250HR RESONANCE DURABILITY

Test No.	BE-DUR-004	Engine Variant	GEN1	Issue level & Date	Issue 01 16 June 2021

1 TEST OVERVIEW

The purpose of the 250hr Resonance durability test (also known as Critical speed test) is to validate the complete engine assembly and its constituent system component's durability and robustness, specifically to vibration-induced failures.

This test will identify the speeds and loads within the operating range of the engine that result in vibration resonance frequencies of critical measured components and cause them maximum vibration excitation.

Once the individual component critical frequencies are identified a customised resonance test cycle is created in order to excite the components for a target duration (based on the component's material fatigue properties and expected duty in service), in order to try to provoke vibration-induced fatigue, or associated wear/overload failures.

2 GENERAL DETAILS

This test consists of two discrete tests phases separated by a data analysis and test cycle formulation phase, as follows :

2.1 TEST PHASE 1 – COMPONENT RESONANCE SURVEY

The purpose of this phase is :

- to ascertain the engine speeds and loads that create large displacement or high frequency vibrations within key components
- To determine the effect of different ancillary component loading conditions

This is achieved by :

- Instrumentation of targeted engine components with accelerometers
- Log accelerometer output (against engine crank angle) whilst running over short (90 second duration) engine speed and load sweeps
    - Multiple sweeps with accelerometers repositioned between each will likely be required (dependant on the number of targeted components and measurement positions and number of accelerometers or data acquisition channels available)

2.2 DATA ANALYSIS / CYCLE CREATION PHASE

The purpose of this phase is to :

- Analyse the Accelerometer data to determine the most critical resonances for each measured component and vibration axis
- Determine the effect of ancillary loading on component vibration
- Create filtered list of resonances which are to be assessed during the test
- Formulate a bespoke speed ramping resonance test cycle designed to exercise all targeted components at their resonance conditions.
- The engine run time at the different speed / load conditions will need to be customised in order to achieve the target fatigue cycle run-out number of cycles (1E7 or 2E7) appropriate for the component materials

Note that this phase typically takes 3-4 days to complete depending on the number and nature of the resonances identified. To minimise test delay, it is sometimes possible to quickly develop an interim cycle with which Test Phase 2 may commence for a target number of hours (e.g. if there are a large number of resonances within a low engine speed/frequency band).

2.3 TEST PHASE 2 – CRITICAL SPEED VIBRATION TEST CYCLING

The purpose of this phase is to :

- Exercise all targeted components over the cycle determined in 2.2 above for a duration long enough to accumulate the fatigue run-out number of vibration cycles appropriate for their material, for all highlighted resonances selected in 2.1 and 2.2 above.

Note - It is expected that a large proportion of this test will be run at full-engine load (potentially all) unless particular resonances are found to be more severe at reduced engine loads.

The test may need to be run with continuous or varying ancillary system loading (e.g. electrical generator loading, or periods of air compressor operation) if this is shown to contribute to peak torsional vibration resonances identified in Phase 1

Oil & filter servicing is initially recommended every 100hrs due to the likely amount of high power and speed content. Oil samples should be taken for subsequent analysis to monitor internal engine condition and oil quality/ageing, but it is not expected that the service interval will be adjusted for this test.

An Engine performance check (including blowby) should be scheduled approximately every 100hrs

3 ENGINE AND TESTBED PREPARATION / INSTALLATION

To understand engine wear characteristics over this test it is advisable to measure key engine components prior to or during engine assembly, and also during or following the post-test engine teardown.

Appendix 1 contains an <u>example list</u> of engine measurements. An updated list of requirements will be developed and finalised through the engine definitive design phase. The test engineer should verify the required measurements or checks have been made and are satisfactory before proceeding with the test.

During engine build, the full build process should be adhered to, ensuring that the following tasks are completed and recorded:

- Final torque values for critical fasteners are recorded in the build book

- Measure and record the vacuum achieved for intake and exhaust ports in cylinder head with valves installed
- Check engine for fluid leakages using engine build pressure leakage and vacuum decay tests
- Record the final valve clearances
- Record any issues found on build
- Record any modifications or build deviations made during build

Additionally, in order to be able to visually monitor critical fixing tightness the critical fasteners for targeted external components should have their as-built final rotational position identified with a suitable paint mark or scribe mark on the fastener head against their mating components.

Ensure all parts that require adaption for instrumentation are modified, thoroughly cleaned (and where applicable leak-checked), prior to engine assembly.

It is possible that the engine for this test will have a modified engine front cover specified with an access panel around the crank damper, in order that a toothed wheel and associated crank position sensor maybe easily fitted and removed, in order to carry out crank torsional vibration measurements. Once these measurements have been made the wheel and sensor should be removed whilst running phase 2.

Fluid specifications for this test are:

Fluid	Required Specification	Notes
Fuel	DHPP - A	EN590 or Winter-grade DHPP-A may also be used if specifically requested
Lube Oil	5W50 (Mobil 1 or equiv.)	Renew Oil & filter @ 200hrs
Engine coolant	Demineralised water with 2.5% (volume) Servo Anticorr BF corrosion inhibitor (Normal coolant spec.)	40:60 Water/Eth. Glycol mix (Winter spec.) may also be used if specifically requested

4 EQUIPMENT AND INSTRUMENTATION REQUIREMENTS

Refer to procedure **BE-GEN-001 – Test Cell Set Up** for details on test cell facilities and test bed control parameters.

For this test, only the standard durability test instrumentation shall be fitted to the engine. **BE-GEN-001 – Test Cell Set Up** for details of standard instrumentation list.

Start and end-of test Performance rating to be carried out as per ISO 1585 (accuracy & accessories).

The test bed installation should also enable inclusion of, and logging from, a blowby meter during the scheduled performance checks. This will likely require the provision of suitable pipework and connections between the engine oil tank breather outlet and the engine vee-mounted air-oil separator.

It is recommended that during GEN1 the blowby meter circuit should also include an upstream oil catch-can type vessel (Min.2L volume) to prevent the blowby meter from becoming contaminated or overwhelmed with any oil mist or droplets being carried over from the tank.

However if the CCV system connecting pipework between the engine oil tanks and the final oil/air separator locate in the engine vee is listed as one of the targeted critical items for this test then the engine will need to run with the pipework as per vehicle specification (i.e. with no oil catch cans or blowby measurement capability) during test phases 1 & 2).

Note that this test may require an appropriate loading capability for the ancillary systems (e.g. Air compressor, Electrical generators). Where possible the loading should be capable of being controlled and monitored by the test bed sequencing system in order that the loads may be varied for various test cycle stages. This will be specified further during the definitive design phase as the likely requirements for this are better understood.

5 LOGGING REQUIREMENTS

In addition to logging of the standard durability test instrumentation described in **BE-GEN-001 – Test Cell Set Up** the following parameters should also be logged:

- Ongoing incremental counts of the instances and duration of hot shutdown pump activation
- If ancillary loading is required:
    - Generator load (current)
    - Air compressor output pressure

Note: further instrumentation and logging requirements may need to be added as the definitive design phase progresses and any potential risks are highlighted by the FMEA process.

5.1 ECU PARAMETER LOGGING REQUIREMENTS

Other than the Standard ECU parameters defined in **BE-GEN-001 – Test Cell Set Up** no additional ECU parameters are required to be logged during this test unless specifically requested by the test engineer.

