve physical understanding.

FILTER THE TASK REQUEST

Fortunately many engineering decisions begin with the statement “we need data.” Unfortunately, many measurement projects begin with the statement “we need data.” Upon hearing these three words, the new measurement engineer should invoke the “six whys.” In other words, the instinctive and immediate response should be “Why?” The first explanation may seem satisfactory, but much effort can be wasted if one does not get to the root cause for the request. The six “whys?” may need to be asked over a few days or weeks--patience and tact is required. The full answers will payoff more than any other labors.

Hopefully, asking the six “whys?” will show that the data is needed for of the following reasons:

- as the basis of a accelerated laboratory simulation of the service life
- to document that a product meets a user-defined specification
- to identify the source of a field failure, and a suitable remedy

Furthermore, these answers should lead to the important measurands and the required precision. For example, the assignment might be to find the root source of a particular noise emanating from a machine. This involves measuring sound pressure, but may not require much precise frequency or amplitude value. Conversely, ensuring that the machine does not exceed a federal noise **standard** might require precise sound pressure samples for many such machines to statistically prove that non-conforming exceptions do not exist.

Mechanical measurement engineers work with various physical phenomena. This paper focuses on the motion-related issues such as force, acceleration, velocity, displacement, strain, and noise. Many problems given to the measurement engineer are not explicitly posed as a measure of the first four--force, acceleration, velocity, displacement. Instead, the structure or component either doesn’t work properly, or it annoys people. In these cases, the engineer may use objective measurements to diagnose and remedy the problem. However, even if low amplitudes are found, the engineer cannot pronounce the product acceptable without performance improvements. (i.e. the test is not the end in itself).

Exceptions are qualification tests, the specified parameter limits to help ensure that the device works properly and/or doesn’t annoy people. In these cases, passing the qualification test becomes the end in itself. However, even in this case, whether the product is indeed acceptable depends on the specification. A perfect specification would pass only acceptable structures (or components), and reject only unacceptable structures. Few specifications work so well, but in general they add more value than risk. Incomplete specifications are in use in various industries (e.g. maximum magnitude limits on lowpass filtered accelerations--but with ambiguous specification of filter type, order, and cutoff). Ill defined specifications can lead to “testsmanship,” or designed-in biases of results.

Finally, negotiate the documentation required with your customer. Some customers require only a verbal report to a verbal request. Others may want an extensive report suitable for publication. Regardless, for future reference (and potential test duplication) a good logbook should be kept. Again, extra time defining what data to collect will yield less time solving the problem.

FREQUENCIES OF INTEREST – STRUCTURAL RESPONSE BASED

More measurements (more channels, higher acquisition rates, longer recording times, and as many test conditions as possible) must not be confused as better measurements. Data should be sampled only often enough to describe the physics of the measurands. For example, if temperature of a large structure (e.g. thermally expanding process piping) is in question, perhaps a few samples per hour are enough. For acoustics or shock data, 100,000 samples per second per channel may be necessary.

This paper is oriented toward structural measurements such as displacement, velocity, acceleration, force, strain and noise. For these measurands, the flexibility of the assembly or component involved will govern the sampling rate. Resonance occurs when a structure is subject to time-varying forces or motions that coincide with the structure’s own natural frequency of vibration. Hence, sometimes the structure responds with much larger motion than it would for similar excitations at a slightly different excitation frequency. Since natural frequencies are directly related to the square-root of stiffness over mass, meaningful response frequencies of a small rigid component will be far different from those for a massive flexible structure. Table I lists common ranges for response natural frequencies [Refs. 1-9]. A first approximate for sampling rate would be ten times the higher values.

In typical mechanical structures, the dynamic magnification of motion at resonance generally decreases and the damping increases at subsequent (higher frequency) modes [10]. For broadband excitation such as impacts or random inputs, this means that the responses at the first several modes are those most likely to cause problems. Impacts may be external to the structure such as road "potholes", or internal structure non-linearities such as loose joints. While higher frequency modes may be excited by such broadband inputs, the response magnitudes are likely to be insignificant relative to the low frequency modes.

Description	**Typical Resonance Ranges (Hz)**
Buildings	0.1 – 10
Ship Hulls	1 – 10
Rail Cars	0.5 - 9
Light Aircraft	3.6 - 20
Highway Trucks, Subassemblies	10 - 35
Highway Trucks/Trailers	1 - 10
Helicopters	5 - 25
Highway Trucks (Suspension Components)	10 - 15
Process Machinery	10 - 25
Machine Tools	20 - 200
Passenger Cars	3 - 30
Electromechanical Components	Up to 500
Electronic Components	150-2500

Table I: Typical resonance frequencies for mechanical structures.

FREQUENCIES OF INTEREST – ENERGY SOURCE BASED

Unlike the broadband forcing functions, periodic excitation concentrates forcing energy in specific bands (often at high frequencies relative to the first several resonances). Examples are rotating machinery unbalances, reciprocating pistons, and bearing defects. These periodic forces can create problems if they align with a higher structural resonance. With rotating machinery such as engines and compressors, the peak excitation frequencies involved may reach 2000 Hz.

FREQUENCIES OF INTEREST – MEASURAND BASED

The physical relationships between force, acceleration, velocity, displacement, strain, and noise often control the test frequencies of interest. Force is directly related to sum of the products of acceleration and mass, velocity and damping, and displacement and stiffness. In the time domain, the derivative of displacement is velocity, and the derivative of velocity is acceleration. For sinusoidal components, each derivative operation introduces the product of frequency. Therefore, velocity measurements tend to emphasize high frequencies relative to displacement measurements, and accelerations even more so. In this manner, the measurand itself is a form of filter.

