AN INEXPENSIVE DIY IMPACT HAMMER FOR VIBRATION ANALYSIS OF BUILDINGS

Dr. Carl Howard
School of Mechanical Engineering
The University of Adelaide
S.A. 5005
carl.howard@adelaide.edu.au

The characterisation of vibration in buildings often involves exciting the building structure with a force and measuring the vibration response. The two common non-destructive force excitation methods are the use of an instrumented impact hammer or an electromagnetic vibration shaker. This paper contains a discussion on how to build a low cost instrumented hammer, and compares the performance of the hammer with a commercially available impact hammer and a commercially available electromagnetic shaker for vibrating buildings. The merits and disadvantages of each of these three instruments are discussed and it is the opinion of the author that for the vibration analyses often conducted in semiconductor manufacturing facilities, laboratories, and offices, the use of an instrumented impact hammer can provide higher quality measurements at a lower cost than the use of an electromagnetic shaker.

INTRODUCTION

The forced response analysis of civil structures can involve the application of enormous forces such as explosive devices and rocket engines to excite dam walls [1], large rotary eccentric mass shakers [2] to excite horizontal motion in the upper levels of skyscrapers (as was used to test the San Francisco Trans-America Pyramid building [3]), to relatively small forces such as a person walking. Each excitation method has its advantages and disadvantages and force / time characteristics that are suited to a particular structural excitation problem. Furthermore, vibration analysts have personal preferences and can justify why their chosen method is more advantageous than another. The focus of the work presented in this paper is the methods used to induce vibration in buildings using relatively small forces imparted by a sledge hammer. Alternative methods might be necessary depending on the type of vibration analysis that will be conducted.

There are several commercially available instrumented sledge hammers that are suitable for vibration and modal analysis of buildings, however they can cost in excess of $5000. An electromagnetic shaker for modal analysis of buildings will cost in excess of $10,000. A cheaper alternative discussed here is the construction of an instrument using a sledge hammer purchased from a hardware store and an accelerometer fixed to the back of the hammer head, which is suitable for some types of vibration analyses of buildings.

The first part of this paper discusses the construction of this Do-It-Yourself (DIY) instrumented sledge hammer. Comparisons between its performance and a commercially available instrumented hammer are used to demonstrate that the DIY hammer has the same results as the commercially available hammer. The second part of this paper contains experimental results of vibration measurements conducted in a semiconductor manufacturing facility using the DIY sledge hammer and a building shaker system. The results show that the use of the sledge hammer gave similar or better results than the shaker system. The last part of the paper contains a discussion of additional factors to consider before selecting the excitation method for a vibration analysis of a building; such as the weight of the equipment and the number of people required to conduct the tests.

Reynolds and Pavic [4] have conducted a similar comparison of a commercially available instrumented sledge hammer and an electromagnetic shaker, and concluded that the use of the electromagnetic shaker gave better quality measurements than the instrumented hammer, based on a single hammer strike. The authors should have compared the average of multiple of hammer strikes to the average of multiple transfer functions using the shaker system. They suggest that a hammer can be used as 'starter' floor modal testing system to obtain results of limited quality. They also claim that the shaker system can impart excitation energy that is many orders of magnitude higher than from hammer impulse excitation. This statement might be true for excitation at a single frequency, however for broadband excitation the results in this paper show the opposite to their findings. The use of a sledge hammer is able to impart greater excitation force to the structure than the shaker system, since the shaker system is limited to vibrating the reaction mass to 1g, otherwise the shaker will lift off the floor. Whilst it is possible to bolt the shaker to the floor, this is usually not permitted by buildings owners. Greater excitation energy can be applied by the sledge hammer by merely swinging it harder, or obtaining a sledge hammer with a heavier mass [2]. Clearly, there is a practical limit for increasing the impact force until the hammer strike can damage the structure, in which case an alternative excitation method must be employed such as an electrodynamic shaker. The findings of Reynolds and Pavic are further discussed at the end of this paper. It is surprising that in an earlier paper Pavic, et.al. [5] describe hammer testing as an " excellent investigative tool..". The use of impact hammers for modal analysis of buildings is well established [2, 5] and this paper shows how one can build a low-cost instrumented sledge hammer.

