THE MEASUREMENT OF HAND-ARM VIBRATION IN INDUSTRY

R. Kitchener

ABSTRACT

This paper covers the practical problems involved in measuring hand-arm vibration in industry. It firstly deals with the selection of the best transducer and its correct method of mounting, including the difficulties presented by high impulsive forces. A discussion of the most suitable type of analysis including the possibility of characterizing the vibration by a single figure using a frequency weighting network follows. Next the instrumentation needed to deal with the range of frequency and amplitude is considered. Finally, a few results are given of the vibration levels found in the metal working industry.

INTRODUCTION

Although vibration induced white finger (VWF) has been known for many years, only recently has it become possible to measure easily the vibration of hand-held objects in an industrial situation. This has meant that the harmful effect of different frequencies, amplitudes, and exposure times has not been established objectively. All the proposed standards in this field are based on vibration sensation levels. Although these do not contradict the industrial vibration measurements that have been made, a great deal of work is necessary to establish a reliable "dose-response" relation. This paper reviews the practical problems arising in the course of measuring hand-arm vibration in industry.

THE TRANSDUCER

The most important part of the vibration measuring equipment is the transducer, which converts the mechanical motion of the object into an electrical voltage. If this does not operate correctly, the most sophisticated electronic analyzing instruments attached to it will not produce meaningful results.

The almost-universally used transduced is the piezoelectric accelerometer because of its small size and wide frequency and amplitude range.

Since the acceleration is transformed into a charge on a capacitor, its low frequency response is determined by the input resistance of the preamplifier. Its high frequency response is limited by the fundamental resonance of the accelerometer or by the method of fixing it to the object under examination.

The frequency range of interest in hand-arm vibration is considered to be from about 2 Hz to 2,000 Hz, which is well within the limits noted above. Its amplitude range is about 100,000 to 1, the actual values depending on the design of the accelerometer. A suitable range would be from 0.1 m/s^2 to 10,000 m/s^2.

Note, however, that acceleration peaks greatly in excess of this can be present in reciprocating pneumatic tools and during the fettling of castings. In extreme cases, these shocks can destroy the accelerometer and, in more common cases, produce sudden random shifts in output (Figure 1). These shifts, after passing through an amplifier and tape recorder, may be mistaken for low frequency vibration (Figure 2).

To avoid these effects, it is advisable to connect the accelerometer to the vibrating object by means of a damped resilient pad. This can act as a mechanical filter, progressively attenuating frequencies above 3,000 Hz.

Another cause of false signals can be vibration of the cable from the accelerometer to the amplifying equipment. These are due to movements of the outer sheath of the coaxial cable that produce capacity and charge variations. Special cable is used to reduce these effects, and at the levels of vibration believed connected with white finger syndrome, they are rarely significant.

MOUNTING THE TRANSDUCER

The simplest method of using the transducer is to screw it rigidly to a flat surface on the vibrating object, which has a tapped hole at its center. Alternatively, a suitably drilled and tapped block can be strapped tightly to a tool handle with a hose clip. In this case, care should be taken to see that no reso-

