ETS Solutions NA
P.O. Box 1225, Bath OH 44210
Sales: (520) 603-1557
Applications: (248) 726-2316
sales@etssolution.com

‘Dos and don’ts’ in Vibration Testing

This Application Note provides guidance on avoiding pitfalls and difficulties commonly encountered during the design, installation and operation of vibration testing systems. It is based on ETS engineers’ many years of experience of the range of problems that can arise during vibration testing.

While this Application Note has been written with ETS equipment primarily in mind, the underlying principles apply to any vibration testing equipment. Advice on good practice should be followed whatever equipment is used.

To ensure that they are aware of established good practice in vibration testing, customers are strongly advised to

- Read this Application Note in detail before first using vibration testing equipment
- Review the latest issue (available on the ETS website) at regular intervals

Contents of this Application Note

The topics discussed in this Application Note are grouped as shown below.

1. Site design

Layout

Position of control room

The control room should if possible be positioned within sight of the vibrator. If this is not possible a CCTV system should be installed to provide a view of the vibrator.

Room access

There should be adequate access both for installation and maintenance of the vibration system and to allow mounting of payloads.

Vibration

Consideration should be given to the vibration, especially at low frequencies, that will be transmitted into the floor during testing. Various mounting options are available to reduce vibration transmission but all have a low frequency limit.

An unsuitable isolation mounting resonance can lead to excessive motion of the vibrator and even damage to the building containing the system.

Location of amplifier

The system amplifier should not be sited directly against a wall as this will restrict the air flow available to cool it; maintenance will also be easier if the amplifier is surrounded by free space. ETS systems manuals contain detailed recommendations.

Airglide mounts

Where equipment to be installed is fitted with 'Airglide' mounts, ensure that the floor has a suitable finish and level as specified in manuals.

Blower hoses

Extended blower hoses should not be fitted without consulting ETS as their extra length can cause overheating of the vibrator. For the same reason sharp bends in hoses should be avoided, and hose arrangements shown in outline drawings should not be modified without consulting ETS.

Floor loading

The floor must be able to bear the load of the vibration system – vibrators and their associated equipment are heavy items.

Position of mains isolators

Main electrical isolators and switches should be fitted in an accessible position close to the amplifier. Positioning should comply with relevant safety regulations.

Acoustic noise

Due to the nature of vibration testing, noise is produced by the armature. For larger systems this can lead to high levels of noise. Consideration should be given to the use of soundproof rooms etc. ETS vibrator noise levels are specified in manuals.

Other equipment

Siting vibrators next to other heavy equipment can cause problems due to transmission of vibration or electrical noise.

Environmental

Temperature and humidity

Do not operate ETS equipment outside the temperature and humidity limits specified in the relevant manuals.

High altitudes

At higher altitudes the cooling of the vibrator will be affected by the reduced air density. If this is likely to be a problem, consult ETS.

Cleanliness

The vibrator and other equipment should not be operated in damp, oily, dirty or dusty conditions. Dirt and dust may cause the centre positioning system (where fitted) not to function correctly. Water collection due to damp conditions will cause corrosion of the vibrator and may also lead to electrical short circuits. Oil on or around the vibrator makes surfaces slippery, creating a hazard for operators.

Condensation

If operational temperature and humidity (for instance when operating with a thermal chamber) are such that the temperature of the vibrator armature falls below the dew point, moisture will condense on the armature. This can cause corrosion to the frame and also lead to electrical shorts.

These problems can be avoided by

- The use of a thermal barrier
- Fitting heating elements around the armature/chamber interface
- Directing the blower warm air towards the underside of the chamber

Vacuum

When the vibrator is used with an altitude chamber the chamber will suck on the armature. For ETS air-cooled vibrators the load compensation is based on positive pressure, so special control will be required. Water-cooled ETS vibrators are fitted with a small vacuum pump to provide negative pressure on the armature, however this would be fighting against the vacuum pump for the chamber which is usually larger.

Thermal expansion

When using a thermal chamber be aware of thermal expansion and the stresses it can cause. This is particularly important when the chamber is attached to a multi-bearing slip table.

Corrosion of magnesium components

The magnesium alloy used in slip tables, head expanders and other components is extremely susceptible to atmospheric or other corrosion, and the advice on this topic in ETS manuals should be carefully followed.

Services and cabling

Availability of services

Ensure that all services required for the equipment are available and as specified in the relevant ETS manuals.