Again the definition of unacceptable performance can determine what is of interest here. For unacceptable noise, the sound pressure level and out-of-plane surface motions of that can convert vibrations into sounds are most useful. Since undesired noise is often between several hundred and several thousand Hz [11], measures of sounding board displacements would be difficult. Rather, surface accelerations or variations in pressure (as seen by a microphone) are better measurands of the higher-frequency activity. As another example, localized information on shock absorber bracket loads due primarily to the damping force, measure relative velocity across the shock absorber.

For physical yielding, fatigue, or breakage, the best measure is often strain. Although accelerometers are often the "default" motion sensor (because they are simple to install and rugged), their high frequency emphasis may require lowpass filtering to focus more closely on content related to fatigue. Since strain is a spatial derivative of displacement, not velocity or acceleration, it naturally emphasizes lower frequency data [12]. Therefore lowpass filtering is often unnecessary.

LOWPASS FILTERING IN THE TIME AND FREQUENCY DOMAINS

Filtering is the process of selectively removing some energy from a measurement in order to better understand the phenomena of interest. The most common application is removal of quickly changing or high frequency noise from measurement of a lower frequency mechanical behavior. Such noise may be unrelated voltage variation due to nearby EMF or RF interference, or it may be internal to the structure (e.g. high frequency component caused by a gear train).

Analog filtering can be performed on the original signal using electronic circuits to attenuate higher frequency components while passing lower frequencies. In an increasingly digital world, analog filters continue to be used to prevent aliasing (via high frequency filters with fairly gradual rolloff, ahead of very fast digitizers). Subsequent filtering operations can then be performed digitally with user-selectable filters. This can be done on sampled (digital) time domain signals by convolving the filter's weighting function with the raw data. Alternatively it may be done in the frequency domain by performing a FFT on the raw data, multiplying it in the frequency domain by the filter's transfer function, and performing an inverse FFT on the results.

The traditional filter designs available in analog format have been the Bessel, the Butterworth, the Chebyshev, and the Elliptic. In the past, lab equipment budgets determined the tradeoff between gradual (2-pole) or steep (8-pole) rolloffs, and whether more than one filter design was on-hand. A many-channel complement of high quality hardware 6 or 8-pole filters was relatively expensive. Further, repeating such an investment in order to have several filter banks of various designs was unlikely. Therefore, referring to another engineer's past data was simpler because any filtering typically reflected the local "standard" design. Unlike 15 years ago, most current digital data analysis software allows the user to choose among many filter designs (including digital implementation of the above analog designs), as well as finite impulse response (FIR) filters. In addition, user selectable corner frequencies and cutoff sharpness are available at the touch of a keyboard. Software packages generally allow the selection of cutoff sharpness through the selections of a filter's **order**. For traditional designs, the slope of attenuation approaches similar asymptotic limits for all filters of the same order (e.g. the 6th order Butterworth, and 6th order elliptic have same high frequency rolloff slopes).

However, the order of an FIR is quite different, and herein will be referred to as the number of **taps** instead. Each tap represents a finite difference calculation on the signal [13]. The output lags the input for FIR designs by a number of samples equal to the number of taps. For ballpark similarities between the traditional designs and an FIR filter, many more taps would be selected than traditional orders. Today's flexible filtering routines mean that greater care must be taken when comparing data acquired at different times by different people. Poor documentation of filtering choices carries the risk of incompatible data interpretation.

Filter designs vary in both magnitude response and phase response characteristics. **Magnitude response** describes the filter's effect on the output magnitude versus frequency. A perfect filter would pass all desired frequencies at full amplitude just up to the cutoff, and would totally eliminate undesired frequencies. Various real designs (analog or digital) approach this ideal, but their transitions from pass to stop bands differ. Not only magnitude is affected by the filtering process, but also a particular frequency component's phase relative to the other frequencies passing through the filter may change. That is, some frequency components may travel through the filter faster than others. This means that a complex waveshape may be altered by the filtering process regardless of the filter's magnitude response. **Phase response** describes the filter's ability to keep all frequency components aligned as they were upon entrance to the filter. Square waves illustrate this well because the various harmonics must remain precisely aligned. If some harmonics are delayed relative to the others, the square pulse train will become distorted. As a general rule, the filters designed for best magnitude response have poorer phase response, and vice versa [14].

Using digital signal processing, poor phase response can be compensated by a forward then reverse filtering technique. The time history is passed through a filtered normally (from first sample to last), then this intermediate results is again passed through the same filter, but from last sample to first. This will compensate for phase distortion by the filter. One analogy to this is a footrace started with runners of various speeds. Any time later they will have traveled different distances. However, if a gun is sounded, and they all turn around and continue running, they will arrive at the starting point together again.

For broadband excitation with single-channel analyses to perform, exact preservation of phase is usually less important than accurate magnitude characteristics. This would include PSD generation for shaker input, especially since many PSD shaker-control algorithms randomize phase during the shaker tests anyway. Indeed, for a small component likely to be mounted at several slightly different locations in a manufacturers product, phase between various inputs will vary both spatially and temporally [6]. For multiple shaker road simulators, this is not true however. In such cases, phase reproduction is very important for the duplication of original waveforms.