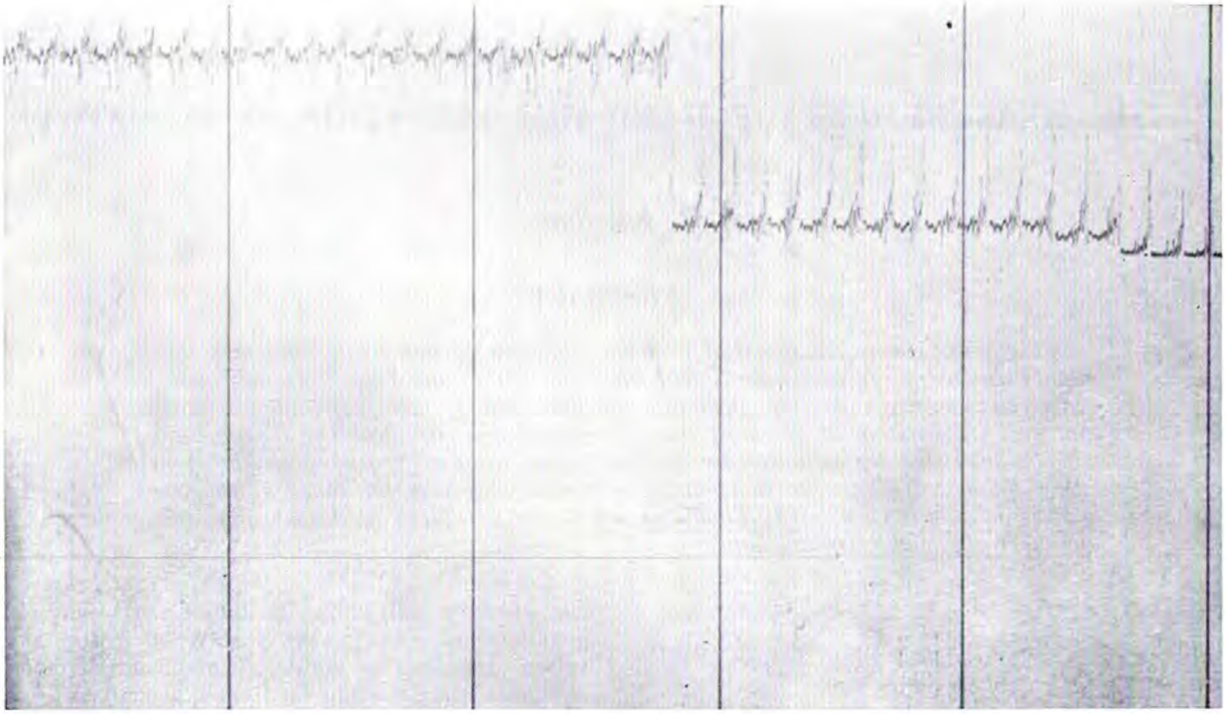

Figure 1. Accelerometer D.C. shifts due to excessive inputs.

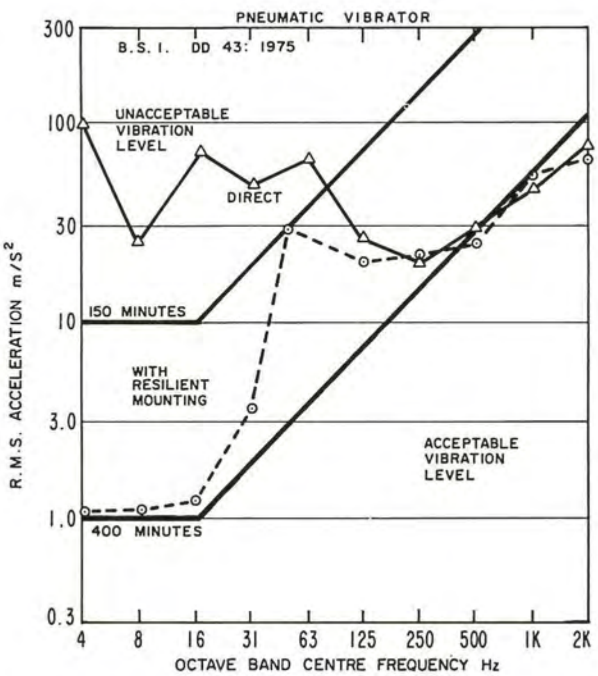

Figure 2. Inaccurate vibration spectrum due to D.C. level shifting corrected by using mechanical "resilient pad" filter.

nances within the frequency range concerned have been introduced by the fixing method. It is highly advisable also to include a resilient washer as mentioned above even if shocks are not anticipated.

It is usually sufficient to use one accelerometer to measure in the three mutually perpendicular directions successively. Triaxial transducers are available, but their extra weight may affect the motion of light objects. Also providing three channels of amplifying and recording equipment is expensive and may not be practical in industrial measuring situations.