6 TEST SAFETY SHUTDOWN LIMITS

Refer to **BE-GEN-001 – Test Cell Set Up** for details on test cell safety shutdown limits.

7 PRE-TEST ACTIVITIES

If the engine has not run before, a standard BIPO should be performed. Refer to test procedure BE-GEN-002.

Prior to the test commencing, the following is to be completed (examine engine build book as some activities may have already been completed):

Measurements *(record in build / logbook)*	• Pre-test crankshaft TV measurement • Cylinder leak down and compression (all cylinders) - see procedure **BE-GEN-003** • Valve clearances post BIPO (optional, may be removed for this test based on previous engine test results)
Components	• Review if there are any necessary engine rework, component replacement or updates required before commencing test. • This test should run with a new vehicle specification air filter assembly

	• A fully jacked-open thermostat may be specified for more reliable test bed temperature control. • The test engineer will advise if any component update requires another performance check to be completed. • Check required critical fixings paint marks are still clear and have not moved during the BIPO • A list of all critical components which are to be measured for vibration (and recommended measurement locations) to be provided for this test.
Post BIPO Review	• Ensure no abnormal noises at idle • Check for any fluid or gas leaks at idle • Review BIPO data and confirm that engine is signed-off prior to commencing durability test • Check performance test completed to ISO 1585 • Collect used-oil sample from engine post BIPO (100ml)
Oil Requirements	• Engine is to be filled with fresh oil and fitted with new oil filter prior to start of the durability test • Sample of the fresh oil added to be retained (100ml) • New oil weight that is added to engine is to be recorded • Check oil level is correct on dipstick and adjust if necessary o To be performed after engine has idled for 300s and stopped for 600s
Pre-test Checks	• Air path leak check • Installation for fluid and gas leaks • Test bed cooling system is fully filled, primed, and bled. Retain 100ml sample of coolant used for fill • Coolant system pressure check at idle for leaks • All instrumentation is responding and reading zero/ambient • Check for correct function of Hot shutdown coolant pump • All necessary instrument and equipment calibrations have been completed (i.e. test cell calibration certificate is current) • Check exhaust back pressure valve function and setting • Infra-red thermal image recordings of the whole engine or particular components may also be requested
SOT Requirements	• Initiate logger at 10Hz • Switch ignition on and observe correct operation of priming pump and ensure oil pressure in main gallery exceeds 100kPa • Ignition off, stop logger o If required oil pressure is not achieved, stop and investigate • If any engine or test cell rework or update activities have taken place following BIPO the carry out a SOT performance test to ISO 1585

Any issues found on test, or details of component updates post-BIPO should be noted in the testbed logbook and any parts changed retained.

NB. Further requirements maybe added as the definitive design and associated FMEA activities progress

8 TEST PROCEDURE

8.1 TEST OVERVIEW

As stated previously this test consists of two distinct test phases detailed in sections 8.2 & 8.3 below.

- Phase 1 – Component Resonance Survey
  - Intensive component vibration measurements (approx. duration 2-3 days)
  - Engine instrumentation with accelerometers run over multiple 90sec speed ramps (with different load conditions) for data acquisition
  - Toothed wheel (or flywheel starter teeth and once per rev feature) used for crank angle measurement
- Phase 2 – Critical speed cycling
  - Approx. 250hrs of test cycling (final target duration is dependant on phase 1 results)

Unless there are any abnormal temperature-dependant resonances highlighted or found, both of these test phases should be carried out with normal-ambient representative fluid temperatures, as summarised below:

Parameter	Unit	Initial Target	Allowable range for test
HT Coolant Outlet Temperature	°C	90 +/- 5	85- 105
LT Coolant Rad.Out Temperature	°C	42 +/- 5	35 - 72
Oil temperature	°C	No external control intervention, allow to float within engine limits	90 - 110
Charge Air temperature	°C		65 - 90
Fuel Temperature (LPFP in.)	°C	40 +/- 5	30 - 70
Air Intake Temperature	°C	30 +/- 5	20 - 40
Oil Level	Initial Max fill. Ensure engine is checked at approx. 10hr intervals for check and top-up to Max level. Record all oil additions.		

8.2 PHASE 1 TEST PROCEDURE – COMPONENT RESONANCE SURVEY SPEED SWEEPS

Prior to starting this Phase 1 testing ensure that the engine has been satisfactorily BIPO'd and review that the engine performance is representative and acceptable.

The list of target components which are to be surveyed should be reviewed by the test engineer, NVH-specialist engineer and the instrumentation technician who is responsible for instrumenting the engine with the accelerometers and recording their data.

The team should formulate an instrumentation plan of considering the number and placement location and sensor specification in order that the vibration measurements are arranged into batches (to suit the number and type of sensors available).

Note - Each measurement batch should include at least one reference position (normally on the cylinder block) which is carried over and common in all batched runs. This helps to verify that the engine operation and its vibration-forcing behaviour is consistent between different batch speed-sweeps.

8.2.1 ACCELEROMETER INSTALLATION

A summary of accelerometer fixing methods is shown in Figure 1 and Figure 2 below. The adhesive mount (2) is generally the most commonly used and recommended on engine components. Wherever possible the most convenient method is with 3 accelerometers arranged in the 3 coordinate axes within a mounting block (see Figure 2 below).

The hand probe should be avoided as results can be too variable.

FIGURE 1 - TYPICAL ACCELEROMETER ATTACHMENT METHODS

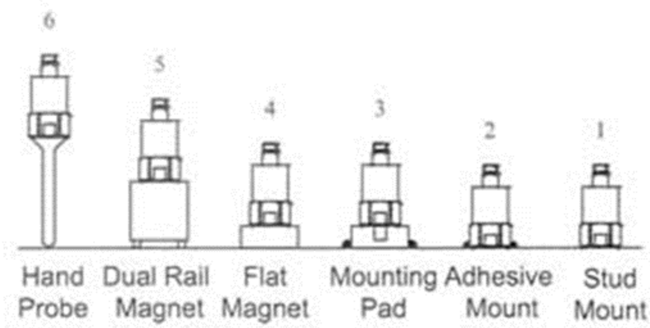


FIGURE 2 - TRIAXIAL ACCELEROMETER MOUNTING BLOCK ARRANGEMENT

Note that in some cases it may be necessary to protect the accelerometer from conducted and radiated/convected heat. If the accelerometer needs to be mounted to a hot surface such as the turbine housing or exhaust manifold it will need to be mounted on an insulating (ceramic) or water-cooled block. To protect from radiated or convected heat thermal insulation wrapping may be used or alternatively the sensor cooled by an appropriate low-velocity fan. The NVH specialist should be able to advise the best options. In such cases the sensor leads must also be appropriately insulated or cooled.

On completion of the accelerometer installation, the cables can be connected to a suitable datalogger (ideally minimum **5 kHz** logging capability).

Ensure all cables are attached and have heat protective wrap where required. If cable ties are used to secure the cables, ensure that there is some slack to the accelerometers.

The data acquisition equipment will also need an engine speed trace. This may be provided by a toothed wheel rotor fixed to the engine crank damper and appropriate gear-tooth hall effect sensor. It is envisaged that a modified front cover will be designed and specified for the GEN1 durability tests enabling the rotor and sensor to be mounted without a large amount of engine component removal or disturbance. Further details will be provided during definitive design.