Given such variations in phase and magnitude response, modern software filters may lead to selection of the filter design most favorable to the resulting data. If for example, measurements are needed only to verify compliance with an ambiguous test specification, this may lead to repeated data analyses attempts using many different filter designs. Consider a specification of the peak acceleration transmitted to passengers or equipment by a vehicle. The goal is to limit discomfort or damage, and therefore a 15 Hz lowpass filter operation is specified on the vertical acceleration. Unfortunately, filters of various poles (sharpness) and designs (Butterworth, Bessel, Elliptic, Chebyshev, or others) may be tried on a data set until the output waveform meets the specification. Since the specification writers probably used a specific filter design, the measurement engineer should investigate and choose the same filter.

CASE STUDY – VEHICLE SIDE MIRRORS

As a new commercial vehicle design criteria, the vibration of existing side mirrors was deemed excessive. This broad problem was narrowed using the six “whys,” and answers consequently directed both the test excitation method, and the measurement methods used.

The undesired performance was found to occur primarily during specific operations. That is, a truck driver wants the clearest view behind his rig when backing to a loading dock, but often has no rear window. Therefore existing over-the-road vibrations were deemed acceptable. During slow speed backing operations, the engine is typically at idle (600 RPM) and exhibits it’s lowest normal firing frequency of 20 Hz. Unfortunately, some side mirror assembles resonate near 20 Hz as well. Thus, the test excitation was selected as a idling engine (effectively filtering the input to important frequencies).

Measurement of mirror vibration initially seemed straightforward, however the undesired behavior **is visual image distortion**, which may be related to but is not acceleration. For example if a mirror vibrates wildly, but stays in the same plane, the image remains steady. Therefore, neither vertical vibration nor planar motion toward-or-away from the eye cause objections, instead mirror rotation is the real problem. Various mirror measurements schemes were discussed including angular accelerometers. However angular displacement was deemed the better measurement, and a simple measurement of the distortion was eventually chosen. In this case, a 35 mm slide projector was aimed at the mirror from the rear corner of the vehicle. The projected slide contained merely a small white dot, which was reflected onto a paper target. The target was fixed to the drivers seat, and placed at the normal eye position of a driver. During operation, the dot of light vibrated at 20 Hz and the displacement envelope of the vibration could be traced. Smaller displacement envelopes indicated less image distortion.

Stein has discussed similar relationships of vibration problems to measurable quantities [15].

CASE STUDY – ROADBED FORCE VERSUS DEFLECTION

Force versus displacement measurements were requested by commercial transportation researchers investigating the causes of weak support for aggregate roadbeds. The desired load application was a quasi-static force ramp from zero to 20,000 pounds, over a period of two minutes. Hydraulic actuators on a mobile laboratory were used to apply the force, and resulting data was recorded on-board. The potential for minor noise on the force or displacement signals was anticipated, due either to engine/hydraulic pump vibrations transmitted into the actuator, or due to 60 Hz on-board power generation. Due to the quasi-static nature of the test, the author suggested a low-pass filter of 20 Hz on all signals. The measurement engineer complied, and set the sampling frequency to allow ten samples per highest passband frequency (common practice for peak reproduction). This yielded larger data files sizes than expected by the customer. Each quasi-static 120 second force ramp yielded over 20,000 data points per channel, which the data customer later decimated to approximately two per second with a spreadsheet macro.

These measurements were successful. However, the author could have precluded the later decimation effort with better test explanation to the mobile lab crew. A brief discussion of the difference between selecting a filter to eliminate a specific noise potential (i.e. the 20 Hz lowpass of a quasi-static phenomena), versus choosing a sampling rate to catch the highest potential passband frequency would have helped. In this case, the highest frequency of interest was just above DC, not 20 Hz.

If higher speed cross-channel analyses are to be performed (e.g. force vs. deflection) it is important use the same filter on both signals <u>even if one channel doesn't need it</u>. This will preserve phasing between the quantities, which is especially important in damping measurements. False phase shifts between channels can seriously corrupt hysteresis calculations, especially for lightly damped components.

CASE STUDY – THERMAL TRANSIENT RESPONSE IN PIEZOELECTRIC ACCELEROMETER

A compression-style piezoelectric accelerometer and charge amplifier exhibited a wandering (near-DC) output in addition to the expected dynamic vibration output. The quick solution was to switch the recording unit to AC coupling [16]. However, this did not satisfy the novice engineer, who investigated further. It was found that the accelerometer case was very sensitive to minor temperature changes of the surrounding air. Although the AC-coupling switch was a possibility, this coupling circuit was found to begin attenuating signals just below 2 Hz, which was near the lowest frequencies of interest. Also, the engineer was concerned that the accelerometer/charge amp system might wander off-scale and become non-linear. Instead, the air temperature transients were reduced to acceptable levels with a thermal low-pass filter--fabricated from closed-cell rubber foam and duct tape. (In subsequent tests, the engineer opted for delta shear accelerometers without this drawback.)

CASE STUDY – WELDING INTERFERENCE IN PIEZOELECTRIC ACCELEROMETER

This problem does not directly address a filtering application. However, this reflects an accelerometer failure that might not be apparent at the output of some lowpass filters.

A modal test employed a miniature piezoelectric accelerometer. This was manufactured with integral signal conditioning, and connected to power supplies via integral ribbon cable (several feet long) before connecting to approximately 100 feet of shielded RG58U cable, and teed into a FFT analyzer and oscilloscope. After the first of several measurements, infrequent but violent off-scale transients were seen on the scope. The remainder of the day was used to look for the source of this problem (troubleshooting cables, connectors, circuit board solder joints) but to no avail.

