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DESIGNING FOR GOOD VIBRATIONS

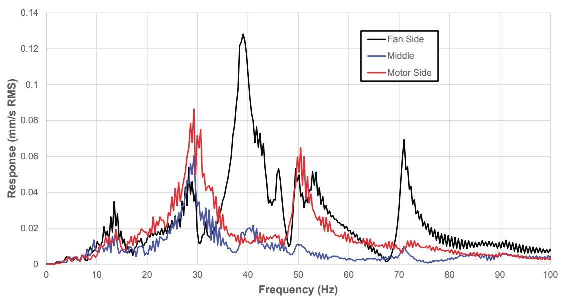
Dr John Irons, Halifax Fan UK, and Diane Wang, Halifax Fan China, explore fans and anti-vibration mounts.

Fans are used to move air and process gas in many industries, including cement plant applications. Large fans are typically put on substantial foundation blocks at ground level and, for other fans, there are a variety of solutions ranging from bolting a fan to steelwork, bolting a fan to the floor, and bolting a fan at ground level to a thicker floor section. The location of the fan will depend on customer requirements and knowledge of how the fan will interact with the structure supporting it.

Foundation blocks can represent a substantial cost and a substantial impact on the installation time. Fans are most often installed in existing plants, typically for new processes or replacing existing fans at an available outage. However, on existing plants, there is often a lack of construction drawings and the potential deterioration of structure. This deterioration would not be significant enough to affect the structural integrity, but may affect the structure's stiffness. There is also often a lack of accurate underground cable and pipe details. This means that digging a substantial hole in the ground can represent a major risk. At a minimum, there may be substantial cost over runs associated with rerouting cables or pipes. Of more significance, there could be an unplanned plant shutdown associated with a cable or pipe being broken.

The location of a fan can also be an issue. Where there are constraints on the fan location, there may be implications on the length of duct runs. Extensive duct runs can be a substantial installation cost, especially with the highly erosive dust seen in the cement industry. In addition to installation cost, there can be cost associated with heat loss. Another aspect to consider, especially with large dust loads and high temperatures, is that it might not be possible to install in-duct silencers. With no in-duct silencers, duct breakout noise (the noise coming out of the duct), can become an issue. The larger a noise source, i.e. the longer the duct, the larger the noise effect for a given breakout sound pressure. This means that, especially with no in-duct silencer, ducting can be a substantially greater noise source than the fan itself. This is often the case in plants where there is high work level noise.

With the desire to avoid foundation blocks and long duct runs, many fans are installed on anti-vibration mounts.



Horizontal bump test on steelwork under a fan.

Large cement fan on floor close to process using anti-vibration mounts.

Large cement fan at ground level. Ducts rising to process using anti-vibration mounts.

Vibration behaviour of fans on anti-vibration mounts

The basic approach to designing fans to operate on anti-vibration mounts is to have the vertical bounce mode at about 10% of running speed, to give 90% isolation. This would imply that that the fan can only move one way on anti-vibration mounts: up and down. This simplified approach to assessing anti-vibration mounts enables the anti-vibration mounts to be selected based on the fan weight. It also aligns with the anti-vibration mounts being selected based on the vertical stiffness – usually the only stiffness readily available for anti-vibration mounts.

A lumped mass has six degrees of freedom: three linear and three rotational. This means that fans and other machines have six distinct modes of behaviour on anti-vibration mounts. These modes are essentially as follows:

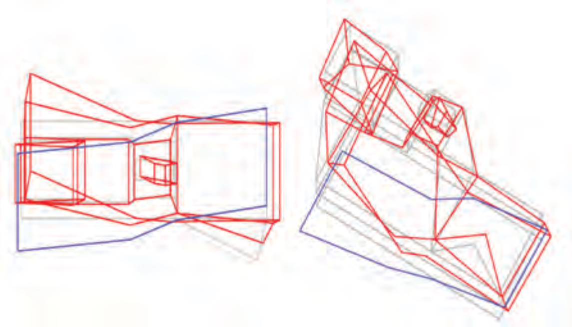
- Vertical translation.
- Vertical rotation.
- Horizontal rotation about the spring centre.
- Axial rotation about the spring centre.
- Horizontal rotation about the centre of mass.
- Axial rotation about the centre of mass.