If there is some resilient material present between the hand and the vibrating surface, say a rubber grip, the situation is more complex. Merely attaching an accelerometer to the resilient surface would completely alter the motion of the grip-hand interface. Miwa[1] believes that this should not be attempted, whereas Louda[2] speaks of attaching the accelerometer to a "thin, suitably formed metal sheet."

The problem arises because the accelerometer is much denser than flesh and so would create a resonance between the mass of the accelerometer and the stiffness of the flesh and rubber grip. This would alter the vibration of the hand-grip interface. A possible solution is to enclose the accelerometer in a light rigid shell so that its overall density is that of flesh. Thus, although a small extra mass would be present, the character of the vibration would not be seriously altered.

ANALYSIS

Hand-arm vibration in industry may consist of a number of discrete frequencies, but is more likely to be random or pseudo-random in nature and even non-stationary. This raises the problem of how to characterize the vibration in a simple way. The ideal is to produce a single figure of "harmfulness" that can be correlated with the clinical results.

The usual method of dealing with random vibrations is to measure the Root Mean Square (RMS) value since this is related to energy—probably the most significant parameter. This is usually done by using an R.C. time constant to effect a pseudo-integration, which is only accurate if the vibrations are "stationary" for a period of many time constants.

This condition presents a very real measuring difficulty since the vibration may only last a few seconds and may be altering during this time as well. One solution is to record the vibrations and form the tape into an endless loop. If the time constant is made much longer than the loop time, an accurate result is obtained.

Another method is to use true integration; this will give a correct result no matter how short the signal or how narrow a filter it has been passed through. Such an integration is performed in the so-called noise dose meters, and so these instruments can be used for the measurement of vibration.

The differing effects of different frequencies can be expressed sufficiently accurately by measuring the RMS level in octave bands over the frequency range. This will give about 10 results for each recording, but this may be further simplified if the relative harmfulness of the different frequencies is firmly established.

For example, if the curve given by Miwa[1] is correct, a frequency selective network can be made that will "weight" each frequency according to its harmfulness and a single figure for the level of vibration will be produced. This is analogous to the A-weighted scale used in noise level measurements.

INSTRUMENTATION

If the simplest method of analysis, described above, is all that is required, then the instrumentation would consist merely of a suitable amplifier, weighting network, RMS detector, and meter. However, it is usually better to have the octave band levels. These can be recorded simultaneously with a real time analyzer, but this is an expensive instrument and rather delicate to be exposed to an industrial environment.

The usual method is to record the vibration and analyze it on a later occasion by repeated playback through an octave band filter.

In any case, it is important that the amplifiers are able to cope with the large range of amplitudes that can be present—as much as 60 dB dynamic range. In most cases of industrial vibration, the acceleration rises with frequency—in fact, approximates a constant velocity. It is thus good practice to insert an integrator into the amplifier chain, preferably straight after the accelerometer. Figure 3 shows how this re-

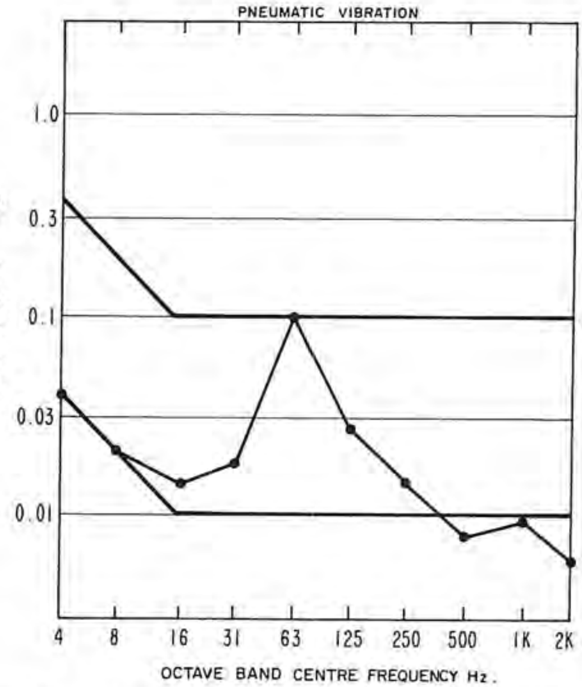

Figure 3. Reduced vibration amplitude range brought about by inserting an integrator between the accelerometer and the amplifier.

duces the amplitude range. The results should be converted back to acceleration by calculation as this is the quantity actually being measured.