In an adjacent high-bay the next morning, the engineer heard the sound of an overhead arc welder which seemed to start and stop similar to the accelerometer problems. A craftsman was modifying the steel truss roof approximately 150 feet from the measurement location. The arcing proved to be the source of the transients.

Since mass loading of the test unit was not a concern, the engineer switched to a larger triaxial accelerometer with shielded cable between it and the power supply, and the problem was eliminated.

Other transducers may be temporarily over-ranged either mechanically or electrically, and if a filter (either internal to the transducer or external) operates on the output before inspection, detection of the erroneous data is unlikely. In such cases high-frequency overloads can create low frequency garbage, fooling the measurement engineer.

CASE STUDY – VARIOUS FILTERS APPLIED TO COMMERCIAL VEHICLE DATA

This case study illustrates changes in waveforms and estimated signal amplitude peaks for various filter selections. 32 channels of strain and acceleration were recorded during a field transient (handling) event for a large vehicle. Figure 1 shows a strain response and a nearby acceleration and on a structural member versus time (normalized by their maximum values of strain and acceleration amplitudes). The strain signal has been shifted vertically to allow better visual comparison. Due to hardware and memory limitations, several initial trial events were recorded to select the lowest anti-aliasing filters (30 Hz for strains, 150 Hz for accelerations), and sampling rates (300 Hz for strains, 1000 Hz for accelerations) while retaining peak amplitudes. As expected, the strain signal (spatial derivative of displacement) is dominated by much lower frequencies than the accelerometer.

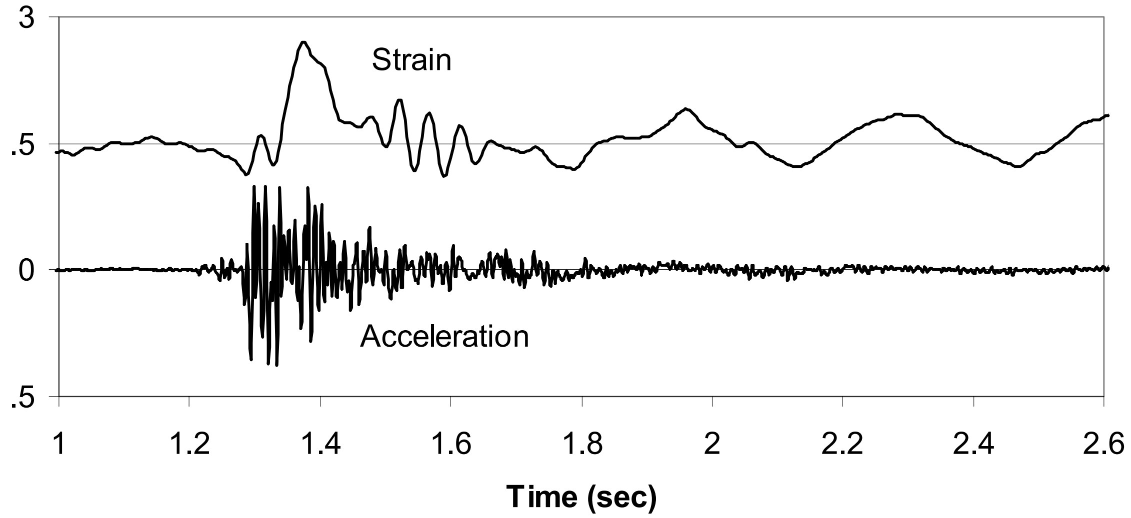

Figure 1: Recorded strain and acceleration histories for transient handling event on shipping container.

Wright [17] has shown the uncertainty caused by various "similar" filters upon a step function, an excellent diagnostic technique. Examples herein will quantify similar filtering variations upon field data. To examine the potential for differences in reported peak acceleration levels due to various filtering methods, the acceleration history has been passed through four lowpass filters: a 1024 tap finite impulse response (FIR) filter, a 4 pole Butterworth, a 4 Pole Type I Chebychev, and a 4 pole Elliptic. All filters were specified with the same cutoff frequency of 100 Hz, and the outputs are shown along with the original signal (topmost) in Figure 2. Each trace has been shifted vertically to allow better comparison. Figures 3 and 4 repeat this process with the four filters, except with cutoff frequencies specified at 30 Hz, and 10 Hz, respectively. The very low cutoff frequency of 10 Hz reflects an industry specification, however this specification does not require a particular filter design other than 4 pole or greater.