8.2.2 SPEED-SWEEP DATA CAPTURE

Prior to start of data capture the following steps must be adhered to:

- Record test bed running hours and set test hours to zero
- Ensure all available and defined accelerometers are fitted to the engine
- Check conditioning rig to engine fuel supply is open
- Check all instrumentation is functional
- Testbed logger set to 10 Hz sampling frequency
- Turn ignition on and verify that the priming pump is operating, and minimum oil pressure threshold is met (>1 bar)
- Crank engine and start
    - Do not crank the engine for longer than 20s x 3 times to prevent damage
    - If exceed 3 cranks stop, contact requesting engineer and investigate
- Verify fuel system is primed by checking rail pressure is achieving the required demand
- Idle engine at 0% load
    - Confirm that main gallery oil pressure exceeds 100 kPa and stabilises within 5s of start up
- Idle engine for 120s at 0% load
    - Confirm that all sensors are working and are reading correctly
    - Visually check for any leaks or abnormal noises, ensure accelerometers and cabling are secure and safe
- Set engine speed to 50% and load to 50% and run for 300s
    - Check engine is stable and functioning correctly with no abnormal noises
- Allow for temperatures to stabilise
- Set engine to idle and load to zero
- Start High frequency accelerometer data logger
- Conduct the following set of 90 second speed sweeps at normal-ambient operating temperatures :

Set	Speed Sweep	Dyno. Load	Ancillary Loads (TBC)	Iterations
1	Idle to maximum speed (90secs)	Min. Load	None	Repeat x3
2	Idle to maximum speed (90secs)	50%	None	Repeat x3
3	Idle to maximum speed (90secs)	100%	None	Repeat x3
4	Idle to maximum speed (90secs)	100%	With Max. generator loading (TBC)	Repeat x3
5	Idle to maximum speed (90secs)	100%	With Max. compressor loading (TBC)	Repeat x3
6	Idle to maximum speed (90secs)	100%	With Max. generator AND compressor loading (TBC)	Repeat x3

NB. This may be revised during the definitive design phase pending further analysis. It is possible the ancillary loading requirements may not be required or may be reduced.

As each sweep is completed the data should be quickly reviewed for any accelerometer channels that are not functioning or are causing amplifier overload. If this occurs the problem must be rectified, and the sweep repeated.

Upon successful acquisition of the data from the planned sweeps outlined above, the accelerometers may be removed and repositioned for the next batch of measurements and the process described above repeated.

Note that it is important that measured components are not disturbed (unless necessary for servicing) as even if the same component is removed and refitted to the engine its vibration resonances may shift slightly in frequency which may mean that the component is not adequately validated by the critical speed testing.

8.2.3 DATA POST-PROCESSING

Following completion of the speed sweeps described above the data must be post-processed by an engine NVH specialist.

The specialist will typically produce plots for each component and measurement axes showing :

- Measured component amplitude vs engine speed
- Frequency spectra and waterfall plots
- Colour maps

(see Appendix 4 for examples)

From further analysis of this data the NVH engineer should create a table listing all of the critical resonances identified for each component and each measured vibration axis.

The table should note the displacement threshold used for selection of resonances (typically 0.01mm), the frequencies between which the limit is exceeded, and the measured resonance frequency and amplitude peak values, together with the engine vibration order and associated engine speed. An example table can be found in Appendix 5.

8.2.4 FORMULATION OF PHASE 2 TEST CYCLE

Using the post-processed accelerometer data and table of resonances described above, the test cycle for phase 2 may be formulated.

The intention of the phase 2 testing cycle is to run through discrete saw-tooth profile engine speed bands in order to accumulate enough vibration cycles for each component's resonances, to satisfy the following :

TABLE 1 - PHASE 2 SPEED BAND DEFINITION PARAMETERS

Parameter	Unit	Value
Target No. of Resonance Cycles Required – Ferrous components		10,000,000
Target No. of Resonance Cycles Required – Non-Ferrous components		20,000,000
Saw Tooth Segment Duration (X)	s	180
Target Saw-tooth Engine Speed Band Width	rpm	+/-100*

**In order to reduce the number of discrete bands required and preserve the total test duration this value may be increased*

See Figure 3 below for example of a single speed-band test profile :

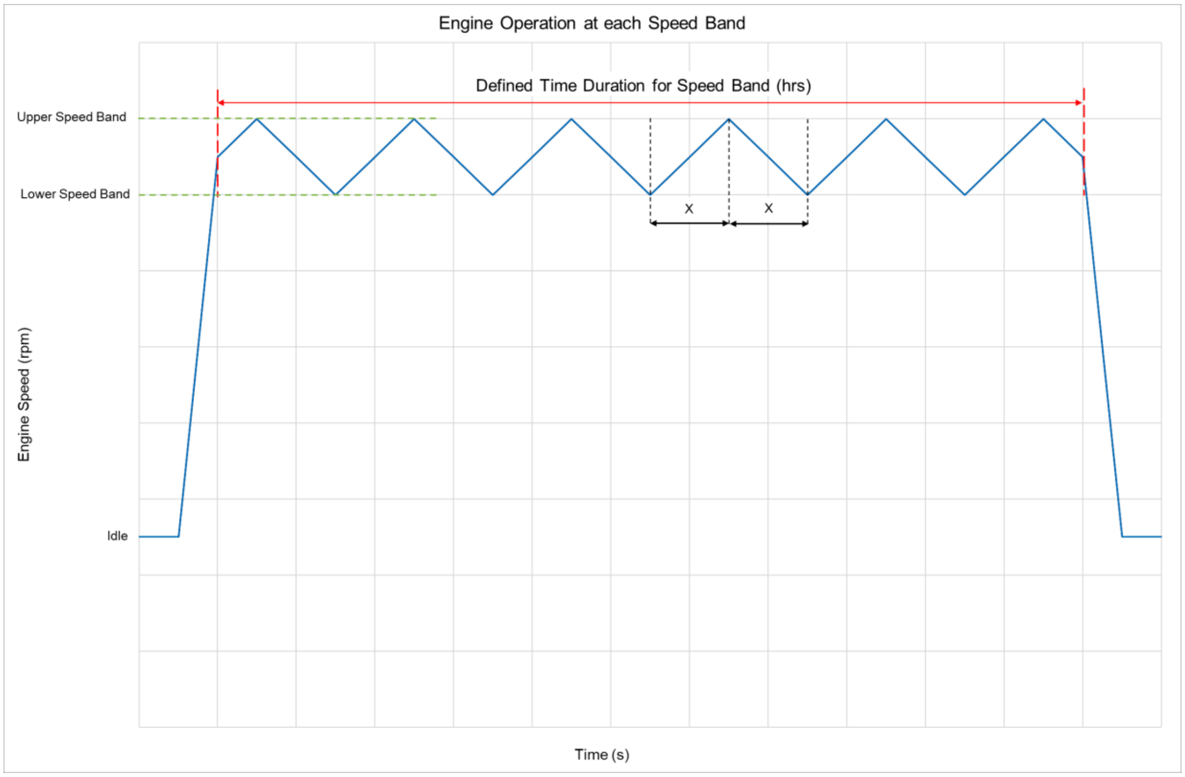


FIGURE 3 - EXAMPLE OF ENGINE SPEED BAND TEST PROFILE

The Phase 2 test cycle will be made up of a combination of this style of test bands, running between appropriate engine speeds (and loads), and for a calculated duration based upon the resonances that they are intended to cover.