Alternatively, the integrator could be replaced by the Miwa weighting network, which would achieve a similar result in compressing the amplitude range but also enable the single vibration figure to be obtained directly if desired.

An amplitude-modulated (A.M.) magnetic tape recorder has a good signal-to-noise ratio (65 dB) and can record over the desired frequency range of 2 Hz to 2,000 Hz at a slow tape speed. However, the playback must be made at a higher speed. If this is eight times the recording speed, then the standard octave filter set, starting at 31.5 Hz, can be conveniently used.

Alternatively, a frequency-modulated tape recorder can be used. This has the advantage of a low frequency response that goes down to D.C., but the signal-to-noise ratio is not as good (45 dB). In particular, any fluctuation of the tape speed will be mistaken for low frequency vibration, whereas in the A.M. recorder, these appear as insignificant frequency variations.

VIBRATION LEVELS IN INDUSTRY

In Figures 4 to 8 are a few examples of vibration levels encountered in the metal working industry. The highest level is produced on a pedestal grinder during the wheel dressing operation (Figure 4).

The result of grinding the flash off a casting is shown in Figure 5 and of balancing a crank shaft, in Figure 6. The operation is basically the same in both cases, but the lower level in the latter is due to using a smoother wheel.

Small pneumatic hand-held grinders show a still lower level (Figure 7). However, a peak may develop in the octave band corresponding to the shaft revolutions because of wear in the bearings.

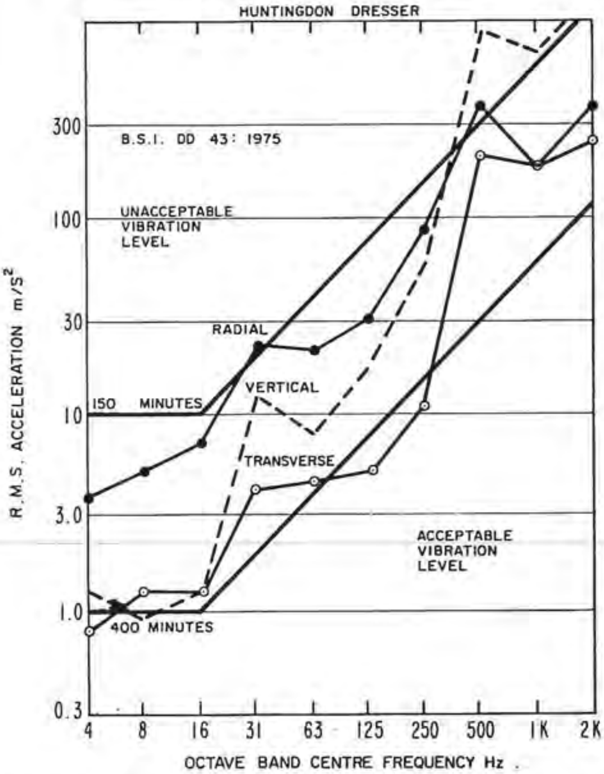

Figure 4. Vibration level produced on a pedestal grinder during wheel dressing operation.

