EDG Vibrations and Mitigation

100 operational years in
four nuclear power
stations with 12 reactors

Vibration Causes and Corrective Actions

Based on operating history from 45 years

Some 40 sets from old to some years of age

A selection of the sets will follow

Forsmark 3 and Oskarshamn 3 Nohab - Wärtsilä

Figures from ISO 8528-9

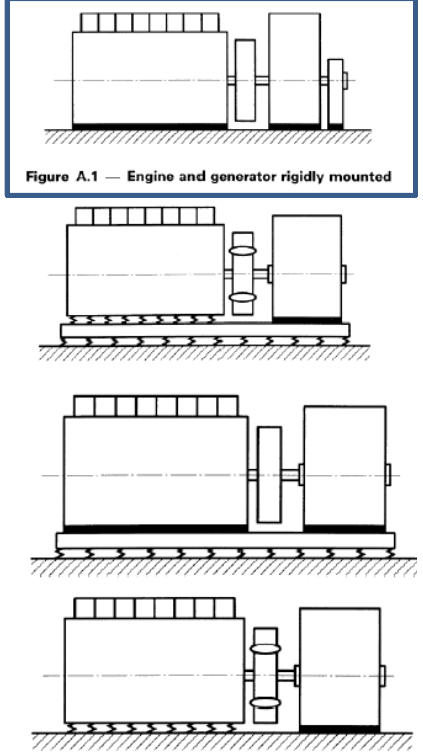
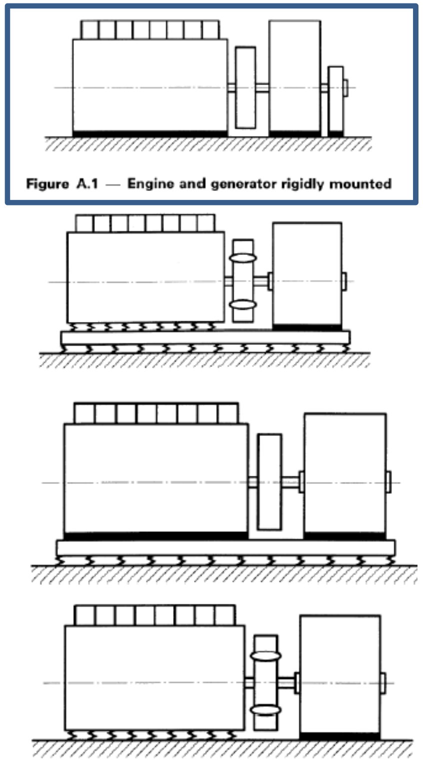


Figure A.1 — Engine and generator rigidly mounted

Ringhals 3 and 4 Nohab

Figures from ISO 8528-9



Atlas Copco starting air compressor

Ringhals 3 and 4 Wärtsilä

Figures from ISO 8528-9

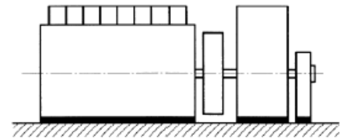
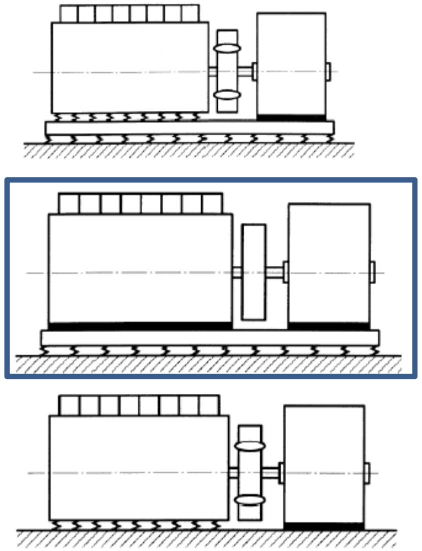
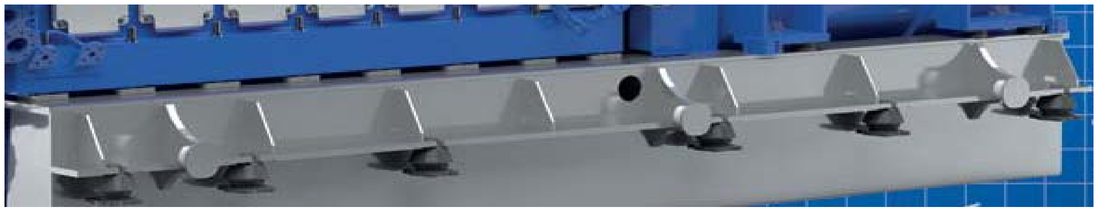