Looking vertically down, the centre of mass is surrounded by the anti-vibration mounts, so there are separate linear and rotational modes. However, looking from the side it can be seen that the centre of mass is above the anti-vibration mounts. This is why there are two combined linear/rotation modes for the axial and horizontal modes. These are rigid body modes associated with the spring distribution and mass distribution. This means that they can be calculated using formulae. A finite element analysis is not required.

The way a fan will move depends on the mode closest to running speed. For fans on foundation blocks, where the soil and piles act like anti-vibration mounts, the middle two modes are usually closest to the running speed, so a fan on a foundation block typically has the lowest vibration at ground level and higher vibration at the bearings. For fans on anti-vibration mounts, the last two modes are typically the modes with the highest natural frequency. It is also typical for fans to have the centre of mass close to the shaft centre-line. So, when the fan is running at full speed there is relatively low vibration at the bearings and there can be relatively high vibration at the base where the anti-vibration mounts are located. There will also be relatively high vibration at the fan discharge.

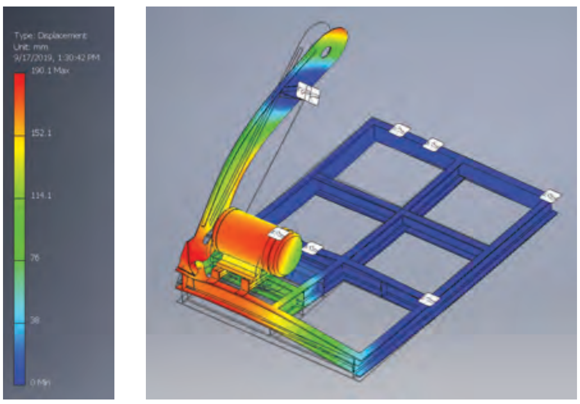
For fans, anti-vibration mounts are normally designed to be equally spaced, taking into consideration geometry constraints. It is often the case that, with identical anti-vibration mounts, the fan would not sit level on level ground. This would mean that the fan would have to be levelled when installed. To ensure that the fan sits level, calculations would have to be carried out to determine the correct anti-vibration mount to use for each location. This often results in at least two or three stiffnesses being used for a fan. For slower fans, the impeller and casing would normally be the heaviest part of the assembly, so would have the stiffest anti-vibration mounts. For faster fans, 3000 RPM or 3600 RPM, the motor would normally be the heaviest part of the assembly, so these would have the stiffest anti-vibration mounts.

If high vibration forces are predicted, for example fans that are expected to go out of balance, then it may be that the optimal anti-vibration choice for natural frequencies results in springs that are too soft. Increasing the spring stiffness while keeping the natural frequencies the same requires the mass to be increased. This method is known as having an inertia base. One method used with fans is to have the fan on a base-frame and to fill the base-frame with concrete. For some large fans (e.g. power station main air fans), the fan can even be on a concrete block supported by anti-vibration mounts.



Vibration survey of fan on steel support structure. Grey – undeflected, red – fan, blue – steel support structure.

Belt-driven fan on anti-vibration mounts.



Simplified finite element model used to solve belt-driven fan motor vibration problem.

Types of anti-vibration mount used with fans

There are two main types of anti-vibration mount: those based on springs and those based on rubber. Both the spring type and the rubber type are well established designs. There are a variety of ant-vibration mounts with similar load carrying and stiffness characteristics. However, this does not mean that there are not design features that differentiate the manufacturers.

Spring anti-vibration mounts are the most flexible of the two main types. Changing the coil diameter allows manufacturers to offer a range of anti-vibration mounts with the same geometry but with different stiffnesses. The number of springs can be increased from one to two or four, giving higher stiffness solutions. For fans, typical applications use anti-vibration mounts with one or two springs. Spring anti-vibration mounts are typically designed with the intention that the operating height is between 20 mm and 25 mm. However, special solutions can be offered with higher deflection. This would be to give the same strength with a lower anti-vibration mount solution.

Both spring anti-vibration mounts and rubber anti-vibration mounts are bolted to the support structure and the fan. For spring anti-vibration mounts, the bolt connecting the fan to the anti-vibration mount pushes on a pressure plate on top of the spring. The fan level is adjusted by screwing down the bolt, increasing the gap between the top of the spring and the fan base. Screwing down the bolts does not increase the average spring compression, as the springs are being compressed by the fan weight. However, it will increase the deflection of the spring under the bolt. If care is not taken, the result can be that an anti-vibration mount becomes spring bound. When this happens, the anti-vibration mount stiffness will increase dramatically, which can cause vibration problems. When the anti-vibration mounts are all levelled, the nut is tightened to fix the bolt position.