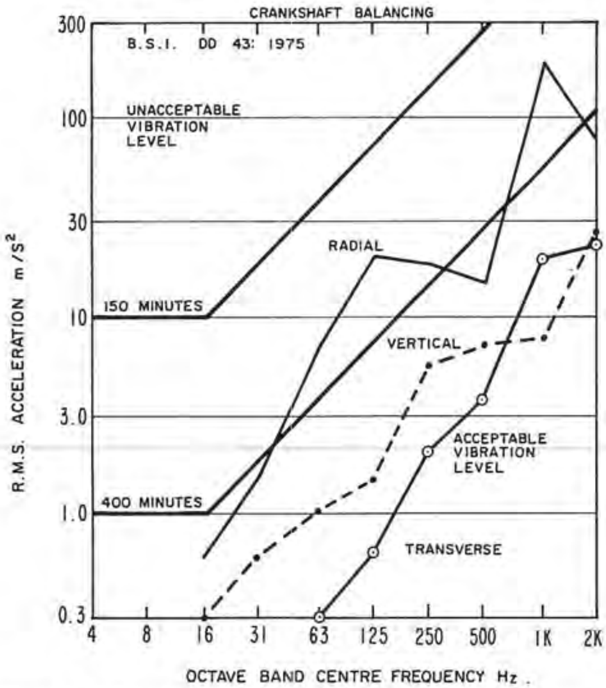

Figure 6. Vibration level produced on a pedestal grinder while balancing a crank shaft.

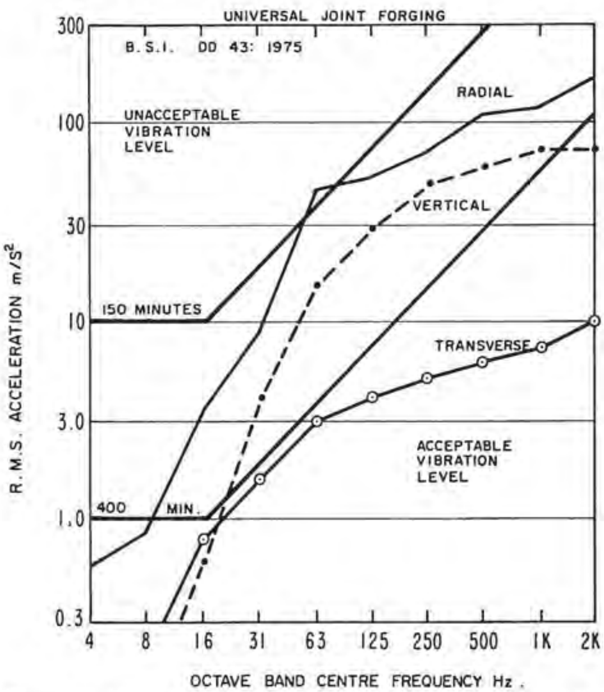

Figure 5. Vibration level produced on a pedestal grinder while grinding flash from a forging.

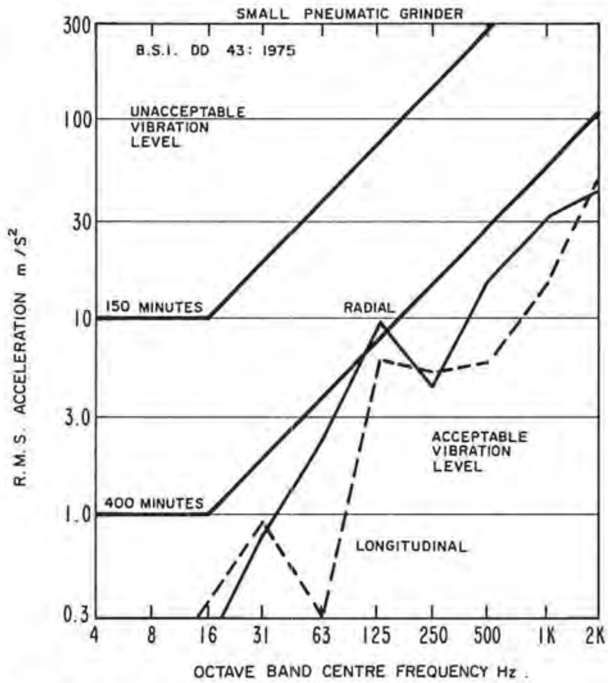

Figure 7. Vibration level produced by a small pneumatic grinder.

Finally, the vibration levels measured by an accelerometer directly on a forging and by a miniature accelerometer (0.5 gm) strapped to the grinder's thumb can be compared in Figure 8. The levels are sufficiently consistent to suppose that the actual hand-glove interface vibration may be being measured.