Depending on the number and frequency-spread of the test bands the phase 2 testing will either be designed to run through each band in sequence (for the required total duration), or will create a multi-stage cycle that repeatedly skips between each band's conditions.

The method for creating the individual speed band limits and required duration is as follows:

- From Phase 1, the mean resonance frequency will be determined for each of the component being based on frequencies resulting in high acceleration levels or component displacement :
    - Each component resonance's Lower and Upper frequency is calculated using the measured mean resonance (peak) frequency as below:

$$\frac{Lower}{Upper} Frequency = Mean\ Frequency\ \times \left(1 \pm \frac{1}{\sqrt{2\ x\ Mean\ Frequency}}\right)$$

- Using the mean resonance frequency, the duration which the engine needs to spend at this frequency to accumulate enough simulated damage cycles (see target No. of resonance cycles in table above) can be calculated as:

$$Duration\ (hrs) = \frac{Number\ of\ Resonance\ Cycles\ Required}{\left(\frac{Mean\ Resonance\ Frequency\ (Hz)}{3600}\right)}$$

- The testing conducted during Phase 1 will also determine at which engine order this resonance frequency occurs
- Based on the resonance frequency and engine order, the engine speed can be calculated:

$$Speed\ (rpm) = \frac{Resoance\ Frequency\ (Hz) \times 60}{Engine\ Order}$$

- This is the engine speed at which the component may accumulate damage due to experiencing high levels of vibration
- Using the low and high frequency band, an engine critical speed band for each component can be determined
- Based on the defined allowed engine speed band width (in Table 1 above), group the calculated engine speeds maybe combined into distinct engine speed bands
    - These are the engine speeds that will be used for the test cycles
    - Note, the engine speed bands should not overlap as this would lead to unnecessary duplicated testing
- Using these defined engine speed bands, identify the components that fall within the speed bands and the required duration of the resonance cycle for that component
- Within the defined speed band, the component that has the longest duration requirement defines the duration that the engine needs to run for in that speed band, for example:

Component / direction	Mean Resonance (Hz)	Time (Hrs)	Engine Order	Mean Engine Speed (rpm)
A – x-axis	233	12	7	1993
B – Z-axis	101	28	3	2020
C – X-axis	170	16	5	2048

These 3 components all fall within an engine speed band of 2000 ±100rpm
Component B has a low engine order and frequency so has the longest duration requirement of 28hrs
Therefore, the engine will need to run a cycle with a speed band of 2000 ±100rpm for 28hrs to accumulate the required number of resonance cycles

- For each speed/load band, the engine is to run a 'saw tooth' profile where the speed varies linearly between the upper and lower engine speed band points (see Figure 3 example above)
- The time taken for each linear ramp segment of the saw tooth profile (X) is defined in the Table 1 above
- The total duration of the test will be defined by the number of speed/load bands identified and the duration at which each speed/load band is required to run for.

Note that in some cases (depending on the number, frequency / engine speed and vibration order of the resonances identified it may be necessary to exceed the target duration of 250hrs.

For example, if there are a large number of relatively low-frequency resonances this will require longer engine running to generate the target number of vibration cycles.

Therefore, if the overall duration of this test is fixed at 250hrs it may be necessary to reduce the test content in the resonance cycling phase using one of (or combination of) the following methods:

- Consider only the worst resonance for each component (in terms of displacement or acceleration) – components will often have two or more resonances within the engine operating window and often oscillating in different directions, which will need to be carefully considered, especially for components mounted on brackets which may have different strength levels in different directions.
- Reduction of the target number of resonance cycles for particular components and their different resonances. In some cases, the target may exceed what can be reasonably expected in service operation and so may be reduced accordingly.
- Review if any of the resonances identified are adequately covered by other durability test cycles (e.g. the accelerated durability test cycle includes 10e7 cycles at rated speed condition, so resonance that fall within this speed may be chosen to be ignored (as the component's durability is adequately covered by the other test)

8.3 PHASE 2 TEST PROCEDURE – CRITICAL SPEED TESTING

As stated in 8.2.4 above the phase 2 testing will either be designed to run through each band in sequence (for the required total duration), or will create a multistage cycle that repeatedly skips between each band condition.

Instructions for engine key-point logging, health monitoring measurements, and servicing will need to be provided once the speed bands are defined.

It is recommended to provision for oil and filter servicing every 100hrs for this test.

Also, a performance check should be made along with other engine health monitoring activities at 100hr intervals (to augment the standard Start of test and end of test checks).

8.4 TEST CYCLE SPEED/LOAD CONTENT

The overall test cycles speed & load content will need to be calculated once the Phase 2 testing saw-tooth profiles have been determined.

It is likely that the test content at full engine load will be high during this test (possibly the complete test duration).

8.5 TEST CYCLE SEQUENCE

The phase 2 testing cycle sequences will also need to be formulated once the Phase 2 testing saw-tooth profiles have been determined.

It is envisaged that the complete test will be run with the normal-ambient representative fluid temperatures as shown in 8.1 above.

8.6 TEST PARAMETER LOGGING

For engine condition monitoring and verification of correct test control, averaged logs of all the engine and test facility parameters stipulated in section 5 above, should be recorded at fixed points through the engine test cycle, (known as key point logs).

This enables easier ongoing engine health and trend monitoring analysis to be performed, by cross-plotting the same test condition from each test cycle throughout the test (see example in Figure 4 in section 0 below).

The key point log parameters should be averaged over a 30-second steady-state running period and automatically initiated by the test bed control and automation system (for repeatability).

The recommended cycle timings for initiation of the 30s averaging periods for the key points logs will need to be specified during the formulation of the phase 2 test cycle (following completion of the resonance measurements). Where possible the phase 2 speed bands cycles will include a short period of 60s steady-state running in which the key-point averaged logs should be taken.

Additionally, the complete test duration should be logged continuously at 1Hz so that in case of an engine durability, functional or performance issue, regular cycle data from preceding cycles may be examined and analysed to determine the possible onset of the issue, and assist in the determination of the root cause. **Due to the transient nature of this test continuous 1Hz logging is crucially important**

8.7 TARGET TEST STAGE FLUID TEMPERATURES

It is envisaged that the complete test will be run with normal-ambient representative fluid temperatures as defined in 8.1 above.

For the purposes of regulating the engine test temperatures against these requirements, the following instrumentation measurement positions and control methods should be used:

- Coolant (HT & LT)
    - HT Temperature measured at the Engine coolant outlet to test bed HT cooler (close to engine).
    - LT Temperature measured at the LT coolant radiator outlet (TBC)
    - Temperatures regulated by the temperature & flow of test facility cooling water through the test bed HT & LT heat exchangers.

  (Note in order to assist temperature control the engine thermostat may be replace with a jacked-open version for this test)

- Oil
    - Temperature measured either in the crankcase 'sump' (if available) or if not the oil tank bulk oil (e.g. from tank drain plug)
    - Oil temperature is not directly controlled but may be regulated by the temperature & flow of test facility cooling water through the test bed LT heat exchanger (influencing engine oil cooler heat rejection).
- Charge Air
    - Temperature to be measured from the intake manifold plenum (similar position on each bank, to be specified)

- Charge air temperature is not directly controlled but may be regulated by the temperature & flow of test facility cooling water through the test bed LT & HT heat exchangers (influencing the engine charge air cooler heat rejection).