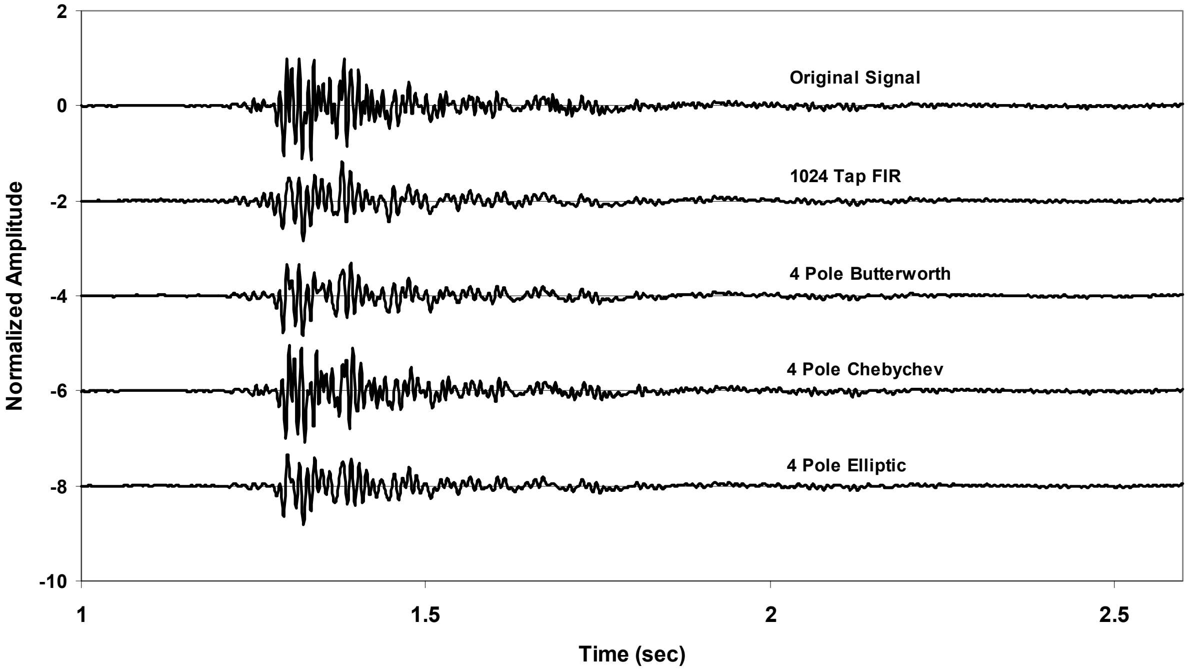

Figure 2: Output of four 100 Hz lowpass filters to transient handling event.

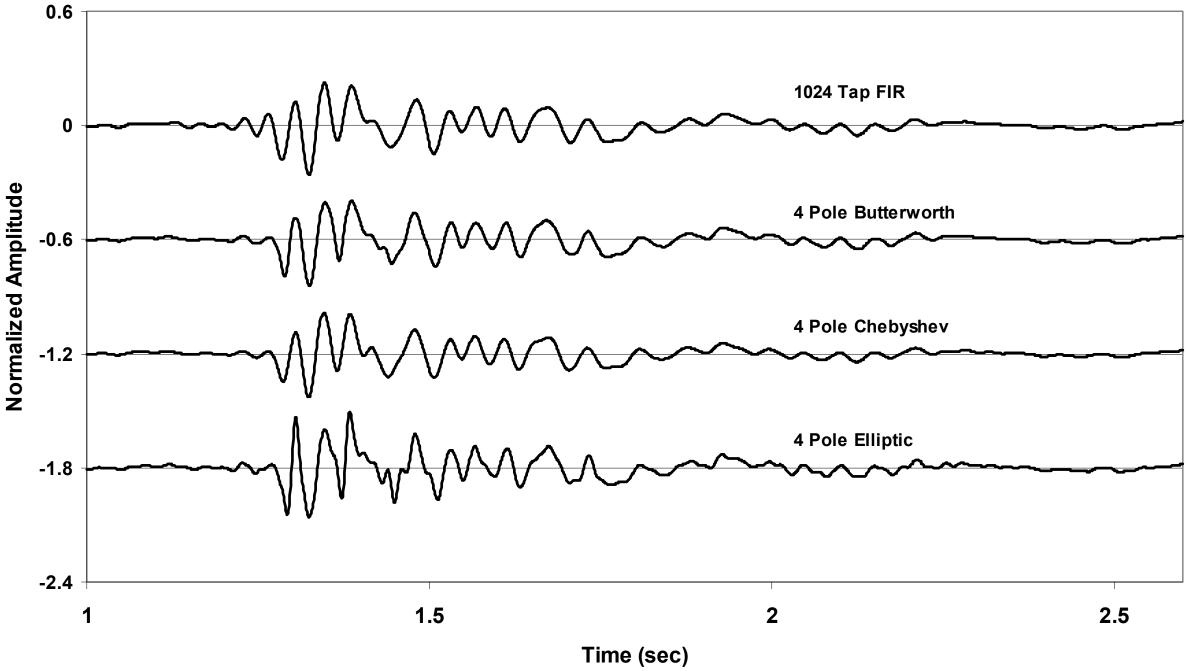

Figure 3: Output of four 30 Hz lowpass filters to transient handling event.