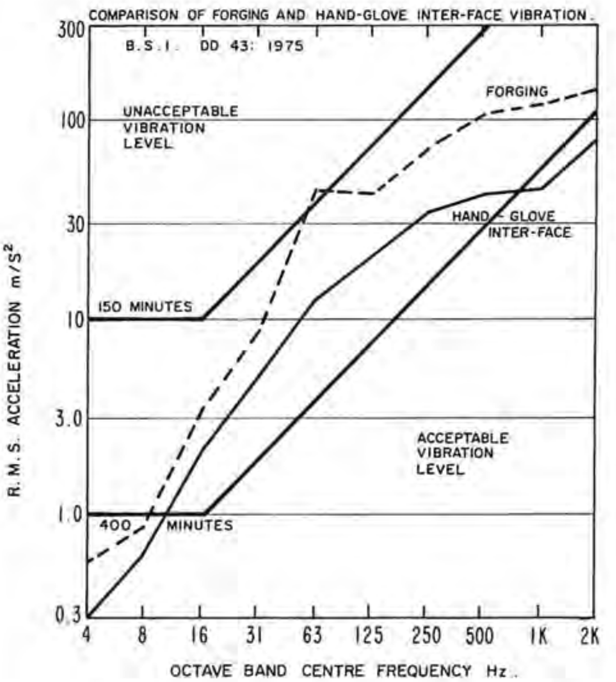

Figure 8. Comparison of vibration levels of forging accelerometer and operator's thumb accelerometer during grinding operation.

REFERENCES

1. Miwa, T.: ISO/TC108/WG7 (MIWA/Japan-4), 35.
2. Louda, L.: ISO/TC108/WG7 (CSSR-4), 26.

QUESTIONS, ANSWERS, AND COMMENTARY

Question (R. Willoughby, Ingersoll-Rand Company): You are not the first researcher who has told us of a number of problems relating to the use of accelerometers, transient spikes, etc. I'd like to address a question to the group at large. Has anyone tried any optical methods of measuring the vibration? It might not be practical for field measurements such as you've been telling us about, but I wonder if they couldn't be used in the laboratory?

Response (D. Reynolds, University of Texas): Are you by any chance referring to Optitron?

Response (R. Willoughby): I'm familiar with the Optitron unit and its capabilities, but I haven't used it for making hand-tool-vibration or hand-vibration measurements.

Comment (R. Kitchener): Let me comment on this. It's difficult to do. You can imagine a holographic approach in theory, looking at the back of the hand. If it's successful, then you can tell the exact movement of every patch of skin on the back of the hand. What on earth would you do with all of that information? What I would like to see is one single figure, and this optical idea seems to be moving away from that, not toward it.

Comment (G. Rasmussen, Brüel and Kjaer Company): Certainly we use optical means for detecting vibration, but calibration is normally done using a laser technique. One main reason is that you have to work with real things, and therefore, you have to work with an absolute type of displacement, referred to a point in space that is fixed. And that is always difficult. Optical techniques have been used, including the Schlierren technique. For example, for measuring the turbulence from jet exhausts, and for that sort of thing, it's very good. But in the cases here, I think there is a problem in using optical techniques. For some things, we could still use the Schlierren technique in the laboratory. But it becomes very elaborate, and I still think that you have far more pitfalls in doing that that way than in using the normal transducer technique. The problems in transducer techniques are not as difficult as indicated here; all of the problems associated with these techniques can to some extent be overcome. But it's all a compromise.

Question (D. Wasserman, NIOSH): I would like to ask Mr. Kitchener why he hasn't considered the use of piezoresistive accelerometers that we and Dr. Reynolds and Dr. Von Gierke's laboratory have found very useful?

Answer and Question (R. Kitchener): Well, what puts me off is that they always quote a maximum permissible acceleration. You can get quite large spikes and the possibility exists of damaging the device. I also get the impression they're somewhat nonlinear and noisy. Perhaps you could tell me what the signal-to-noise ratio is?