Cabling

The following points should be borne in mind when running cabling:

- All cable lengths should be kept to a minimum, as cables longer than those specified in manuals may restrict the performance of a system. If in doubt, consult ETS Engineering Dept.
- Care should be taken not to apply undue loads to cable terminations.
- Ducting for armature drive and field cables should be ventilated to avoid the possibility of heat build-up in the cables.
- Cables should be routed neatly and safely to avoid possible trip hazards.
- Power and signal cables should be routed separately to avoid interference problems.
- All signal cables should be screened; triaxial cables should be used for analogue signals over long lengths.

Detailed guidance on cabling is given in ETS system manuals.

Electromagnetic

Safety and RFI earths

Ensure that safety earths are fitted and used. RFI earths should be used and be of the correct type as specified in manuals.

Detailed guidance on earthing is given in ETS system manuals.

Mounting the vibrator

The body of the vibrator is constructed from steel in order to conduct the magnetic fieETS. If the body is connected to large steel components other than supplied by ETS, these fieETS will flow in the connecting parts. This can cause problems with magnetised plates, loss of flux within the vibrator and / or large stray field ETS.

Siting of control equipment

If control equipment is sited close to the vibrator the stray field may distort monitor displays.

ETS recommend that personnel, particularly those with medical implants, do not enter the danger zone specified in manuals While the vibrator is running.

2. Vibrators

Air-cooled vibrators

Dirt and dust

If the vibrator is operated in dirty and dusty conditions air vents will become blocked and vibrator cooling will be impaired.

Ambient temperatures

If the vibrator is operated at high ambient temperatures (above 30° C) the vibrator coils will overheat at full force. The cooler the air to the vibrator the longer the life will be. If temperatures cannot be kept below 30° C the vibrator must be de-rated in force.

Air cooling hoses

Hose lengths should be as short as is practical. Where the standard supplied length of hose is too short, ETS should be consulted as to the requirements for long ducts. Long ducts can increase the pressure drop seen by the fan and thus restrict the flow of air to the vibrator.

A kinked or damaged cooling hose reduces the flow of air to the vibrator, leading to increased running temperatures which reduce the life of the vibrator.

Air supply

Particularly where air compressors may turn off overnight, consideration should be given to fitting a safety switch to ensure that the vibrator cannot run without an air supply present.

Air quality

Air supply should conform to ISO 8573-1: class 1.7.1, with maximum particle size of 0.01 microns and remaining oil content of 0.01 ppm. Water or oil traps should be fitted if necessary.

Water-cooled vibrators

Cooling unit, oil

Raw water supplied to the cooling unit should always be within specification for temperature and flow. High raw water temperatures or low flow will cause the system to trip as the cooling unit coils will not be able to reject all their heat.

Where the cooling unit is sited either above or below the vibrator, special consideration is required to how water and oil are returned from the vibrator. If the cooling unit is below the vibrator, siphoning can occur from the vibrator. If above, scavenging will be required for the oil.

Oil scavenging should also be considered if supply hoses are unusually long.

The cooling unit tank must always be full, to avoid damage to both the vibrator and the cooling unit.

Economy tap

When running on economy tap the vibrator will not be able to produce full force. Full field will be required in order to do this.

Maximizing armature life

While vibrators are extremely robust, the armature is a lifted component: the high numbers of stress cycles, high stresses and high temperatures will ultimately lead to failure and the need for replacement.

The time taken for an armature to fail depends on

- primarily the force level at which it is running
- secondarily the type of test
- other factors which will influence its life

Life is affected by the type of test run as shown below (higher values leading to reduced life):

Sine sweep	1 run >30 min at 80% or less of capacity
Random broad band (20-2000 Hz)	1 "
Shock	1.5 run >30 min at 80% or less of capacity
SRS	2 run >30 min at 70% or less of capacity
Sine on random	2 "
Narrow band random	2 "
Fixed frequency sine(Dwell)	3 run >30 min at 70% or less of capacity

Other risk factors tending to reduce armature life are

- High temperature of raw cooling air or water
- Distortion caused by ‘slapping’ components.
- High ‘g’ levels
- Humid or dusty atmosphere
- High frequency > f_n
- Large displacement
- Horizontal running
- Running under a chamber
- Large moment applied
- Large velocity
- Drive high

- Lively payload
- Poor control
- Not keeping reference plots
- Poor maintenance
- Unattended operation
- Large payload

Maximum armature life will be obtained when these factors are avoided as far as possible, while using the vibrator well within its specified performance range.

3. Testing

Test design

Test dynamics

The combined dynamics of the item under test, fixtures and vibrator armature should be well understood, especially where the payload is large or the test is severe.