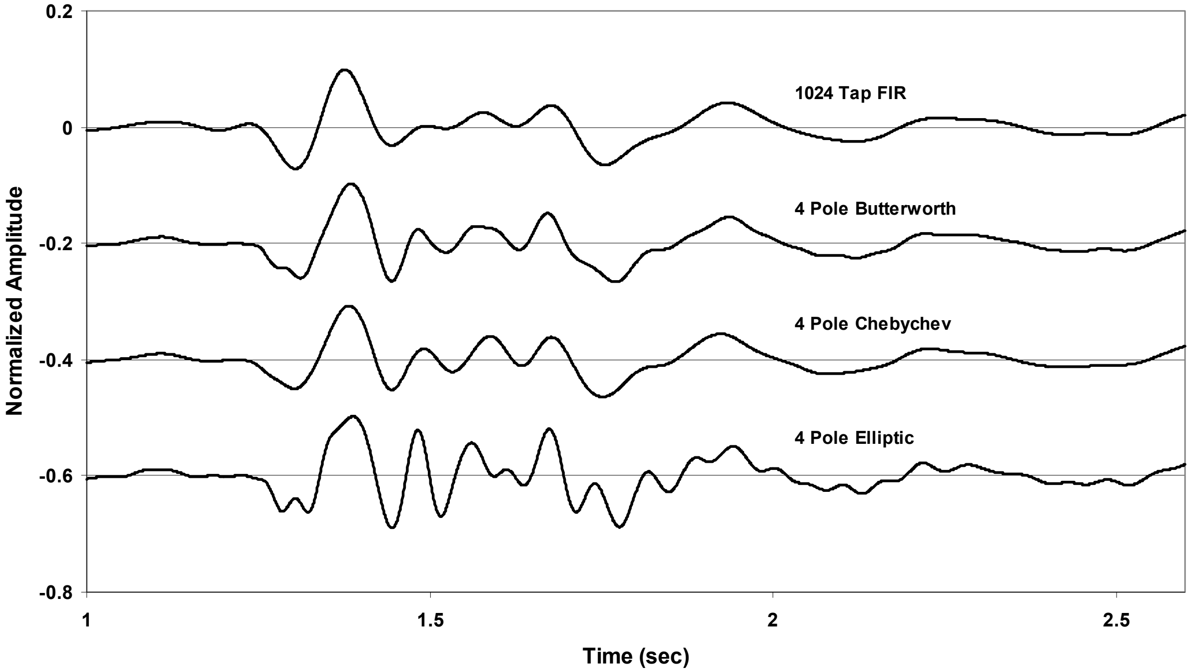

Figure 4: Output of four 10 Hz lowpass filters to transient handling event.

Since the results in the figures are difficult to quantify, Figure 5 shows the maxima and minima values for all cases in Figures 2-4. Again, the original signal was normalized by its own peak amplitude. As shown, all the post-filtered results are truncated relative to the original. This is to be expected since each case successively truncates more energy from the original signal. This would not be expected if the original signal was itself band-limited to a value lower than one or more of the filter cutoffs. This shows the importance of documenting the cutoff frequency for each channel, every time measurements are obtained. Furthermore, the variation of maxima and minima within the three trials makes comparison of data sets obtained with different filter designs almost impossible. (Some relief may be obtained using inverse frequency response functions as equalization [18].) As shown in Figure 5, the peak output amplitudes of the 100 Hz Chebychev and Elliptic filters are 67% and 95% of the input peak magnitude. This severe example presents the instance of undocumented data being worse than no data, especially if the workplace has data acquisition hardware (or software) of different vintage and/or maker. This also yields the opportunity for testmanship to skew results.

As stated previously, the broadband energy in the original acceleration signal is truncated by each of the three (100 Hz, 30 Hz, and 10 Hz) filter cutoff frequencies. To better show the trend of the truncation with frequency, twelve filters of varying cutoff frequencies (10 to 120 Hz) were applied to this acceleration signal. This was done first for a 4-pole Butterworth filter, with results shown in Figure 6. Trial and error was then used to find a FIR filter design producing a similar waveform as the Butterworth. A 64 tap FIR filter was chosen, results shown in Figure 6 as well. However, although the maxima and minima acceleration results approximate each other for these two filter designs, the time histories as output visually showed that the FIR design did not attenuate the stop band frequencies as much as the Butterworth filter. The amplitude similarities in Figure 6 are specific to this input data and sampling conditions.

A similar trial and error technique was used to find approximate trend similarities for other Butterworth and FIR designs. Results are shown in Figure 7. This resulted in the following crude correlation between FIR tap number and Butterworth pole number—for this acceleration input data. Equation (1) is only intended as a rough indicator of an initial guess one might chose between IIR pole numbers and similar FIR tap numbers. (The much larger typical value for FIR taps shows that the relationship between filter order and asymptotic cutoff slope of IIR filters does not apply to the FIR finite-difference order number.)

$$(\text{No. FIR taps}) \approx (18.6*(\text{No. Butterworth poles})) - 10.5 \qquad (1)$$

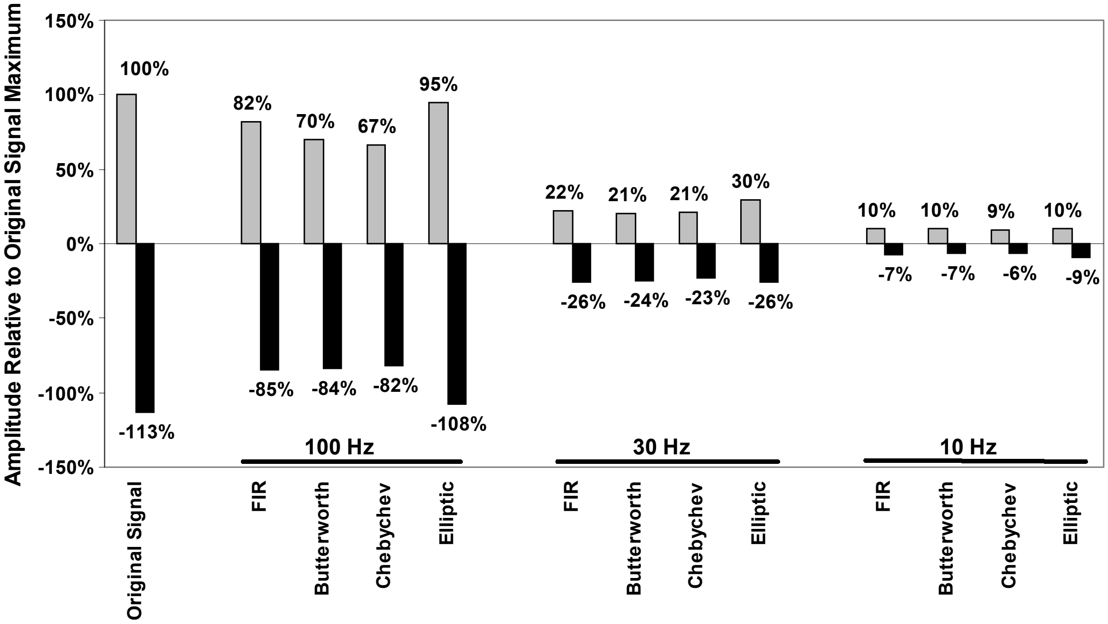

Figure 5: Attenuation of acceleration maxima and minima for various cutoff frequencies specific for four different lowpass filter designs. Results are specific to input acceleration history, and will vary depending on input spectrum shape.

