Handout 7 – Experimental methods

The material in this handout is not examinable

So far we have looked at calculating:

- vibration mode shapes and natural frequencies
- forced harmonic response and transfer functions
- transient response (forced or from initial conditions)

But how do you actually go about measuring a transfer function in practice? There is a huge variety of methods, and what is 'best' very much depends on the application and what you are trying to measure. Here we focus on the most common methods for vibration measurements of 'typical' engineering structures.

In order to make any transfer function measurement we need:

- a known input excitation (*instrumented input*)
- a measurement of the response (*sensor*)
- a way to condition the signals (*amplifiers and filters*)
- a way of storing and processing the data (*data logger*)

Stepped sine method (Part IB textbook method)

Reminder of linear systems theory:

To measure the transfer function of a linear time-invariant system (which could be visualised as a Bode or Nyquist diagram):

1. Input a sinusoid of a known frequency and amplitude
2. Wait for transients to decay
3. Measure the gain and phase shift with respect to the input signal
4. Repeat for a range of frequencies of interest

Choose excitation: soundcard output from computer
Choose measurement: microphone input from computer
What is the ‘system’ being measured? [Amplifier + speaker + room + microphone] characteristics
see `HS_TF_stepped_sine.m`

Other kinds of input

The stepped sine test is reliable and accurate, but slow. When we are dealing with linear systems, it is much more common to use signals that span a range of frequencies and use Fourier analysis to identify the transfer function:

This is valid over all frequencies for which $F(\omega)$ is not zero, or in practice not too small. So the process becomes:

1. Apply a broadband input signal $f(t)$ with frequency content that spans the range of frequencies of interest
2. Measure the response $y(t)$
3. Compute the Fourier Transforms $F(\omega)$ and $Y(\omega)$: actually we usually have sampled data so we need the DFT, which can be computed efficiently using the FFT.
4. Calculate the ratio $Y(\omega) / F(\omega)$ to give the transfer function $G(\omega)$

Common choices for input signals include

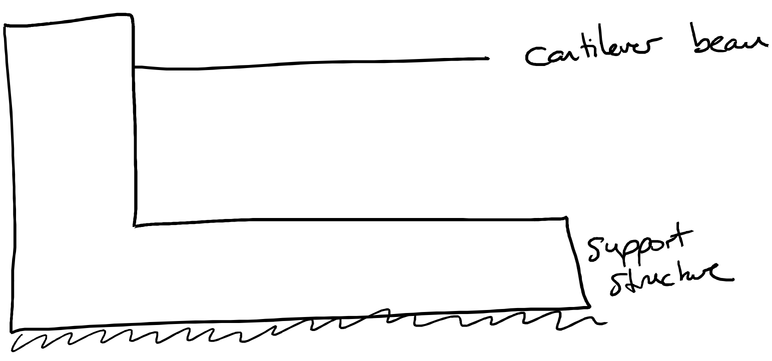
- *Impulse*: probably the most common method for structural vibration. Can exceed the operating ranges of speakers / microphones so this is less common for acoustic measurements.

- *Step*: sometimes it is easier to apply the integral of an impulse, e.g. by suddenly setting a drillstring into rotation, or by pulling a wire until it snaps

- *Noise* ('white' or 'pink' noise): all frequencies are simultaneously present while the signal is being emitted. Very simple to implement as it is commonly available on signal generators. See `H7_TF_noise.m`

- *Sweeps* or 'chirps': a common method for applying a range of frequencies over a chosen time window. Fairly simple to implement as it is commonly an option for PC-based signal generators. See `H7_TF_sweep.m`

A typical structural vibration measurement (the 3C6 experiment)



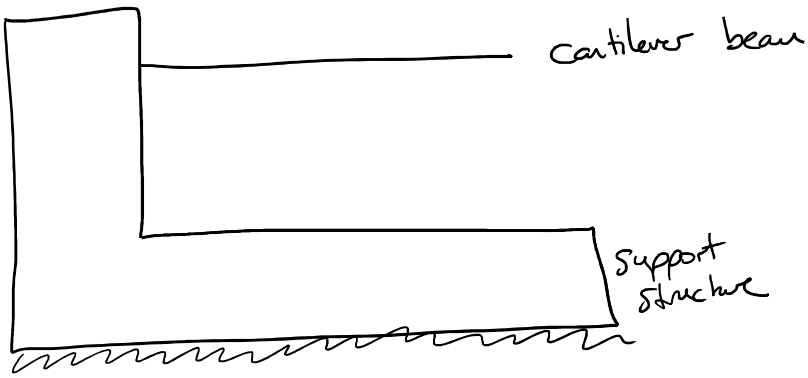
Input: shaker
- stepped sine input
- noise input