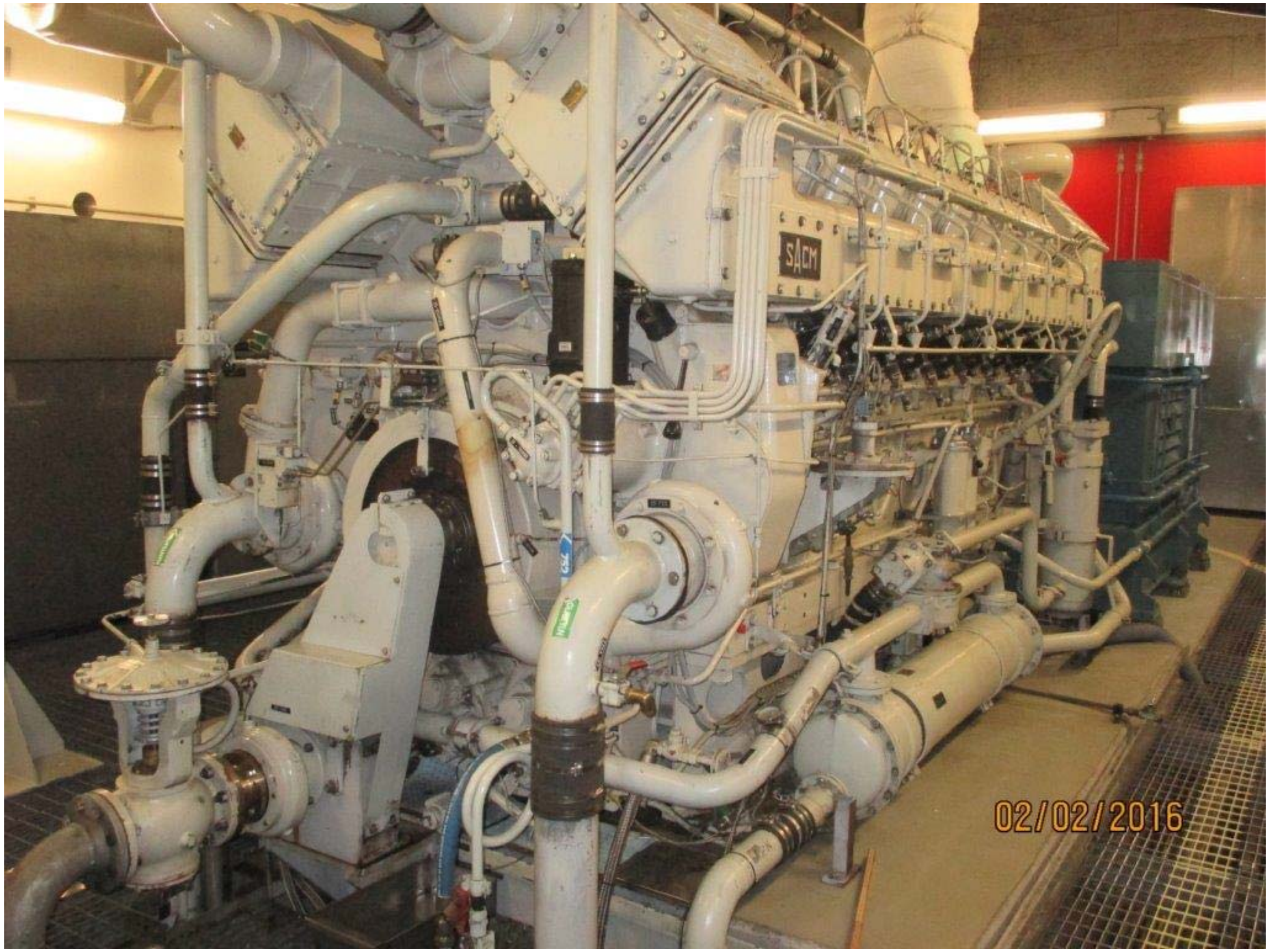
Figure A.1 — Engine and generator rigidly mounted