The data presented thus far has focused on the acceleration signal, which has significant wideband energy content. As stated earlier, lower frequencies dominated the strain signal to a much greater degree than the acceleration signal. Figure 8 shows the effect of various 25 Hz lowpass filter rolloff slopes for both Butterworth and FIR designs applied to the strain signal. When compared with Figure 5, the strain maxima variability is much less than the accelation variability. This is because the strain signal has little energy above 20 Hz, approximately 20% below the cutoff frequency selection of 25 Hz. Since no significant energy exists in the transition bands or stop bands for this signal, the various filter outputs are more consistent.

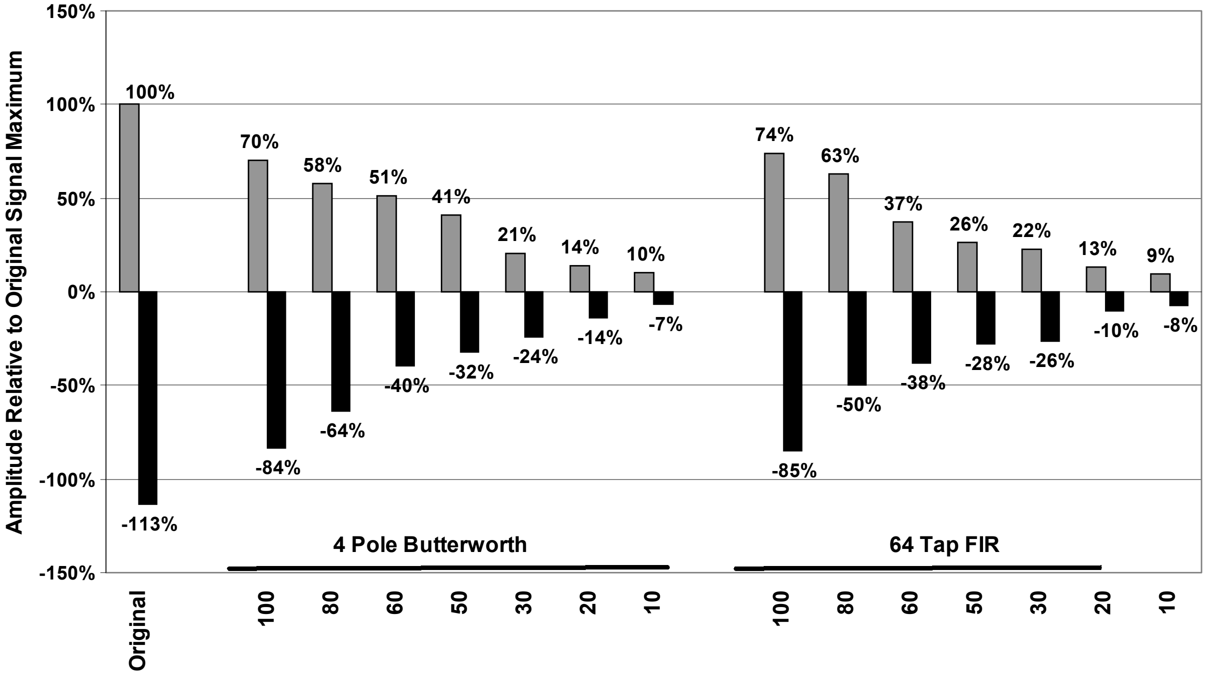

Figure 6: Attenuation of acceleration maxima and minima for two lowpass filter designs at various cutoff frequencies.