INSTRUMENTED IMPACT HAMMERS

There are a number of commercially available instrumented impact hammers that are suitable for inducing vibration in buildings. Vendors include Bruel and Kjaer, PCB Piezotronics, Dytran, and Endevco. A commercial-off-the-shelf instrumented sledge hammer can cost in excess of $A5000. An inexpensive Do-It-Yourself instrumented hammer can be constructed using a sledge hammer purchased from a hardware store and an accelerometer glued to the back of the mass of the sledge hammer. The following discussion shows that the DIY sledge hammer will provide results that are of the same quality as a more expensive commercially available instrumented hammer, at a fraction of the cost. The point impedance of a concrete floor was measured using both a commercial and DIY hammer and it is shown that similar results were obtained.

A DIY instrumented hammer was built from a sledge hammer purchased from a hardware store. The mass of the steel head on the hammer was 7.95kg. An aluminium block was glued to one end of a sledge hammer using epoxy glue and a Bruel and Kjaer type 4394 accelerometer was screwed onto the aluminium block. Previous testing using cyano-acrylate (super-glue) was unsuccessful as this type of glue is too brittle for impact loads. The accelerometer can also be attached to the hammer head with a threaded stud, however care must be taken when tapping into the steel head as the material is case hardened and it is very easy to break a tap in the head. A long micro-dot cable was connected to the accelerometer and taped along the length of the handle. The cable was connected to a Bruel and Kjaer type 2635 charge amplifier. A Bruel and Kjaer type 8318 accelerometer was used to measure the vibration response of a concrete slab-on-grade floor and was connected to a Bruel and Kjaer charge amplifier. Both charge amplifiers were set to measure acceleration and their outputs were connected to a two-channel Data Physics ACE signal analyser. The sledge hammer was used to strike two rubber pads, placed on top of each other, that were resting on a concrete slab-on-grade floor. The rubber pads had a total thickness of about 50mm and a durometer rating (the units used to define the stiffness of rubber) of 50. The purpose of the rubber pads is to mechanically filter the impact load so that only low frequency force is applied to the structure, which in this case is the concrete floor. Lower durometer (softer) rubber pads that are thinner are also suitable for impact testing, however care must be taken to ensure that the hammer does not pierce the soft rubber, which will degrade the repeatability of the measurements after several strikes. The useful frequency range for a hammer and rubber pads is a function of the system resonance frequency which is given by the square root of the contact stiffness divided by the mass of the hammer head [2], and can be checked by examining the autospectrum of the force pulse. For frequencies above the system resonance, it is difficult for the hammer to impart energy into the structure. As a guide, doubling the useful frequency range would correspond approximately to one-quarter the pad thickness (for constant material properties). The magnitude of the impact is determined by the mass of the hammer head and the velocity with which it is moving when it strikes the rubber pads [2]. The operator controls the velocity rather than the force level.

The commercially available hammer that was used for the comparison was a PCB Model 086D20 instrumented impact hammer that has a 1.1kg head, an ICP powered force transducer between the steel head and inter-changeable rubber tips of various stiffnesses. The force transducer on the PCB hammer was connected to the PCB ICP voltage amplifier. A Bruel and Kjaer type 8318 accelerometer was used to measure the vibration response of the floor.

It is beyond the scope of this paper to discuss the signal processing methods appropriate for impact testing. There are many references that discuss appropriate testing methods for modal analysis using an impact hammer [2, 5-10].

Figure 1 shows the measured accelerance of the concrete slab-on-grade floor using the two types of hammers. The accelerance is the acceleration response of the floor, in m/s^2, divided by the force applied by the hammer, in Newtons.

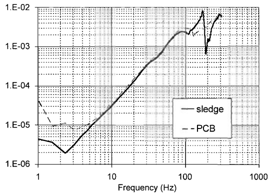

Figure 1: Comparison of the measured accelerance of the floor using the sledge hammer and the PCB hammer.