Test frequencies

The vibrator should only be run within both its maximum and minimum frequencies.

Accelerometers

Ensure that accelerometers are rigidly mounted and will not fall off during the course of the test.

Cross-axial motion

Monitor cross-axial motion carefully to avoid exceeding vibrator moment capability.

Loads and fixtures

Suitability for purpose

Ensure that fixtures are suitable for the purpose required of them.

Thermal expansion

Jig design should take account of thermal expansion. Different materials when fastened together and subjected to changes in temperature will induce stress in the components.

Slip tables in thermal chambers are particularly susceptible: bearings can be damaged if jig bolts are tightened before the slip plate has reached the working temperature of the chamber.

Torque settings

Inserts and payload bolts should always be tightened to the correct torques as defined in manuals. Over tightening can cause damage to the inserts, while under tightening can cause the payload to rattle or work loose.

Load support

Always use the load support system as described in manuals.

Accelerometer positioning

Accelerometer positions should be chosen with great care. Control accelerometers must not be positioned at vibration nodes or the vibrator armature may be severely damaged.

Fixing the load

Use as many fixing points as possible to attach a fixture or payload. Use short fixing bolts rather than long ones which may resonate.

Overturning

The vibrator can be damaged by payloads that are unstable or mounted so as to exceed its moment capabilities. Accelerometers can be used to limit the overturning moment applied to the system.

Payload dimensions

For payloads wider than the diameter of the vibrator armature a head expander or extender must be used.

Decoupling

This section gives general guidance on the causes and possible effects of decoupling, together with advice on how decoupling may be avoided.

How is decoupling caused?

In a vibration test the aim is always to connect the item under test (payload) to the vibrator as directly as possible. This is done by minimising the length of connection so that resonant frequencies are kept high, and by ensuring that connections are all linear.

A linear connection is one that, for a reversal in applied load, will deflect as much as previously but in the opposite direction. A non-linear connection – an example might be a plate loosely resting on the vibrator – will not show this behaviour. When the vibrator drives upwards the plate moves with the vibrator, but when the vibrator drives downwards at more than 1 g_n the plate will separate from the vibrator. When the vibrator drives upwards again the plate will hit the vibrator with a hammer blow effect.

The effects of decoupling

This effect results in high energy accelerations over a large range of frequencies being input into both plate and vibrator, which may change the test dramatically. A sine test is normally at one frequency at any given instant, and not a range.

As well as affecting the test, decoupling may also damage both payload and vibrator, as extra accelerations are input in an uncontrolled manner. High energy accelerations, particularly at high frequencies, can excite subcomponents of both vibrator armature and payload sufficiently to cause damage or breakage.

Clearly decoupling is to be avoided. The 'unbolted' example just given is trivial and the cure is obvious, however decoupling can occur less obviously within a test setup. One common way for decoupling to occur is to have an unsupported length in contact with another: if the plate above is bolted to the flat vibrator armature at its periphery only, then at low accelerations the system will be linear, as both plate and armature move together. At some higher acceleration level the centre of the plate will move up as the vibrator drives toward the plate, but will separate from the armature very slightly when the vibrator drives away, because of the inertia of the plate. When the vibrator drives toward the plate again a hit will result: decoupling has occurred.

Decoupling can also occur where bolts have been insufficiently torqued down. A lightly torqued bolt can allow separation to occur at low force levels between the surfaces being clamped. If these are within the force capability of the vibrator then damage will result.

Dos and don'ts to avoid decoupling

Do

- Torque all bolts correctly
- Minimise unsupported lengths in contact
- Minimise exposed bolt lengths
- Use full thread engagement (1.5D) with bolts
- Use all the armature fixing holes to attach any payload of fixture
- Where large unsupported lengths are unavoidable, relieve the surfaces between hold down points so that contact cannot occur
- Have tight flatness tolerances for contacting surfaces
- Have tight parallelism tolerances where needed

Don't

- Have fixing bolts greater than 100 mm apart on contacting surfaces
- Use bolts without stiff washers – bolt heads will sink into the material being clamped, lowering the holding force
- Run tests without supervision – if decoupling occurs the test must be stopped at once
- Use thin plates – these can deflect
- Use unsymmetrical (unbalanced) fixtures or adaptors

Guidelines for good practice

When designing and assembling fixture arrangements, always bear in mind the principles outlined above ie

- Symmetry
- Use of thick sections
- Use of all armature fixing holes

- Use of flatness tolerances
- Use of parallelism tolerances
- Use of minimal exposed bolt lengths

Further reading

Fixture design for vibration and shock testing, George Hieber, Tustin Technical Institute Ltd, California, 1993.