Sensors:
- accelerometer
- output voltage from signal generator

Amplifiers:
- power amplifier
- charge amplifier for accelerometer

Data logger:
- Data Acquisition Card
- PC
- Jim's datalogger software

In the experiment you also swap out the shaker and use an instrumented impulse hammer as the input. The setup becomes (changes in bold):



Input: **impulse hammer**

Sensors:
- accelerometer
- **force transducer**

Amplifiers:
- charge amplifiers for accelerometer **and force transducer**

Data logger:
- Data Acquisition Card
- PC
- Jim's datalogger software

We will now briefly consider the main components in turn.

Accelerometers

There are several kinds of accelerometer, but a common type for laboratory tests is the piezoelectric accelerometer. It consists of a small mass mounted onto a piezo-crystal element, supported by the accelerometer housing. When the base of the accelerometer oscillates, the force required to accelerate the small mass is provided by the piezo-crystal element which in turn produces a charge in proportion to its compression or extension.

The charge is small and is easily corrupted by electromagnetic noise, so careful shielding is required on the cables coming from the accelerometer. The charge signal is amplified using a charge-amplifier circuit.

Things that can go wrong:

Problem	Solution
Insufficiently sensitive accelerometer	Use a bigger accelerometer, or turn up the gain
Signal clipping or saturating	Use a smaller accelerometer, or turn down the gain
Internal resonance	Use a smaller accelerometer (and check the datasheet)
Mounting resonance	Attach the accelerometer more securely
Insufficiently responsive at low frequency	Use a bigger accelerometer

And a couple of other things to note:

- Charge amplifiers can't measure DC acceleration as there is always a bit of 'charge leakage': there's a limit to how low frequency is possible to measure.

- They add mass to the structure: you can use a smaller accelerometer, or if added mass is really important to avoid then there are non-contact ways of measuring motion (e.g. laser vibrometer)

Shakers

These essentially act as a loudspeaker where the speaker cone is attached the structure by a rod (called a *stinger*). A strong permanent magnet is at its core, and a permeable material (e.g. soft iron) is assembled around the magnet to concentrate the magnetic flux across a narrow air gap. A light-weight coil fits inside the air gap: the coil is attached to the connection point to the structure (the *load table*). The load table is connected to the frame by a *support flexure* which allows motion in the excitation direction but which keeps the moving coil aligned inside the small air gap.

Characteristics of shakers:

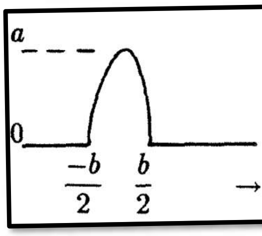
- Add mass to the structure (standard small lab shaker has a moving mass around 20g)
- Add damping
    - motion induces a back-current in the coil which gives a force approximately proportional to velocity. Amount of damping depends on what the shaker's electrical terminals are connected to.
    - material damping in the support flexure / a little bit of friction
- Performance is best when force is large and displacement is small (don't place them at antinodes of vibration modes, or if you do don't drive them too hard)
- They have a maximum displacement before they hit end-stops (limited throw)
- They can deliver a wide bandwidth of force input
- It's hard to measure the force applied to the structure:
    - Can estimate force using measurement of signal input to shaker
    - Can try to measure force using a force transducer between the stinger and the structure, but need to apply mass compensation otherwise they act like an accelerometer

Impulse hammers

The word 'hammer' gives the wrong impression: they are not for hitting structures hard, they are instruments for delivering small amplitude short duration pulses of force. The key component is a force transducer, which measures the compression between its two ends using a piezoelectric element sandwiched between the contacting surfaces. A small hammer tip is mounted on one side and an appropriate mass is mounted on the other side.

Waving the hammer in the air causes negligible signal, because the mass on the hammer-tip side is very small. When the hammer hits a structure, then it acts like a mass (the mass on the back) bouncing on a spring (the hammer tip). Once contact has ended, the signal returns to zero. So it measures the force input to the structure without adding any mass. Therefore a typical force profile is approximately a half-cosine shape.