This design called Wärtsilä 32
will replace the 8 pcs SACM UD33
In Olkiluoto sets soon.

Ringhals 1 and 2 SACM



Figures from ISO 8528-9

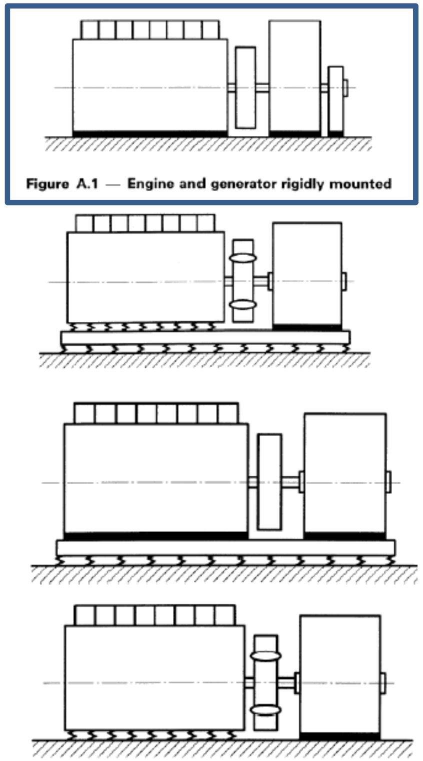
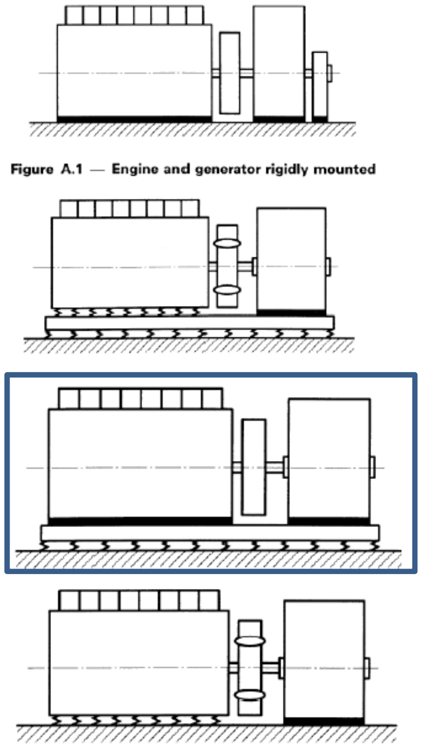


Figure A.1 — Engine and generator rigidly mounted

Forsmark 1 and 2 and Olkiluoto 1 and 2

SACM, UD33

Figures from ISO 8528-9



Oskarshamn 1
EDG A and B
Hedemora

Oskarshamn 2
A and B MTU

Figures from ISO 8528-9

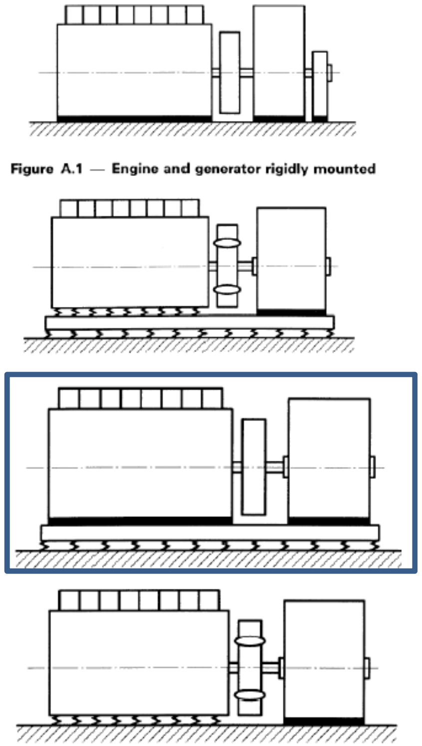


Figure A.1 — Engine and generator rigidly mounted

Vibrations as a reliability related experience

Grouped per type of disturbance

What is special for an Internal Combustion Engine used in all EDGs?