The results show that the accelerances are similar from 6Hz to 100Hz. Note the expected 40dB / decade increase over the frequency range. The response around 100-200Hz is the contact response. This is a function of the hammer mass and rubber stiffness. The commercial impact hammer has a lower quality factor (which is desirable) due to the prudent selection of material. The difference between the two systems occurs above 100Hz which is due to the different force impulses provided by each hammer. The PCB hammer contains a calibrated force transducer that measured the force applied during the impact event directly. The DIY sledge hammer has an accelerometer attached to the head to measure the acceleration of the head. The impact force from the hammer is calculated by multiplying the mass of the hammer head (7.95kg) by the measured acceleration. The mass of the hammer head is measured by placing the hammer head on weighing scales while holding the end of the handle horizontal. Figure 2 show the comparison of the impact forces applied to the concrete floor.

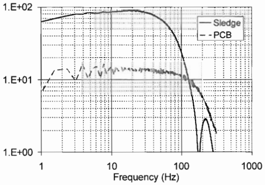

Figure 2: Impulse generated by the sledge hammer and the PCB hammer.

Figure 2 shows that the force exerted by the sledge hammer has a sharp roll off beginning at 30Hz as it approaches a resonance at 220Hz. This resonance is caused by the interaction of the two rubber pads and the hammer head. This is not likely to be an issue for the structural evaluation of buildings as the frequency range of interest is below 100Hz. If the frequency range of interest is greater than 100Hz, an alternative stiffer or thinner rubber pad can be used to generate a different impulse response spectrum.

These results show that the DIY sledge hammer can be used to accurately measure the vibration response of structures such as buildings.

The following section describes the comparison of the experimental results obtained using a DIY instrumented sledge hammer and an electromagnetic shaker to induce vibration in a semiconductor manufacturing facility.

COMPARISON WITH A BUILDING SHAKER SYSTEM

The shaker used to excite buildings in this study was an APS Dynamics Electro-seis Model 113 shaker, that comprises a 13.3kg reaction mass which is suspended by elastic bands, and a flat magnet and electrical coil assembly that is used to move the mass along bearings. The shaker was electrically connected to an APS Model 114-EP power amplifier, which was purpose built to provide high current levels at low frequencies to the electrical coil on the shaker. Typical power amplifiers for audio applications are not designed to generate high current levels at frequencies below about 20Hz.

A comparison was made of the results obtained from the vibration measurements in a semiconductor manufacturing facility using this shaker system and a DIY instrumented sledge hammer. Whilst the building design of semiconductor manufacturing facilities is in a special class of its own, the same comments are also applicable to buildings that use typical construction methods using steel and concrete frames for office buildings, hospitals, sporting stadiums, and car parks.

Semiconductor manufacturing facilities are unique types of buildings that are purpose built for housing extremely vibration sensitive manufacturing equipment. These buildings are designed to have very stiff floors compared to conventional buildings. This is done to support the vibration sensitive equipment and also minimise vibration transmission through the building from vibration sources such as mechanical equipment (for example pumps and air handling units), and from the vibration induced by people walking on floors.

Figure 3 shows a typical design of a building for a semiconductor manufacturing facility. A typical design of the process floor is two-way grillage (also known as a waffle floor, because of the similarity to a cooked waffle) of 60cm thick concrete beams and supported on closely spaced columns. The sub-fab level contains mechanical equipment that generates vibration, such as pumps.

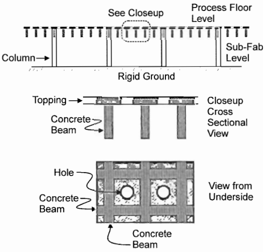

Figure 3: Typical building design for a semiconductor manufacturing facility.

During the commissioning phase of the facilities, often a structural evaluation is conducted to ensure the vibration environment within the building meets the design specifications. Typical investigations involve the measurement of the resonance frequencies of the floors, the ambient vibration amplitude induced by operating mechanical equipment, the vibration attenuation between different floor levels, and the vibration attenuation with distance along the floors [12]. For most civil structures, if the vibration levels are too high, the building owner usually does not care [11]. However, for this type of building if the vibration levels are too high then the manufacturing equipment will not function.