For spring anti-vibration mounts, the fan effectively sits on top of the springs. Therefore, some form of constraint is required. For some spring anti-vibration mounts, the spring is inside a pipe with a cup over the pipe to limit the movement of the fan on the springs. Another arrangement is to use pins to constrain the movement. If excessive movement is expected, for example earthquake-prone regions or ships, stronger constraints are required. These can be built in to the anti-vibration mounts. It is also possible to use independent constraints, such as vibration buffers, to constrain the fan.

Rubber anti-vibration mounts are available in two types: unconstrained and constrained. Unconstrained rubber anti-vibration mounts are essentially rubber mats or blocks, and work on the compression of the rubber. These tend to not be used with smaller fans. Constrained rubber anti-vibration mounts are essentially a cup on a cone connected by rubber. This type of anti-vibration mount works on the shear of the rubber. Different grades of rubber can be used to give different stiffnesses. The operating deflection is less than that for spring anti-vibration mounts, 6 mm being typical. There is also no internal method for levelling rubber anti-vibration mounts, so shims would have to be used. Controlling the stiffness of rubber is more difficult than controlling the stiffness of steel springs, which means that there is more variation in the stiffness of rubber anti-vibration mounts.

When the anti-vibration mounts have been set up correctly, anti-vibration mounts essentially work by using the fan mass to react against the vibration forces. This means that there is no advantage from the inherent damping in rubber anti-vibration mounts. The advantages of rubber anti-vibration mounts are their lower cost and simplicity. The advantages of spring anti-vibration mounts are that, especially for fans weighing over 1000 kg, they are much easier to level and, with stainless steel springs, can provide a solution that is resistant to chemical attack.

Problems with fans on anti-vibration mounts

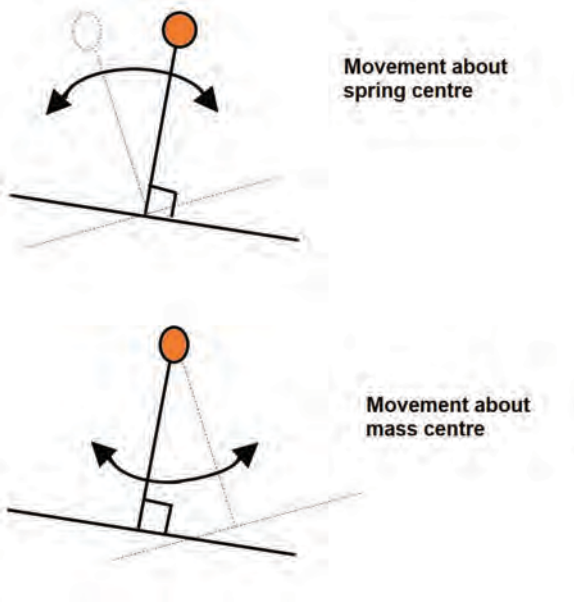
The problems that occur with fans on anti-vibration mounts are essentially vibration problems: vibration of the fan, the motor, or the support structure. Some of these problems can be operational problems and some of them can be design problems.

In order for the fan on anti-vibration mounts to work correctly, the loads on the anti-vibration mounts need to be assessed. The main loads will usually be masses. There can be issues with the loads not being properly calculated, one of the main issues being that lagging and cladding can be ignored. In addition to mass loads, the pressure load can be significant, especially for high pressure fans, either fans operating in a high process pressure or fans with a high pressure rise. Where the loads have not been calculated effectively, the anti-vibration mounts can become overloaded.

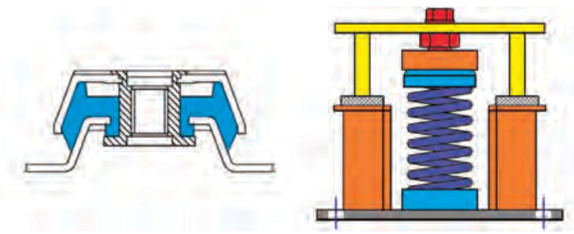
A common problem with fans on anti-vibration mounts is connections – mainly duct connection but also potentially cable connections. The fan will have been designed without any knowledge of how the ducting or cabling has been designed or supported. Therefore, it will have been designed assuming that these have no stiffness. This means that the duct should be connected using flexible joints, cable trays should not be bolted to the fan, and cables should have strain relief (i.e. a loop or bend). Duct flexible joints can have flow guides to prevent flow buffeting of the flexible joint. This means that the fan and duct have to be aligned. With hot processes, consideration has to be made for changes in alignment between the process being hot and cold. This may mean that there has to be a cold offset between the fan and the duct. All of these issues can affect the anti-vibration mount natural frequencies and mode shapes, causing higher vibration. The ducting, especially for hot processes, can also push the fan, leading to the anti-vibration mounts being overloaded.