It is recommended that appropriate test bed parameter warning thresholds are set to flag any test stage operation where the control requirements are within $\pm$ 1 °C of not being met, so that appropriate control setpoint adjustments may be made.

8.8 ENGINE WARM-UP

Following any engine stop the engine the engine temperature must be checked to determine if any warm-up operation is required before resuming the test sequence, as follows:

When Coolant Temperature is	Warm-up load operation (at 1560 rpm)
<45 deg. C	Run 25% load warm-up until >45 deg. C
>45 and <80	Run 50% load warm-up until >80 deg. C
>80	Run 65% load warm-up until aborted stage test conditions are achieved and then restart the stage >110 deg. C

The test bed cooling system target control temperature may be set to 115 deg. C to assist warm-up.

Unless otherwise specified, warm-up conditioning should be run at 1560 rpm (with load as specified above).

Note: All engine warm-up operation is considered ‘off-cycle’ and the running time should not be included in test time but logged separately as ‘total engine hours’

8.9 SCHEDULED ENGINE STOPS

Short scheduled engine-stop periods for engine in-cell inspection, servicing, or maintenance activities will be advised during the phase 2 cycle formulation. For guidance and planning stops should be expected to occur between every 5 to 8 test hours.

Longer stop periods and engine cooldown are expected to occur at least every 100hrs when the engine will have its oil and filters changed and undergo a performance test as well as other measurement activities.

The test data from these performance test and other engine monitoring measurements must be thoroughly reviewed and approval given before proceeding with the test.

Where possible engine starting should alternate between electric and air starting.

8.10 UNSCHEDULED STOPS

If an unscheduled engine stop is required (either by manual or automatic test bed shutdown) the cause of the shutdown must be investigated thoroughly before proceeding.

In cases where the shutdown is unexpected the post-mortem shutdown log must be reviewed, and the cause identified. The test engineer should be notified, and the test may only resume once the engine heath has been confirmed by turning the engine over by hand (minimum) and possibly following further engine external & internal examination.

The shutdown must be logged in the test logbook, together with details of the checks made and any observation or conclusions. Ensure the post-mortem data is archived.

The test stage in which the unscheduled stop occurred, must be repeated, following a suitable period of warm-up (as described in 8.8 above). It is recommended that the engine runs with an operator in attendance upon resuming the test sequence until the engine health and appropriate setting of the test bed automatic shutdown trigger values are satisfied.

As stated previously, any engine restarts required as a result of any unscheduled engine stops should initially be made using the electric starter (once appropriate action depending on the nature of the engine stop has been taken).

9 MONITORING, SERVICING AND REPORTING REQUIREMENTS

9.1 MONITORING AND SERVICING REGIME

During durability testing it is important that all necessary engine & test cell monitoring and servicing requirements are actioned in a timely and organised manner. Also, to maximise the test efficiency wherever possible the actions required should be aligned with the end of a test cycle and not during the cycle.

For this test the oil and oil filter should be replaced every 100hrs unless otherwise specified by the test engineer. It is also important that oil quality is monitored throughout this test by rapid analysis of regular, more frequent, oil samples. This will enable any need for more frequent oil servicing to be identified, or provide insight into ongoing engine wear, damage, or oil-ageing related issues.

The cycle key point (KP) data logs are to be routinely plotted against test time to monitor the performance trend of the various engine parameters (see Figure 4 examples below) :

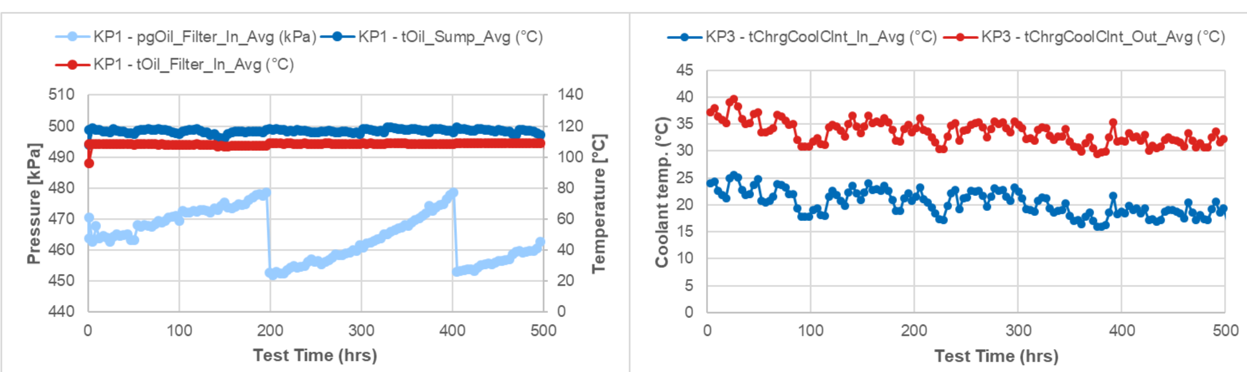


FIGURE 4 - EXAMPLE OF TEST TREND PLOTS

The ongoing oil consumption rate determined from the frequency and quantity of oil top-ups and oil renewal fill & drain amounts, must be continuously reviewed.

Note that the oil consumption rate through this test is likely to vary with the different phase 2 speed-band profiles being run. Any sudden worsening of the consumption rate outside of each speed-band profile's norms should be alerted to the test engineer and further investigative tasks may be necessary.

Similarly, any regular ongoing cooling fluid consumption must be investigated, noted, and monitored.

The results of regular engine leak detection inspections should be noted and monitored.

At 100hr intervals the results of the scheduled engine performance test should be cross plotted with previous results and reported.

An initial draft of the specific monitoring and servicing tasks required for this test are shown in Appendix 2. In order to ensure that all the required tasks take place at the necessary time, and to ensure clarity for the test bed operators, it is recommended that this regime, is adopted and programmed into the test bed control system. An updated schedule will be provided once the phase 2 testing cycle has been formulated.

However, please note that this schedule may need revising or additional requirements added, as the definitive design and associated FMEA activities progress, or based on observations made from any preceding GEN1 functional and durability testing.

9.2 REPORTING

The BE1500 project engineering team should be advised by a daily email of the number of hours achieved by the test engine in the previous 24hr period, together with a summary of results or observations from any servicing or monitoring tasks, and any such items planned over the forthcoming 24hrs.

Also, it is recommended that all of the key-point trend plots (see Figure 4 examples above) are updated and reviewed so that any concerns with changing parameter trends may be reported. If any concerns are observed these should first be reviewed by the responsible test engineer in case any intervention, or further inspection or remedial action is required.

Note - All component replacements or removals must be noted especially of the components targeted for resonance testing.