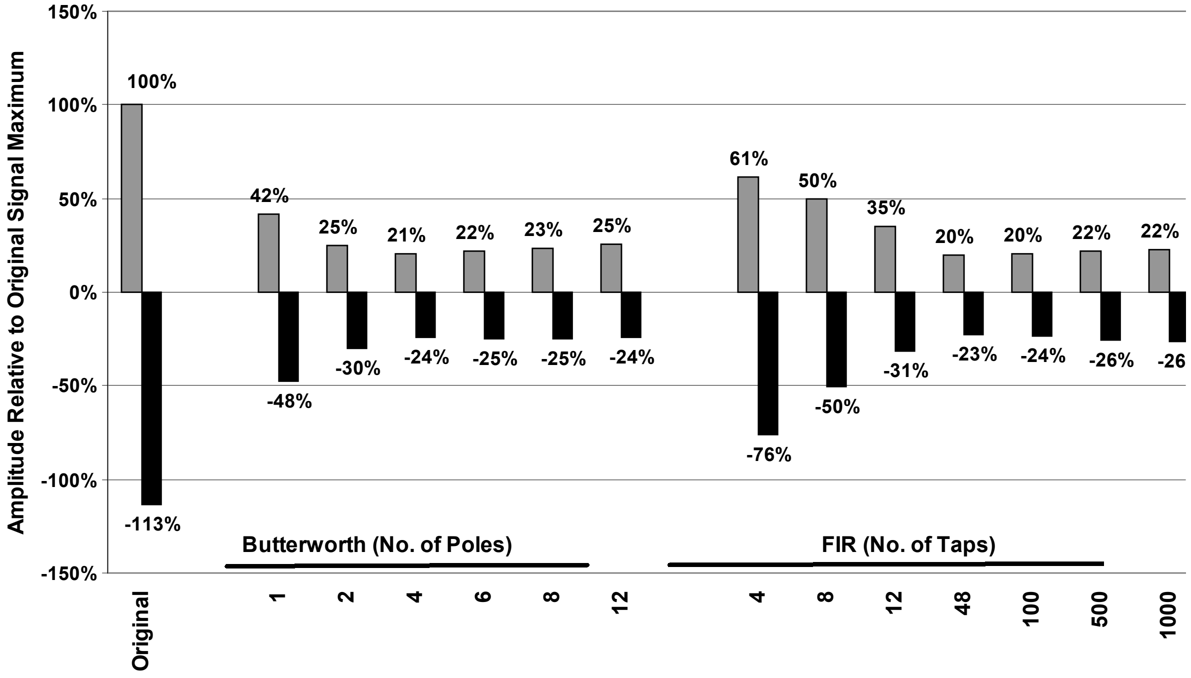

Figure 7: Attenuation of acceleration maxima and minima through 30 Hz lowpass filter designs. Various pole number selections for Butterworth filter design and various tap number selections for FIR design.

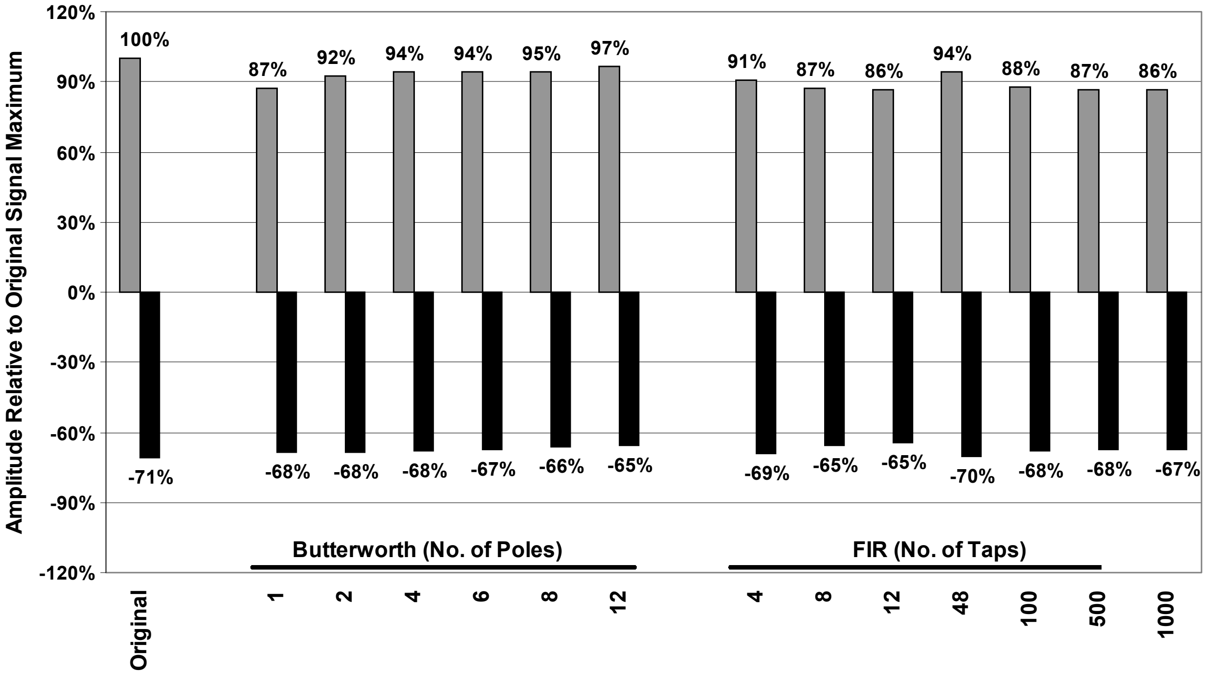

Figure 8: Attenuation of strain maxima and minima through 25 Hz lowpass filter designs. Various pole number selections for Butterworth filter design and various tap number selections for FIR design.

CONCLUSIONS

This paper has discussed basic applications of filtering, as a valuable tehcnique for improved measurement insight. Several important points have been made:

- Fit the measurand and the methodology to the root question at hand.
- Filtered data is difficult to interpret without documentation of the specific filter design used.
- The frequency band of interest depends on the structural natural frequencies, the energy source frequencies, and the measurand needed.
- Displacement-related measurands emphasize low frequencies, acceleration-related measurands emphasize high frequencies.
- Once filtered, offscale events at the transducer may be undetectable, although the nonlinear response will corrupt data.
- For component testing, optimal magnitude response is usually more important than phase.
- For transient waveform recording, or full vehicle shaker simulation correct phase response is important.
- Although IIR filters of the same order have roughly similar assymptotic rolloff effects, an FIR filter of the same order (number of taps) will be significantly different. The number of taps in FIR filters are typically many times the order number of IIR filters.

The bibliography lists several excellent references with more extensive information.

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