Anti-vibration mounts are selected based on the assumption that the fan is rigid. For small fans, this is a reasonable assumption. However, as fans get larger, the natural frequencies of the fan structure get lower. This means that, for larger fans, the modes of the structure may be below maximum running speed. These modes can result in the fan having high bearing vibration in the operating speed range. This can be a problem for a fan that has to operate on variable speed, imposing a limit on the maximum speed or giving barred speeds.

Since cement plants involve hot gases, there is often a requirement for centre-line support, especially for larger fans. For this type of arrangement, the non-drive end pedestal is connected to the main support mass (motor, drive end bearing, and drive



Horizontal and axial movement on anti-vibration mounts.



Different types of anti-vibration mount.

end pedestal) by the base frame. Due to the fact that the casing is between the two pedestals, the connection between the two pedestals is typically two beams or three beams, with the casing providing minimal support. This results in two modes where the non-drive end pedestal nods – one axial nodding and the other horizontal nodding. Running the fan at one of these natural frequencies would result in high non-drive end bearing vibration.

For belt-driven fans, the motor is often located separately from the fan on the base frame. This can give a mode where the motor vibration from a fan out of balance is higher than the fan vibration. This would require a finer balance of the fan to bring the motor vibration down to acceptable levels, for example the motor and fan running at different speeds, even with a 1:1 drive ratio. This can give two potential problems:

- The fan/motor/base frame can have a natural frequency at the motor speed. This needs to be addressed by balancing the motor, not the fan, even if the high vibration appears at the fan.
- For a 1:1 drive ratio, the motor and fan can form a beat that looks like a fan vibration effect. The main problem with this is that the fine balancing of the fan becomes difficult if the mode at running speed is driven by motor vibration.

For all fans, including direct drive overhung impellers, there can be modes that involve pedestal twisting. This would essentially result in the motor and fan bearings moving opposite to each other.

Like the fan, there can be natural frequencies of the structure under the fan in the running speed range. All of these modal effects require a finite element analysis to assess them. When the fan is being analysed, the pedestals, base frame, and casing have to be modelled in full, with the impeller, bearing unit, and motor modelled as lumped masses. Care has to be taken in modelling the connections and joints of the various components to ensure that the correct structural stiffness is achieved. Otherwise, misleading results may be obtained. The rotor modes are typically affected by a gyroscopic effect, which is not easily modelled in a full structural finite element model of the fan. This means that the rotor modes are assessed separately using a dynamic stiffness for the effect of the rotor support structure. The structure under the fan would usually not be known in enough detail by the fan manufacturer, so would need to be analysed by the main contractor or end user. For analysis of the structure under the fan, the fan can be modelled as a lumped mass on springs.

When problems do occur with installed fans on anti-vibration, there are various techniques to identify the problem. The traditional method would be a vibration survey. A vibration survey has one accelerometer that does not move, typically horizontal at one of the bearings. Another accelerometer or tri-axial accelerometer is then moved round the structure and the transfer function is obtained for each measurement. This allows the operating deflected shape and mode shapes to be constructed. This vibration survey can be based on bump tests or can be done with the fan running. A more modern method is a video technique, which amplifies the movement and can apply frequency filters. This method has the advantage of being more easily understood visually, but does not allow for numerical analysis of the movement. Whichever technique is used, there will normally be a requirement for structural analysis to obtain a solution. ■

About the author

Dr John Irons has had over 25 years of fan design and development experience, having joined Halifax Fan in 2015 as the Chief Engineer from Howden Group Technology. He has extensive experience of fan design, including noise, vibration, and fluid dynamics.

Diane Wang joined Halifax Fan China in 2007 and has worked closely with customers to drive product development through providing solutions to customer needs. She is now the Manager of the Shanghai office, with a key focus on serving the cement industry. This year, Diane will receive her MBA from the University of Liège, Belgium.