Answer (D. Wasserman): The signal-to-noise ratio can be as high as 80 dB. They also have the distinct advantage of being able to go down to D.C., and more importantly, they're self-calibrating. They are very small (pea-sized) and a gram or so in weight. They are commercially available from at least three manufacturers in the United States (i.e., Endevco, Entran, and Koolite).

Comment (D. Reynolds): Let me make one comment on the use of piezoresistive accelerometers. If you ever buy any of them and use them, be sure to buy them damped. Do not get them undamped. We have damaged some that were undamped—they are very sensitive to shock if they are undamped.

Comment (L. Muhic, University of Dayton): I've noticed that in about the last three papers everybody is having this problem. And I don't want to be critical of any equipment manufacturer, but it seems to me everybody has the same problem—how to make equipment originally intended for noise measurements solve vibration measurement problems. I submit, there are many manufacturers of fine vibration equipment, which should be investigated.

Answer (R. Kitchener): Yes, there are, but of course, they are all subject to this D.C. shift problem.

Comment (L. Muhic): They are not all subject to this shift. Also when you refer to maximum g's on the accelerometers, you're referring to an impact figure, and I submit you're not in impact work; you are doing vibration measurements! Even when the signal level is several hundred g's and it is repetitive (for example, several hundred times a second), you're no longer in the impact business. So the number is no longer valid.

Question (D. Reynolds): Have you tried using electrical filters? Using a high pass filter to filter off the D.C. filter signal to get rid of this D.C. shift?

Answer: Yes, but that doesn't help, because it's a repeated shift. It's only a D.C. shift if you have a D.C. amplifier. And if you have an A.C. amplifier (and since these little shifts occur at random intervals and several times a second), it looks like low frequency so you must use a mechanical filter so they don't occur.

Question (H. Rafalski): Can you tell me the advantage of measuring acceleration rather than measuring velocity? As you know in eastern European countries, we use velocity.

Answer: Perhaps you mean, should you report it as velocity? Because I think you'll probably use an accelerometer. If there were, in fact, a suitable velocity transducer, then by all means I would use that. But I don't know of one. Usually velocity measurements are derived from an acceleration measurement.

Question (R. Larsen, Outboard Marine Corporation): I noticed that in one of your graphics you showed your accelerometer attached to the vise in your grinding wheel, and I saw your Microdot connectors there in that hostile environment. Have you had any problem with connecting and reconnecting these positions and getting any contamination in that small Microdot connector? We have! If a minuscule amount of petroleum contaminant is present in that connector, we've found that when you take signals you can get results that are not repetitive! Every time we take those connectors apart, we clean them with a solution to minimize erroneous readings. Have you had that problem?

Answer: No, that's one problem I haven't had. You mentioned petroleum?

Reply (R. Larsen): It's a hydrocarbon vapor in the air causing the problem.

Answer: In this grinding situation, there are all sorts of things in the air. But I don't think petroleum is one of them; a great deal of dust and grit, yes. No, I haven't met any contamination like that.

Question (R. Larsen): We thought that we had to clean those things and clean them very thoroughly to get good repeatable results. When there are results that don't repeat, many times it comes from the integrity of the connection. Concerning the question of using optical devices; we have tried them in the laboratory. They'd work very fine if you can get a place where there is zero movement relative to the earth, but I don't know where you'd find that place. We have tried to build large masses as the reference point from which to measure. We've measured vibrations down to fractions of an inch or less, but this is a laboratory type of convenience. I don't think they can be used practically in the field at all. Another question: you spoke of integrators downstream from your accelerometers. What type of integrators are you using?

Answer: The B & K integrator that goes on the end of a sound level meter.

Question (R. Larsen): Is that an R.C.-type integrator?

Answer: Yes.

Question (R. Larsen): How do you integrate a complex signal with an R.C. circuit?

Answer: Well, quite simply. If it has a slope of 6 dB per octave, that's an integration.

Question (R. Larsen): I've compared results using operational amplifiers where I integrated a complex signal and then compared it with systems we built ourselves with an R.C. integrator. There is just no comparison. I don't know how you integrate a complex signal with an R.C. circuit.