Control strategies

This section covers some of the basic ideas and concepts relating to vibration control strategies. It explains the need for control accelerometers and gives guidance on where to place them.

Nearly all vibration tests cover a frequency range where mechanical resonances occur in a system comprising the payload, fixturing and vibrator armature. Nearly every vibration test is controlled in terms of acceleration, relying on the fundamental equation force = mass x acceleration (f = ma) and assuming that mass remains constant. However under resonant conditions the effective mass does not remain constant. For this reason poor control can lead to under- or overtesting of the payload and damage due to overdriving the armature.

The choice of where to control is thus the most critical part of any vibration test. There are no universally suitable control positions and the positions chosen can mean the difference between damaging the vibration equipment or not. Control positioning can also affect dramatically the accelerations applied the item under test (payload).

The following principles should be borne in mind:

- All mechanical structures have resonances.
- The larger (dimensionally or more massive) a structure, the lower the resonant frequency.
- For increased mass without increased stiffness, the resonant frequency will reduce.
- For increased stiffness without increased mass, the resonant frequency will increase.
- In a free system when a purely axial resonance occurs, the most lively points (those moving the most) will always be the ends.

Description of a typical test

A typical vibration test involves three main physical components:

- The vibrator armature.
- The fixture
- The payload (item under test).

Consideration must be given to the resonance not of the individual components but of the entire system which they comprise.

The armature and the payload are normally fixed with no scope for change, but the fixture can consist of a slip plate or head expander and often a mounting fixture.

If the entire system were rigid and its resonances fell outside the range of the test, all points on the system would vibrate at the same level and the position of the control accelerometer would be immaterial.

However for many payloads the size of the fixture in combination with the mass of the payload leads to resonances within the range of the test.

It is these resonances which cause the difficulty in selecting control positions.

Choosing control positions

Control accelerometers are needed so as to:

- Control the acceleration into the payload
- Ensure the vibrator is not damaged

The most obvious reason for control accelerometers is to limit the acceleration into the payload. If the payload is large and or the frequency range is high, at some point one or more resonances will occur. This can be seen as difference in acceleration levels over the fixture.

If only one accelerometer position is used on a test, the control loop only ensures control of acceleration at this position. If this position coincides with a resonance node (a point at which there is little or no movement), then the rest of the structure could be accelerating a hundred times or more than the control level. As the location of nodes changes with frequency, finding a point where they will not occur is difficult. It is for this reason that several accelerometers positions should be used.

The best area to place accelerometers with least risk of finding a node is at the end of the system. On a slip table this would be on the end of the plate furthest away from the vibrator.

When using even one accelerometer, resonances can be spotted. If a flat sine sweep is required, then the control acceleration will also be flat. Looking at the drive from the controller will show the dynamics of the system. This drive is the signal the controller outputs to the amplifier. A drop in the drive indicates a resonance and a rise in the drive indicates an anti-resonance. Anti-resonances indicate that the control accelerometer is placed on a node.

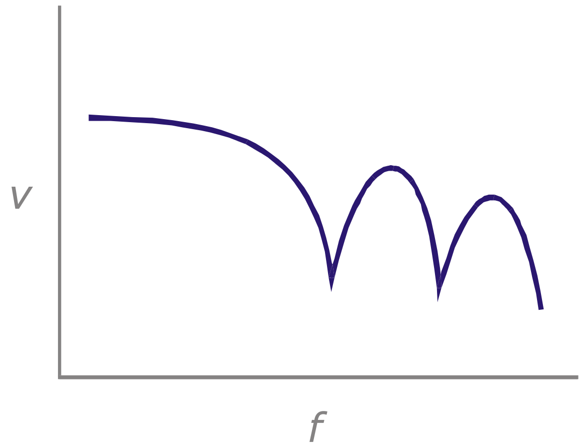
The drive signal is directly proportional to the output from the amplifier to the vibrator. The vibrator will respond to this input from the amplifier to produce force. This follows that if the drive is high, then the force the vibrator is producing will also be high.