Material accumulated in 6 pcs A4 ledgers

There has been a short one day visit to each plant and numerous mail exchanges. Old written material from working with problems since 1975 in the Swedish 12 reactors has been used to support the sorting of problems.

Vibrations as a reliability related experience grouped per type of disturbance is now used to first a review of what is special for an Internal Combustion Engine used in all EDGs.

Further to the application as a prime mover for an electric generator and what is necessary to meet strong demands of availability and reliability.

We use this experience to formulate a framework for rules for procurement of new sets.

What is special for an EDG compared to any process machine?

Forces are made as combustions in cylinders

Car comfort for good availability and reliability

We will cover three main topics in this hour

Emergency Diesel Generator
EDG
Has an Internal Combustion engine and an electric generator

1. **<u>What is special for an Internal Combustion engine</u>**
2. **What can be done to eliminate or at least mitigate**
3. **Requirements for buying a new EDG**

Vibration Sources in General

Both linear and torsional vibration can be from:

- Misalignment of engine and driven equipment.
- Unbalance of rotating parts, engine, coupling, torque damper, generator rotor parts.

Vibration Sources in General

Both linear and torsional vibration can be from:

- Resonance from structural mass (weight) and stiffness (rigidity) combinations, all parts.
- Torque reaction of rotor line as well as combined aggregate structure.

Vibration Sources in General

Both linear and torsional vibration can be from:

- Cylinder misfiring, missing fuel, internal wear
- Combustion forces, simply torque pulsations
- Unbalance of reciprocating parts as well as driven generator rotor parts
- Electromagnetic forces from 2x50Hz in our NPPs

Simplified technical sources of vibrations

The following table correlates vibration characteristics to these possible causes:	
Vibration Characteristic	**Correctable Causes**
Only component motion	Mounting or use (example: flow) of component
1/2 x engine rpm (one-half order)	Misfiring of one or more cylinders. Regularly or occasionally.

Simplified technical sources of vibrations

The following table correlates vibration characteristics to these possible causes:	
1 x engine rpm (first order)	Unbalance (missing balancing weight or assembly run out between rotor parts)
2 x engine rpm (second order)	Misalignment, out-of time balance weights, crankcase overfill

Simplified technical sources of vibrations

The following table correlates vibration characteristics to these possible causes:	
1 1/2, 2 1/2, third and higher orders	Normal cylinder or higher orders combustion (not correctable)

Simplified technical sources of vibrations

The following table correlates vibration characteristics to these possible causes:	
Large vibration motion (often directional, radial or axial)	Unwanted resonance excited by EDGs normal forces
Motion increase with torque when load is applied	Insecure mounting or inadequate base structure

Related to EDG engine properties

CORRECTIVE ACTION ADVICE BASED ON HISTORICAL ACTIONS MADE

1. One Component
2. 1/2 Order Vibration
3. Irregular, Unstable Vibration or Unstable Load
4. 1st Order Vibration
5. 2nd Order Vibration
6. Higher Order Vibration
7. Non-Engine Vibration
8. Excessive Engine Motion