Less frequently (at a frequency to be agreed e.g. aligned with engine performance checks), a more thorough delivery of information will be required, including (but not limited to):

- Latest performance check data (cross-plotted with previous performance results)
- Engine blowby and crankcase pressure data
- Oil consumption trend data
- Oil sample analysis data and plots
- Summary of any service or engine monitoring measurements
- Summary of any component replacements since the preceding review

10 POST-TEST ACTIVITIES

Once the test has been completed, the following tasks are to be completed:

EOT Requirements	• Perform EOT Power curve (with 30s averaged logs at each stabilised speed/load condition and 1Hz logging throughout) o Crankcase blow-by is to be logged during this check • Check all required critical fixings paint marks are still aligned – note any that appear to have moved • IR Thermal image recordings of the engine or individual components may also be requested
Oil Requirements	• Retain 100ml oil sample from the tank, ensure that it is clearly labelled • Drain oil and confirm volume removed from engine using drain and weigh method o Requesting engineer to confirm if drained oil can be discarded
Other Measurements *(record in build / logbook)*	• Post-test crankshaft TV performance • Cylinder leak down and compression on all cylinders - see procedure **BE-GEN-003** • Valve clearances (optional, if requested)
Checks	• Log any fluid or gas leakages o Photograph and record in logbook • Ensure Engine logbook is complete and up to date • Any parts removed from engine during test must be clearly labelled with the engine no., removal date, engine hrs and position on engine (if relevant) • Ensure all test data is suitably archived • All open engine ports or interfaces must be plugged or suitably protected from dust / debris ingress

The test engineer and engineering project team should review the data before engine is removed from the testbed for disassembly.

11 TEARDOWN ACTIVITIES

The engine is to be torn down post-test and fully inspected to determine the amount of wear, damage or distress (e.g. fretting or galling), that has occurred on the various engine components. The requirements and instructions for this will be provided in a dyno. test engine teardown procedure.

Typically, during the teardown, the following activities will need to be completed:

- Inspect engine condition when on stand prior to any part removal and photograph
- Valve clearance measurement and record values
- Measure and record the break-away and back-to-mark torque values of critical engine fasteners and all fasteners being monitored for vibration torque relaxation during this test.
- Measure and record the vacuum achieved for intake and exhaust ports in cylinder head with valves installed
- Ensure engineer is present during teardown to photograph and catalogue any issues and record the general condition as found at the end of test before any components are disturbed.

On dis-assembly key components will need to be examined, measured, and photographed, typical examples for consideration are listed below. The inspection requirements for this specific test will be included in the teardown procedure.

Special attention should be paid to components with large resonances identified and any areas where torque relaxation or fretting have been observed. In some cases, crack detection of components may be necessary (e.g. mounting brackets, cast lugs, etc.)

- Cylinder block (cylinder liners and main bearing bore)
- Cylinder heads
- Head gaskets
- Pistons
- Piston rings
- Main and big end bearings
- Crankshaft
- Conrod little end bush
- Gudgeon pin
- Camshafts
- Valves
- Turbochargers (Visual & supplier inspection)
- Exhaust manifolds
- Intake manifolds
- FIE Turbochargers (Visual & supplier inspection)
- Front and rear geartrain components
- Water pump (Visual & supplier inspection)
- Oil pump (Visual & supplier inspection)

Condition of these components shall be documented in a report pack with all required measurement results and relevant photographs.

12 PASS / FAIL CRITERIA

- Principally, this test will be considered to be a pass if the engine is still functioning correctly at the end of the 250hr test duration and no vibration fatigue failures have occurred on the components highlighted for resonance testing

However, the following criteria should also be met

- EOT engine performance is with ±5% of SOT performance
- No key component failures (i.e. meets critical functions at end of test)
- No significant fluid or gas leakages
- Rate of oil degradation is acceptable for amount of time used
- Oil consumption is within technical specification targets (to be advised)
- Blow by is within technical specification targets (to be advised)
- No significant wear of the cylinder system, crank train, valvetrain, geartrain, intake or exhaust system that may be considered close to failure

- No excessive depositing within the cylinder system, intake or exhaust system that can significantly affect engine function

NB. These criteria may be further revised or added to as the definitive design and associated FMEA activities progress

Should a vibration-related component failure occur during this test, the failed part may be replaced (following all required evidence gathering activities) with a like-for-like replacement, or if available an interim improved 'fix', so that the test may continue to validate the remaining engine components.

If the design or quality of the failed part is subsequently improved it may then be re-evaluated with a more focussed period of running solely at the component's resonance speed(s), either at the end of test (if time permits), or during a repeat Resonance test run (e.g. GEN2). Note that the resonant frequencies of the revised or swapped part will need to be rechecked and the speed-band profile(s) adjusted accordingly.

APPENDICIES

Appendix 1 – Example Of Engine Build Measurement List

Details of pre and post-test component inspection measurements will be advised in a later update of this procedure once relevant detail design and analysis activities are complete

Wherever possible and appropriate pre-test measurements should be made during the engine build

Example measurements are shown in the table below:

COMPONENT	MEASUREMENT	PRE-TEST	POST-TEST
Crankcase	Inner diameter of cylinder bore (3 locations)	X	X
	Inner surface finish of cylinder bore (3 locations)	X	X
	Profile of longitudinal liners for determination of TDC wear		X
	Dimensional measurement of bench supports (Main Bearings)	X	X
	Check alignment of main bearing housings	X	
	Main bearing bore diameter (without bearing)	X	
	Main bearing bore diameter with bearings	X	
	Centre main bearing thrust width	X	
	Flatness of flame face (deck face)	X	X
	Roughness of cylinder head flame face	X	
	Protrusion of cylinder liners from engine block	X	
Piston and Rings	Selection diameters (Gauge point)	X	X
	Gudgeon pin bore diameter	X	X
	Ring groove width (top)	X	X
	Ring groove width (second)	X	X
	Ring groove width (oil control)	X	X
	Mass (excluding rings)	X	
	Mass (including rings)	X	X
	Tangential load (top)	X	X
	Tangential load (second)	X	X
	Tangential load (oil control)	X	X
	Thickness (top)	X	X
	Thickness (second)	X	X
	Thickness (oil control)	X	X
	Fitted gap measured in ring gauge (top)	X	X
	Fitted gap measured in ring gauge (second)	X	X
	Fitted gap measured in ring gauge (oil control)	X	X
	[illegible] proud[illegible]	X	
Piston Pins	Outer diameter of pin in three positions	X	X
	Roughness	X	
Crankshaft	Crank journal and rod pin diameters (main and big end)	X	X
	Crank journal and rod pin roughness (main and big end)	X	X
	Crank thrust width	X	
	Crank thrust [illegible] roughness	[illegible]	
	[illegible]	X	
Rods	Big end diameters	X	X
	Big end diameters with bearings fitted	X	X
	[illegible]d surface roughness	X	
	[illegible]	X	X
	[illegible]	X	X
	Bore parallism	X	
	Mass	X	
	Small end roughness	X	X
	Perpendicularity	X	
Main and Big End Bearings	Thickness	X	X
	Protrusion under load indicated on drawing (crush)	X	
	Inner diameter of half bearings installed in rod big end and main bearings (tighten to specification)	X	X
Cylinder Bore (with head plate fitted if required) [Bore distortion]	Cylindricity 1	X	X
	Cylindricity 2	X	X
	Cylindricity 3	X	X
	Cylindricity 4	X	X
	Cylindricity 5	X	X
	Cylindricity 6	X	X
	Cylindricity 7	X	X
	Cylindricity 8	X	X
	Cylinder 1 – 2nd, 3rd, 4th order	X	X
	Cylinder 2 – 2nd, 3rd, 4th order	X	X
	Cylinder 3 – 2nd, 3rd, 4th order	X	X
	Cylinder 4 – 2nd, 3rd, 4th order	X	X
	Cylinder 5 – 2nd, 3rd, 4th order	X	X
	Cylinder 6 – 2nd, 3rd, 4th order	X	X

	Cylinder 7 – 2nd, 3rd, 4th order	X	X
	Cylinder 8 – 2nd, 3rd, 4th order	X	X
Cylinder Head	Gas face flatness	X	X
	Gas face roughness	X	
	Valve guide diameter	X	X
	Valve stand proud or sunk down	X	X
	Camshaft bore thrust width and finish	X	
	Valve guide to seat run out	X	X
	Camshaft bearing carrier diameter	X	X
Cylinder Head Fasteners	Length	X	X
Valves	Stem diameter	X	X
	Stem roughness	X	X
	Stem to seat run out	X	X
	Valve height	X	X
	Seat profile	X	X
Camshaft	Journal diameter		X
	Cam thrust width	X	
	Cam roughness		X
	Cam hardness	X	
	Valve lift	X	
Valve Tappets	Diameters	X	X
	Roughness	X	
Valve Springs	Free length of spring	X	X
	Spring rate	X	
Gear Drive	Backlash	X	X

Note all fastener crack-off and back-to-mark torques to be noted on critical fasteners only.