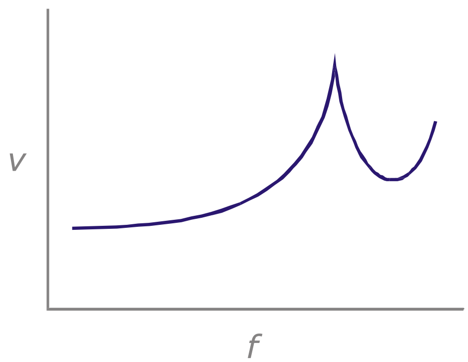
Anti-resonances are the most dangerous to the vibrator, as the force the vibrator will be producing will be far higher than the simple calculation of force = mass x acceleration.

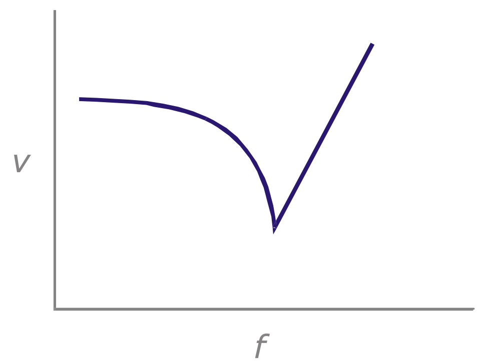
The drive signal is the most useful piece of information about the vibrator. It demonstrates how good the control strategy is as well as the force that the vibrator is producing.

The drive signal should not rise above the nominal level for the test if the structure were rigid. Control positions should be changed or more added if this is the case.

Examples of good and bad drive plots are shown below.







Choosing locations for monitoring

It may not be possible to always put a control accelerometer at the end of the system, if this is not possible, then monitors should be placed there with notching levels set so that damage to the vibrator does not occur.

Random vs. sine testing

There is a difference between sine and random testing in how an ETS vibration system protects itself.

Under sine testing the amplifier monitors the voltage and current supplied to the vibrator, stopping the test if either exceeds preset trip levels. Should the test be a high level test and the control position at a node, the drive power increases past the trip levels and the system shuts down.

In random testing the amplifier monitors r.m.s. voltage and current in a similar manner. However if control is at a node and the drive increases around the node, the amplifier will not shut down as long as the overall voltage and current remain below trip level, even though the vibrator may producing more force than required.

A further complication is that at the resonant frequency of the armature itself (normally around 2000 Hz) there is a large amount of 'free energy'. Little voltage and current is required to drive the armature at this frequency and it is possible to damage the armature by overdriving the vibrator (exceeding its limits in both force and acceleration) without causing amplifier shutdown.

Placing a control accelerometer at the remote end of the system will protect against this danger as this end moves in a similar manner to the armature at the other end.

Good practice in testing

Following good practice as described below (common for any type of testing, sine, random, shock etc) will maximise the life of the equipment:

1. Always fit an accelerometer on the end of the system to either control or, if this is not possible, monitor with limit set at the maximum theoretical acceleration using f = ma calculation.
2. Large slip tables may require several control accelerometers at the end as the corner of the plate will be vibrating at a different level to the centre at higher frequencies.
3. Run low level sine sweeps over the entire testing frequency range to characterise the fixture and payload. This could be low level random if sine is prohibited. Low level means approx. –12 dB of full test level.
4. Review the drive to ensure there are no rises past the nominal drive level.
5. Use the results to modify the control strategy if required.
6. Look at the out of band energy during random running as this can indicate other problems: the bandwidth should be at least 1.5 times the highest control frequency. Where this energy is large or at the same level as the controlled energy, this indicates problems with the test. Investigate before continuing.
7. Where problems may occur, look at the real time trace of acceleration as this may show problems not seen in the frequency domain.
8. If all looks OK, proceed to the test level.

This will ensure that the vibrator is protected as far as possible against damage. If these precautions are not taken, immediate damage may not occur, but forcing the vibrator to provide more than its designed force or acceleration levels will lead to reduced life.

Controllers usually offer a range of control strategies – single point, average, weighted average, extremal etc. The best from a vibrator protection point of view is extremal but if this is not practical and average or single point is employed, the monitor at the end of the system must be fitted with a limit. If this end point were included in a two point average, where the other point drops to zero, the vibrator would have to provide double the force required by an extremal strategy.

Summary

- Control accelerometers are used to protect the vibrator as well as control the test level.

- Use the drive plot to assess the control strategy and protect the vibrator.
- Random vibration can mask control problems where sine sweeps wouldn't run.
- Always control or monitor at the end (liveliest) parts of the system.
- Consider the whole system not just the item under test.
- Do not assume the characteristics of a system, always establish them by investigation.
- Ensure that the dynamic characteristics of the system are known before testing at full level.