Designer Challenges

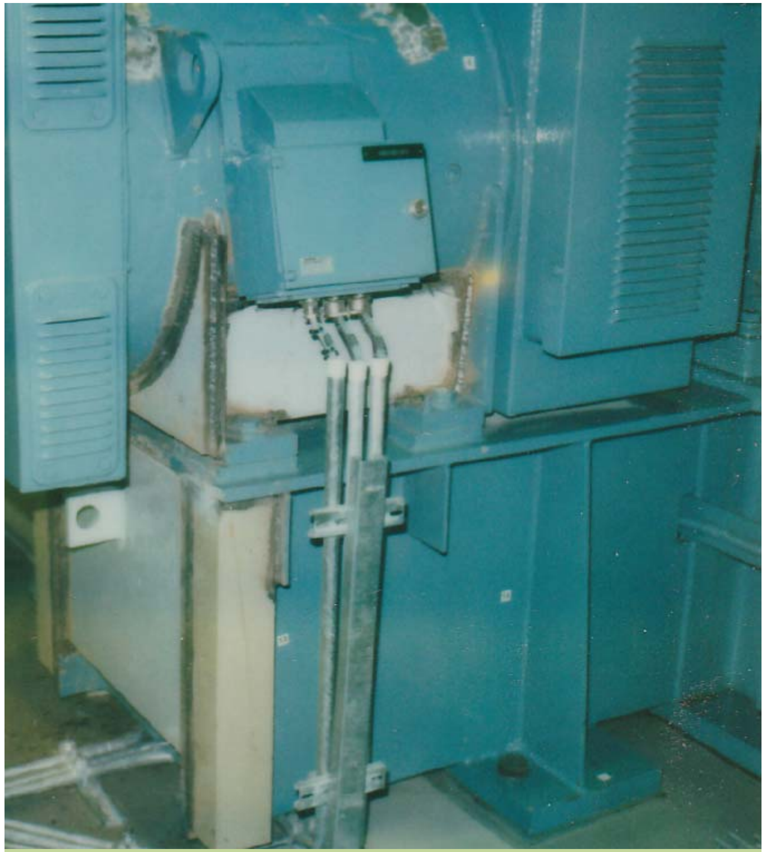
Exhaust from turbo too flexible

Energiforsk

Designer Challenges

Complex piping

Designer Challenges



Exciter too flexible

Designer Challenges

Floor is a table on pillars

Figures from ISO 8528-9

Variations in combining
the engine and generator

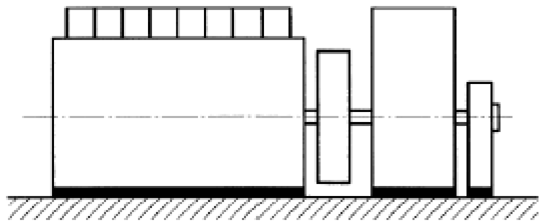
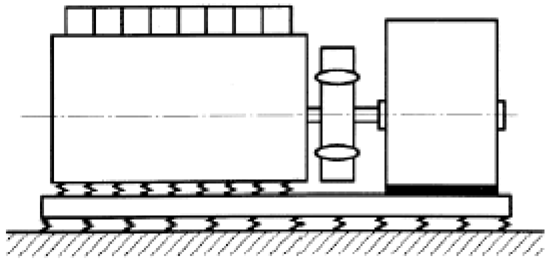
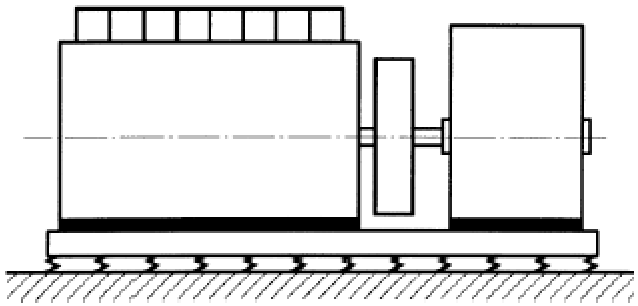
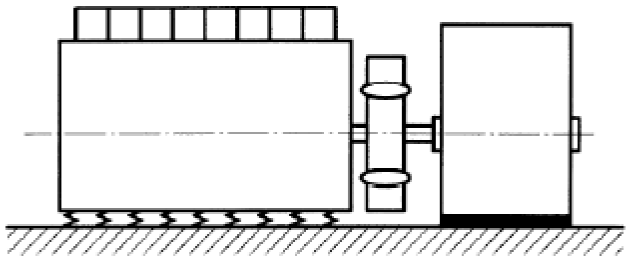