APPENDIX 2 – EXAMPLE TEST MONITORING REGIME

Example for guidance only - Appropriate timing of these tasks will be confirmed following formulation of the phase 2 test cycle

Action	Every x Cycles (~8hrs)	Every xx cycles (~16hrs)	Every xxx cycles (~24hrs)	Every xxxx cycles (~100hrs)
5-minute engine stop (minimum)	Yes	Yes	Yes	Yes
Visual safety check of engine & test cell	Yes	Yes	Yes	Yes
Check oil level and top-up to Max. (record amount of any oil added)	Yes	Yes	Yes	Yes
Visual inspection of all vibration-critical components (TBA)	Yes	Yes	Yes	Yes
Visual engine leak check (record observations in logbook)		Yes	Yes	Yes
Check intake system fluid drains & empty		Yes*	Yes	Yes
Weigh & empty CCV catch cans (if fitted)		Yes*	Yes	Yes
Update and review key-point trend graphs		Yes	Yes	Yes
Take & retain 100ml used oil sample (replace with fresh oil)			Yes	Yes
Perform engine leak-down and compression checks				Yes
Perform other monitoring measurements e.g. valve clearances, Crank TV measurement etc.(TBA)				Yes
Carry out engine performance test				Yes
Oil and filter change				Yes
Review all data before proceeding with test				Yes

* - More frequently if necessary

Note that this schedule may need amending or additional requirements added, as the definitive design and associated FMEA activities progress, or based on observations made from any preceding GEN1 functional and durability testing.

APPENDIX 3 – LIST OF TARGETED COMPONENTS FOR BE1500

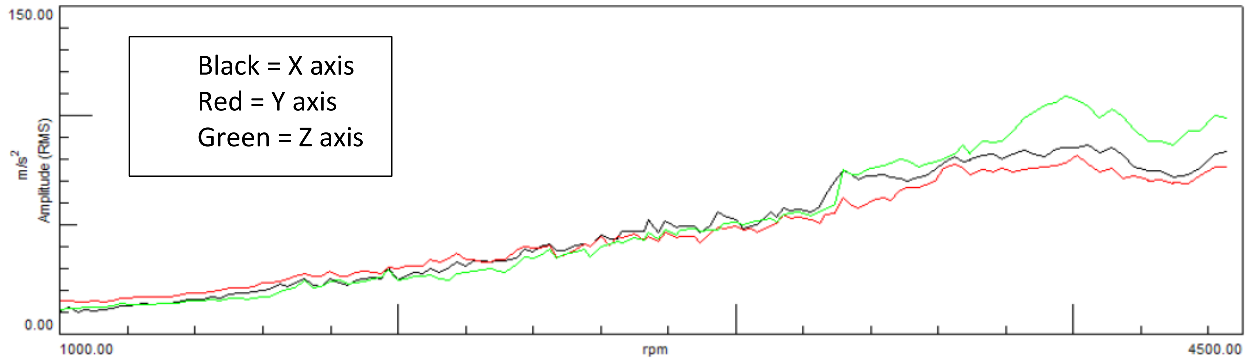
TBC – Typically this test will include vibration assessment of the following components:

- Cylinder block
- Cylinder head
- Oil cooler / filter assembly
- Scavenge/Pressure Oil pump
- Priming oil pump
- Oil sump / tank
- Water pump
- HP Fuel pump
- LP Fuel pump
- Fuel rails
- Injector
- HP Fuel pipe(s)
- Fuel cooler
- Fuel filter assembly
- CAC
- Turbos (both banks if handed)
- Oil sump / tank
- Generators
- Air compressor
- Air filter assembly
- Crank / TV Damper torsional vibration

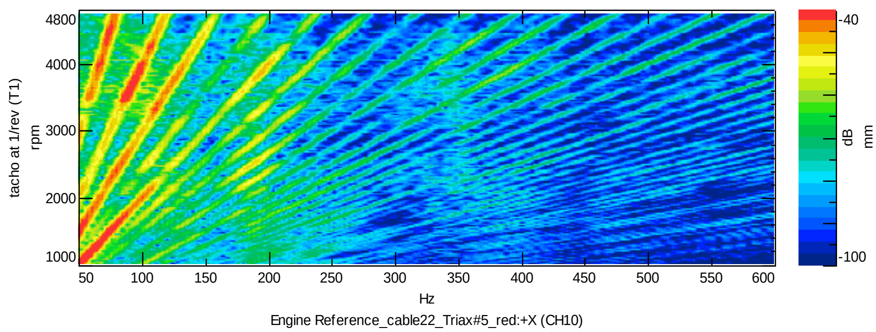
[A full list of components (and specific locations) which are required to be measured and assessed during this test will be defined during the definitive design phase following completion of the necessary design, analysis and FMEA activities and supplier discussions].

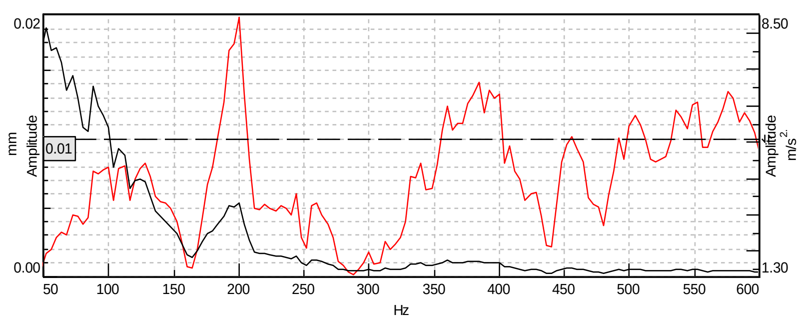
APPENDIX 4 – EXAMPLE OF POST-PROCESSED ACCELEROMETER DATA PLOTS

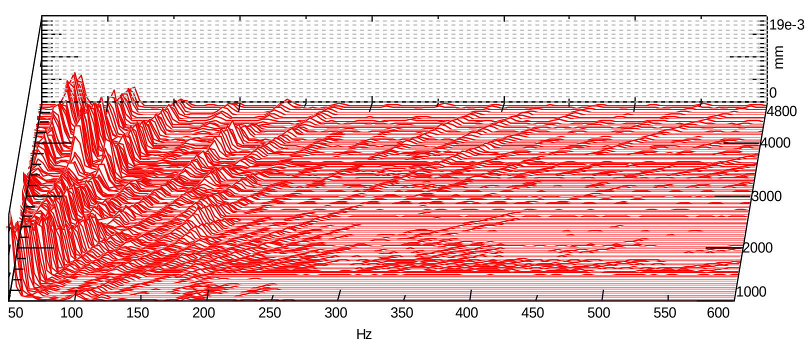
Example of RMS amplitude against engine speed :