The Fourier Transform of the pulse shape (or the FFT) tells us about the frequencies excited by the hammer, i.e. the bandwidth of the force input. From the electrical databook the Fourier Transform of a half-cosine pulse is:

 half-sine pulse	$\frac{ab}{2}\left[\text{sinc}\left(\frac{\omega b-\pi}{2}\right)+\text{sinc}\left(\frac{\omega b+\pi}{2}\right)\right]$

For a pulse duration of T seconds: $F(\omega)=\frac{aT}{2}\text{sinc}\left(\frac{\omega T-\pi}{2}\right)$

which is zero when $$\frac{\omega T-\pi}{2}=n\pi$$

$$\omega=\frac{(2n+1)\pi}{T},\quad \text{where}\quad n\geq 1$$

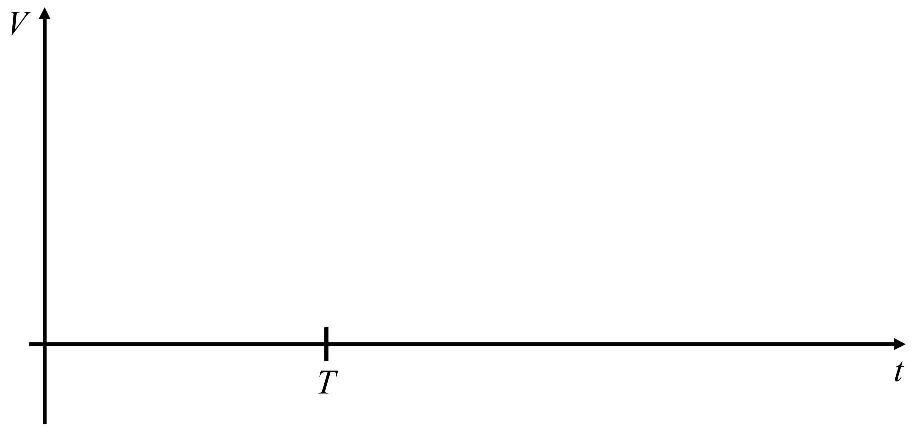
giving the first zero (n=1) at $\omega=\frac{3\pi}{T}$, or $f=\frac{3}{2T}$

So as an easy rule of thumb, we can take the approximate bandwidth of the pulse to be: $f=\frac{1}{T}$

And to change T we can change the mass on the back, or change the stiffness by using different materials and shapes for the hammer tip.

Signal processing artefacts

In practice, the measured impulse looks slightly different to the ideal half sine pulse:



There are two main reasons for this:

1. Piezoelectric force transducers cannot measure DC force so they effectively act as a *high-pass filter* with a slow time constant (low frequency 3dB cutoff)
2. The output of the hammer signal is sometimes filtered by a *low-pass filter* to avoid aliasing (3dB cutoff frequency below $f_s/2$ but high enough to span bandwidth of interest)

See `H7_hammer_pulse_spectrum.m`

Data acquisition (sampling)

We need a way to take the amplified signals and connect them to a computer for storage and processing. The key component here is the data acquisition card (DAQ) which samples and quantises all the signal channels. It's important to know the allowable range of input voltages for the DAQ: the typical cards used at CUED accept ±5V. There are two things to get right:

- the size of the input signals: so that all channels use most of the available voltage range, otherwise there will be unecessary quantisation noise;

- the sampling rate: this needs to be chosen to be at least twice the highest frequency content of the signal to avoid aliasing. In practice the frequency content of signals does not drop to zero, but reduces until it reaches a 'noise floor'. One way to deliberately limit the signal bandwidth is to pass the output of measurements through a low-pass filter, and set the sampling rate to be at least twice the cutoff frequency (and allowing for a transition band of the filter). For linear systems then we often have control over the input bandwidth (e.g. pulse duration), and that will cause a natural roll-off in the response. One rule of thumb is to make sure that the magnitude at the highest measured frequency is at least 60dB lower than the magnitudes at lower frequencies. This would mean choosing the sampling rate to be 50/T.

Summary

- To make a vibration measurement we need: an input; sensors; amplifiers; and a data acquisition system (e.g. sound card).

- Inputs can be: impulse hammers; shakers; loudspeakers. These options allow a variety of kinds of input to be applied to the system.

- The useful bandwidth of an impulse hammer is around 1/T (where T is the pulse duration).

- Accelerometers are the most common structural vibration sensor: large accelerometers are more sensitive and measure lower frequencies; small accelerometers have a higher bandwidth and add less mass to the structure.

- Amplify the signals such that they use most of the allowable range of the data acquisition system

- Choose the sampling rate to be at least twice the highest frequency content of the signal. For an impulse hammer signal one rule of thumb is to sample at $f_s = 50/T$.