The author has conducted numerous structural investigations of semiconductor manufacturing facilities using an electrical shaker system and an instrumented hammer. Both excitation systems were used at one manufacturing facility to compare the advantages and disadvantages of each system.

Figure 4 shows a sketch of the experimental set up for the vibration measurements in the semiconductor manufacturing facility.

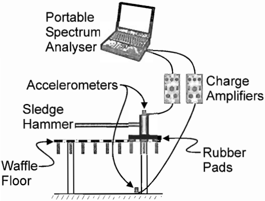

Figure 4: Sketch of the experimental setup for the vibration measurements in a semiconductor manufacturing facility.

The top of a column on the process floor was driven by a vibration source and the vibration response was measured at the base of the column in the sub-fab. This measurement was conducted using both the shaker system and the sledge hammer as excitation sources. When the shaker was used as the excitation source, the ACE signal analyser was used as a signal generator to output a swept sine wave in the frequency range 5Hz to 95Hz into the power amplifier. The shaker's power amplifier was set to the maximum amplification such that the moving mass did not strike the ends stops or cause the shaker to lift off the floor. The limitations on the operation of the shaker are that the acceleration has to be kept to less than 1g, otherwise the shaker will lift off the floor, and the stroke of the moving mass has to be kept below 150mm peak-to-peak otherwise it will strike the end stops. Hence, when using a swept sine wave as a control signal, the maximum displacement of the shaker's moving mass is governed by the acceleration at the highest frequency of the analysis range, which must be kept below 1g. The analyser was configured to collect 30 linearly averaged spectra and the recording was triggered by the start of a sine sweep from the signal generator.

The measurements using the DIY instrumented hammer were conducted using a force-exponential window to capture the dynamic response of the structure. The exponential window applied to the signal for the response of the floor was made as long as possible so as not to distort the results and give the impression of an artificially highly damped structure. This measurement involved collecting 10 linearly averaged spectra. However, usually the results are very repeatable and only 5 linearly averaged spectra are collected for most structural evaluations.

Figure 5 shows the accelerance measured using the two structural excitation methods. Both methods clearly show that the resonance frequency of the column system is about 44Hz. Note that the hammer response compares well against the expected 40dB / decade rise, whereas the shaker driven response does not. The results differ at frequencies below 30Hz, which is due to the loss of signal coherence in the shaker system. The corresponding coherence between the signals for these two structural excitation methods is shown in Figure 6. Figure 6 shows that the coherence using the hammer is consistently greater than using the shaker and extends to a lower frequency range. The reason for the drop in coherence for the shaker system is the lower amplitude in the excitation force compared to the sledge hammer, which is further discussed below.

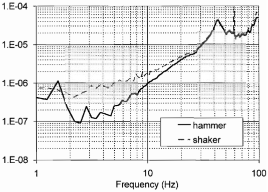

Figure 5: Accelerance between vibration excitation on top of the column and measuring the response at the base of the column in the sub-fab, using the shaker and the hammer as excitation.

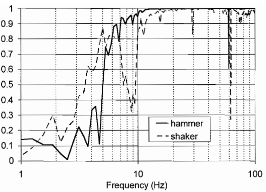

Figure 6: Coherence associated with the measurements shown in Figure 5.

Another comparative measurement was conducted between the two excitation methods by shaking the mid-bay of the process floor and measuring the vibration response at the mid-bay in the sub-fab directly below excitation point. Figure 7 shows the accelerance measured using the two excitation methods, and the results are different at frequencies below 20Hz and above 50Hz.

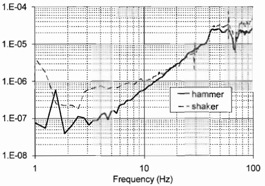

Figure 7: Accelerance measured between excitation of the mid-bay on the process floor using the sledge hammer and the shaker system, and measuring the vibration response of the mid-bay in the sub fab.

Figure 8 shows the coherence for this measurement and reveals that greater coherence is obtained using the instrumented sledge hammer than the shaker system.