Example frequency spectra, waterfall plots and colour-maps are shown below:







APPENDIX 5 - SUMMARY TABLE OF COMPONENT VIBRATION RESONANCES

Example of tabulated results for component vibration below:

FULL LOAD SPEED SWEEP 90s 1000-6500Hz

X = Along Cranks Axis ; Y = Across Crank Axis ; Z = Vertical

Position	Axis	Low Resonance (Hz)	High Resonance (Hz)	Mean Resonance (Hz)	Time	Low Speed (rev/min)	High Speed (rev/min)	Mean Speed (rev/min)	Engine Order	Amplitude (mm)	Amplitude (m/s²)
SCV_out	X	213	235	224	12	3201	3519	3360	4.0	0.012	24.3
Injector Connector Cyl8	Y	439	469	454	6	3292	3518	3405	8.0	0.014	112.2
Injector Connector Cyl8	Z	439	469	454	6	3292	3518	3405	8.0	0.025	202.3
LH_HP Pipe to Rail 2d	X	218	240	229	12	3274	3596	3435	4.0	0.010	20.5
Top Y Pipe	X	246	268	257	11	3685	4025	3855	4.0	0.011	28.4
HPPipe_Front_2f	Z	507	539	523	5	3801	4044	3923	8.0	0.017	185.3
RH_HP Pipe to Rail 2e	Z	[illegible]	539	523	5	[illegible]	[illegible]	3923	8.0	0.017	178.9
HPPipe_Front_2f	Y	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3986	7.0	0.011	92.8
Ign_Coil_8	X	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4040	3.0	0.040	65.9
Injector Connector Cyl1	Z	328	354	341	8	3935	4249	4092	5.0	0.013	57.7
Injector Connector Cyl5	Z	261	285	273	10	3920	4270	4095	4.0	0.019	55.5
Injector Connector Cyl1	X	338	364	351	8	4053	4371	4212	5.0	0.017	84.4
HPPipe_Front_2f	Z	288	312	300	9	4316	4684	4500	4.0	0.026	92.4
Water_ByPass_Pipe	Y	142	160	151	18	4269	4791	4530	2.0	0.075	68.0
Block_ref	Z	142	160	151	18	4269	4791	4530	2.0	0.013	11.9
HP Rail Boss_2C	Y	604	640	622	4	4533	4797	4665	8.0	0.011	162.3

APPENDIX 6 – EXAMPLES OF COMMON TYPES OF TRI-AXIAL ACCELEROMETERS USED

PRODUCT DATA

Piezoelectric Charge Accelerometer Types 4384 and 4384-V

Uses
- General purpose vibration testing and analysis
- High-frequency measurements

Features
- High sensitivity

Description

Type 4384 is a DeltaShear™ Unigain* accelerometer. It features a 10–32 UNF-2A top connector and a 10–32 UNF-2B threaded hole for mounting. Type 4384-V† has the same specifications and stability as Type 4384, but it has a relaxed sensitivity tolerance.

Characteristics

This piezoelectric accelerometer may be treated as a charge source. Its sensitivity is expressed in terms of charge per unit acceleration (pC/ms^{-2}, pC/g).

The DeltaShear design consists of three piezoelectric elements and three seismic masses arranged in a triangular configuration around a triangular centre post. They are held in place by a clamping ring that isolates the configuration from the base. The ring also prestresses the piezoelectric elements to give a high degree of linearity. During vibration, the piezoelectric elements produce a charge that is collected between the housing and the clamping ring. The piezoelectric element used is a PZ 23 lead zirconate titanate element, and the housing material is titanium.

Calibration

For Unigain accelerometers, the sensitivity is calibrated to a convenient value such as 1, 3.16 or 31.6 pC/ms^{-2}. The sensitivity given in the calibration chart has been measured at 159.2 Hz with 95% confidence level, using the coverage factor k = 2.

Fig. 1 Dimensions of Type 4384

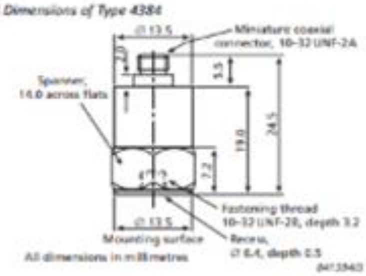
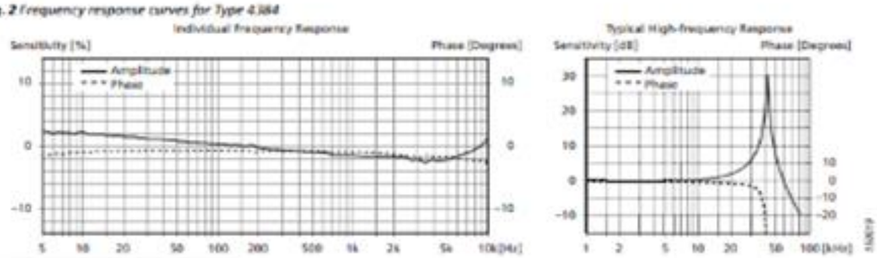


Fig. 2 Frequency response curves for Type 4384



* Unigain: The individual measured sensitivity is within ±2% of the specified sensitivity

† V-type: The individual measured sensitivity is within ±15% of the specified sensitivity

Brüel & Kjær

PRODUCT DATA

Piezoelectric Charge Accelerometer Types 4326-A and 4326-A-001

Types 4326-A and 4326-A-001 are triaxial piezoelectric accelerometers with three independent outputs for simultaneous high-level measurements in three mutually perpendicular directions. The accelerometers feature the ThetaShear™ design and each transducing element is individually calibrated.

The accelerometers have the same rectangular shape and 10−32 UNF connectors. The main differences between the models lie in the housing material, weight, temperature range and dielectric strength (flash over voltage).

Uses and Features

Uses
- General purpose vibration testing and analysis
- Multi-axis vibration and shock measurements
- Measurements in confined spaces
- Measurements in high-temperature environments

Features
- Triaxial
- High sensitivity-to-weight ratio
- Low sensitivity to environmental factors
- Electrically insulated for ground-loop protection
- High resonance frequency
- Easily fitted to test objects using mounting clips

Versions

Table 1
Comparison of Type 4326 versions

Type	Housing Material	Maximum Temperature	Weight	Sensitivity
4326-A	Hard-anodized aluminium	175 °C (347 °F)	13 grams	0.316 pC/ms^{-2} ± 20%
4326-A-001	Titanium	230 °C (446 °F)	17 grams	0.316 pC/ms^{-2} ± 20%

Description

These piezoelectric accelerometers may be treated as charge sources. Their sensitivity is expressed in terms of charge per unit acceleration (pC/ms^{-2}, pC/*g*).

ThetaShear Design
The ThetaShear design consists of a slotted cylindrical post holding a central seismic mass flanked by two piezoelectric plates. This assembly is clamped rigidly by the cover. To ensure optimum accuracy and reliability, molecular adhesion is the only bonding agent used to hold the assembly together. The ThetaShear design provides a combination of high measurement stability, excellent sensitivity-to-weight ratio and low sensitivity to extraneous environmental effects.

Brüel & Kjær