Slip tables

Mating surfaces

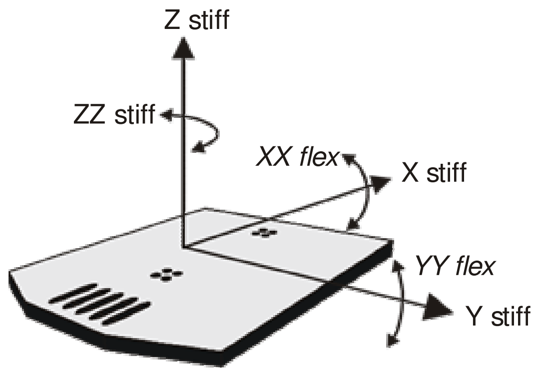
Any mating surfaces should be correctly connected, with no fretting of the surfaces. Surfaces should be flat and smooth, and bolted together using short bolts at close spacings.

Where drive connection is fitted to the armature, ensure that all inserts are used, and the structure is dynamically rigid to the highest drive frequency.

Design of fixtures

Design of jigs should take into account the slip plate overturning moment given in the manual as exceeding this will cause damage to the bearings. When designing jigs to fit on the slip plate, try to cover all available bearings as this will give the best overturning moment.

When designing jigs for slip plates, realize that the slip plate is stiff in the three axes but flexible in the two out of the three rotations (as shown below). Jigs should be designed to add to the stiffness of the slip plate.



Attaching jigs and fixtures

Flatness of jigs and fixtures is critical. Uneven or bowed jigs can cause binding of bearings within the slip plate and rubbing of the slip plate against the granite table base.

Fixing bolts should be of the length specified in manuals. Bolts that are too long will damage the slip plate; bolts that are too short may not fully engage in the insert.

Thermal expansion

Jig design should take account of the effects of thermal expansion. Different materials when fastened together and subjected to changes in temperature will induce stress in the components.

Slip tables in thermal chambers are particularly susceptible: bearings can be damaged if jig bolts are tightened before the slip plate has reached the working temperature of the chamber.

Armature connection

Where possible all armature inserts should be used to attach driver bars or fixtures. Using only a few can cause the inserts to pull out, or the dynamics of the armature to change.

Operation

Users of equipment

Only trained personnel should use the equipment. Contact ETS for details of training courses in vibration testing.

Equipment manuals

Users should familiarise themselves with the equipment manuals including any special addendums.

Before test checks

Ensure that the vibrator and other equipment is working correctly before starting tests.

Test failures

Any failure should be recorded and efforts made to analyse its causes before repeating the test. Doing so will avoid repeated failures caused by the same problem. Where appropriate pass details of failures to ETS including drive and profile plots.

Fixed frequency tests

The vibrator may not run at full performance during fixed frequency tests as test frequencies may coincide with vibrator resonances. This may cause failure to achieve the desired test level and/or damage to the vibrator See also ‘Maximising armature life’ earlier in this Application Note.

System characterisation

To determine the correct control positions for the tests to be run, the system should be characterised by running low level sine sweeps. Characterisation plots should be kept for future reference.

Vibrator specification

The vibrator and other equipment should only be run within specification as detailed in manuals.

Test masses

To avoid overdriving the vibrator, the exact mass of the payload and fixture should be known before starting the test.

Advice from ETS

Advice about vibration testing is readily available from ETS, who should be consulted in case of doubt about a specific test.

4. Maintenance

Programming of maintenance

Regular checks and maintenance activities should be carried out as recommended in manuals. Maintenance should always be carried out by suitably trained personnel.

Calibration

Items such as accelerometers which control test levels should be checked regularly to ensure that they are calibrated and working correctly.

Drive and field cables

All drive and field cable connections should be checked for tightness as loose connections can cause transients to be injected into the test item.

Oil and water supplies

To maximise the life of the vibrator, oil and water should be changed at the intervals recommended in manuals

Air supply

The air supply should always be within specification as dirty or wet air can cause the pneumatic regulators to stick.

Replacement parts

To avoid problems caused by stoppages, a stock of spare parts should always be maintained as recommended in manuals. ETS approved parts should always be used as many are safety critical and most will affect the performance of the equipment.

Lifting equipment

Adequate lifting facilities must be available both for mounting payloads and for servicing the vibrator.

Cleanliness

The equipment and all areas surrounding should be kept as clean as possible.

Always keep the vibrator clean as swarf can damage the top seals, and if pulled into the vibrator body can cause electrical shorts.

Cables

Cables should always be routed so as not to obstruct walkways. No cables should be left where they can be walked on.