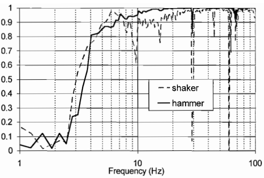

Figure 8: The coherence measurements associated with Figure 7.

Figure 9 shows the excitation force that was applied at the mid-bay of the process floor which is associated with the results shown in Figures 7 and 8. The amplitude of the force applied by the sledge hammer to the floor is greater than the shaker system. This is not a surprising result because greater force can be imparted by the sledge hammer merely by swinging harder, whereas the shaker is limited to the force generated by the reaction mass moving at an acceleration of 1g.

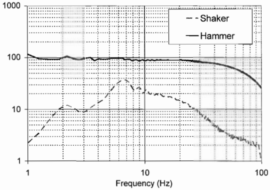

Figure 9: The excitation force from the sledge hammer and the shaker into a mid-bay on the process floor.

These measurements demonstrate that an inexpensive DIY instrumented sledge hammer can be used to conduct structural evaluations of buildings and, in this case, yielded better results than using the shaker system. This is because, in this case, the sledge hammer provided greater excitation force than the shaker system. The acceleration of the shaker system has to be kept below 1g, otherwise it has to be physically attached to the structure. It would be possible to increase the force output from the shaker by using a feedback controller to maximise the force output at each frequency, however this was not available for the testing.

Although results have not been presented in this paper, this sledge hammer system has been used successfully to measure the mode shapes of very stiff floors that support photolithography tools in semiconductor factories, office and laboratory floors and obtain measurements of the horizontal stiffness of buildings such as laboratories and semiconductor factories. The use of an electrodynamic shaker could also provide the same results.

ADDITIONAL FACTORS TO CONSIDERS

The combined weight of the shaker system, power amplifier, carry cases, and instrumentation is in excess of 120kg and is housed in three or four large carry cases. This heavy load requires two people to carry the equipment. The equipment has to be couriered to the building site well in advance of the testing. Upon arrival at the destination airport, the equipment has to be transported in a large vehicle. Vibration measurements on buildings usually occur late at night once all construction activities have ceased for the day. During this time construction lifts are unavailable so people have to carry the equipment up and down flights of stairs.

Reynolds and Pavic [4] describe a similar comparison between building excitation systems using an electrical vibration shaker and an instrumented hammer and reached the opposite preference to that described here, that the shaker system is the preferable measurement method. Reference [13] shows a photograph of their " portable measurement system" that costs between £20,000 [4] and £70,000 [13] and requires three people to operate efficiently [4].

The equipment for the DIY instrumented sledge hammer can fit into a hard cased golf carry bag and transported by air within the luggage limits of most airlines. The equipment can be carried by one person. It is recommended that two people are involved for the efficient operation of measurements [4]. The equipment is relatively light-weight compared to shaker system and is easily carried up and down flights of stairs by a single person.

It is left to the judicious reader to decide on which method is preferable based on the capital and labour costs, measurement efficiency, manual handling, time constraints, and desired quality of results.

CONCLUSIONS

This paper describes the construction of a relatively inexpensive instrumented sledge hammer for use in vibration analysis of building structures. The DIY sledge hammer was compared with a commercially available instrumented hammer to ensure that accurate vibration results could be obtained. The DIY sledge hammer was also compared with an electromagnetic shaker system for exciting buildings. Tests were conducted in a semiconductor manufacturing facility that has very stiff floors compared to conventional buildings. The results show that greater force could be imparted to the building structure by the sledge hammer than the shaker system. This result was not surprising as the greater excitation force can be applied by swinging the hammer harder, whereas the shaker system is limited to a maximum acceleration of 1g before the shaker lifts off the floor. From his experience, it is the opinion of this author that the DIY instrumented sledge hammer is cheaper, provides higher quality results, more easily transported, requires less people to perform measurements, and is quicker to use on-site compared to an electromagnetic shaker. However, in some situations where tonal excitation is necessary, the use of an electromagnetic shaker may be preferable.

ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge Colin Gordon and Associates for providing the experimental data presented in this paper.

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