Answer (G. Rasmussen): Well, you can't do that simple integration with an R.C. circuit; it must be correct to the lower limiting frequency of the R.C. time constant. If you do not get correlation, there is an error somewhere in the system you are comparing. This is similar to what we've been talking about here—there's no thing that is completely true. You can have trouble with your connectors. If you use a quartz type of transducer, you have a very high impedance and trouble with leakage, much more than if you use a ceramic device. Now, if you use a piezoresistive device, you have other types of problems in other places. The only thing we can do in this area is to know the limitation of the set-up. I would recommend that everyone use overload indicators or use an oscilloscope directly behind the transducer. You can never be sure what you're clipping in your electronic circuits if you don't do that. I think it is necessary that the user learn as much as possible about these devices and instruments.

Question (C. Wilson, New Jersey Institute of Technology): Could you tell about mounting with Jubilee clips? I don't know what they are. Could you compare them with gluing and stud mounting?

Answer: It's a hose clip, but not without problems! In trying to find what the maximum acceleration was from this pneumatic tool (which I mentioned at the very beginning), I did some experiments. What I found was roughly this—that if I attached the accelerometer to the body of the tool with this hose clip and tightened it as tightly as I could, I appeared to get a maximum shock of something like 5,000 g's. If I stuck the accelerometer on with Eastman 910 glue and screwed it on with a clip as well, I got a peak of about 10,000 g's. So presumably I was sticking it on a bit tighter. Quite honestly, I don't want to know about such high g's. I don't mind a little bit, you see. In a way, hand-arm vibration has advantages; you don't want to go up to too high a frequency. And, of course, this is the real problem. If you want to attach an accelerometer that measures really high frequencies, you have to be careful about the attachment because you always tend to get a bit of compliance. When you screw it on to something, it's never really an absolutely rigid joint; but with hand-arm vibration, you want a bit of resilience. Thus, I think Jubilee clips are adequate in this particular application.

Comment (D. Reynolds): One more comment in regard to the integrators. We've found that when we use the normal size (15 to 20 grams) piezoelectric accelerometers or force transducers, the input impedance to our operation amplifiers has to be on the order of 40 megohms. We find when we go to the miniature piezoelectric accelerometers that, to get low frequency response, we have to go up somewhere in the neighborhood of 100 to 200 megohms. That presents somewhat of a problem, and that's the reason for the charge amplifiers—to give this very, very high input impedance so you can get a low frequency response. And so if you are using an acceleration signal from a piezoelectric accelerometer into an integrator, which has only about 1 megohm input impedance, you can get all kinds of problems.

Comment (R. Lombard, Homelite Corporation): About 10 years ago, I saw a noncontacting vibration measuring device demonstrated—I believe the capacitance type. It was self-calibrating in that if you held it near an object that had relatively low frequency motion, it would eliminate that and just take the higher frequency components. I saw it demonstrated with a man operating a chain saw; the probe was held approximately an inch away from his elbow and we were actually measuring the vibration levels. I believe the name of the device was Array Data.

PROCEEDINGS OF

THE INTERNATIONAL OCCUPATIONAL HAND-ARM VIBRATION CONFERENCE

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Center for Disease Control
National Institute for Occupational Safety and Health

PROCEEDINGS OF
THE INTERNATIONAL OCCUPATIONAL HAND-ARM VIBRATION CONFERENCE

Sponsored by
National Institute for Occupational Safety and Health
Cincinnati, Ohio, U.S.A.
October 1975

Editors:
D. E. WASSERMAN
W. TAYLOR

Manuscript Editor:
M. G. CURRY

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Center for Disease Control
National Institute for Occupational Safety and Health
Cincinnati, Ohio 45226
April 1977

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

DISCLAIMER

The sponsoring of this symposium and publication of this proceedings does not constitute endorsement by the National Institute for Occupational Safety and Health of the views expressed or recommendation for any commercial product, commodity, or service mentioned herein.

DHEW (NIOSH) Publication No. 77-170