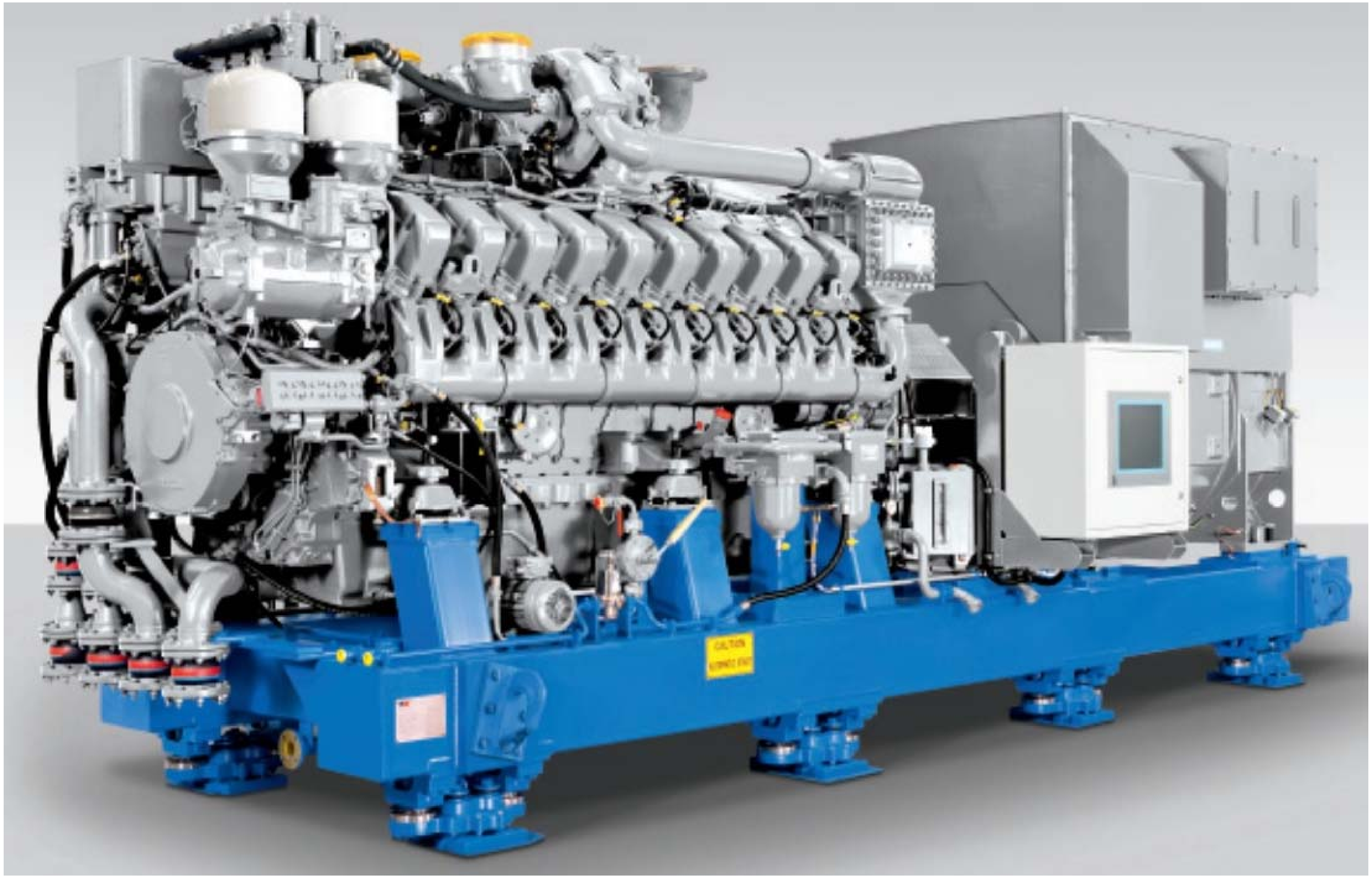
Figure A.1 — Engine and generator rigidly mounted







Just briefly how a well functioning EGD looks like

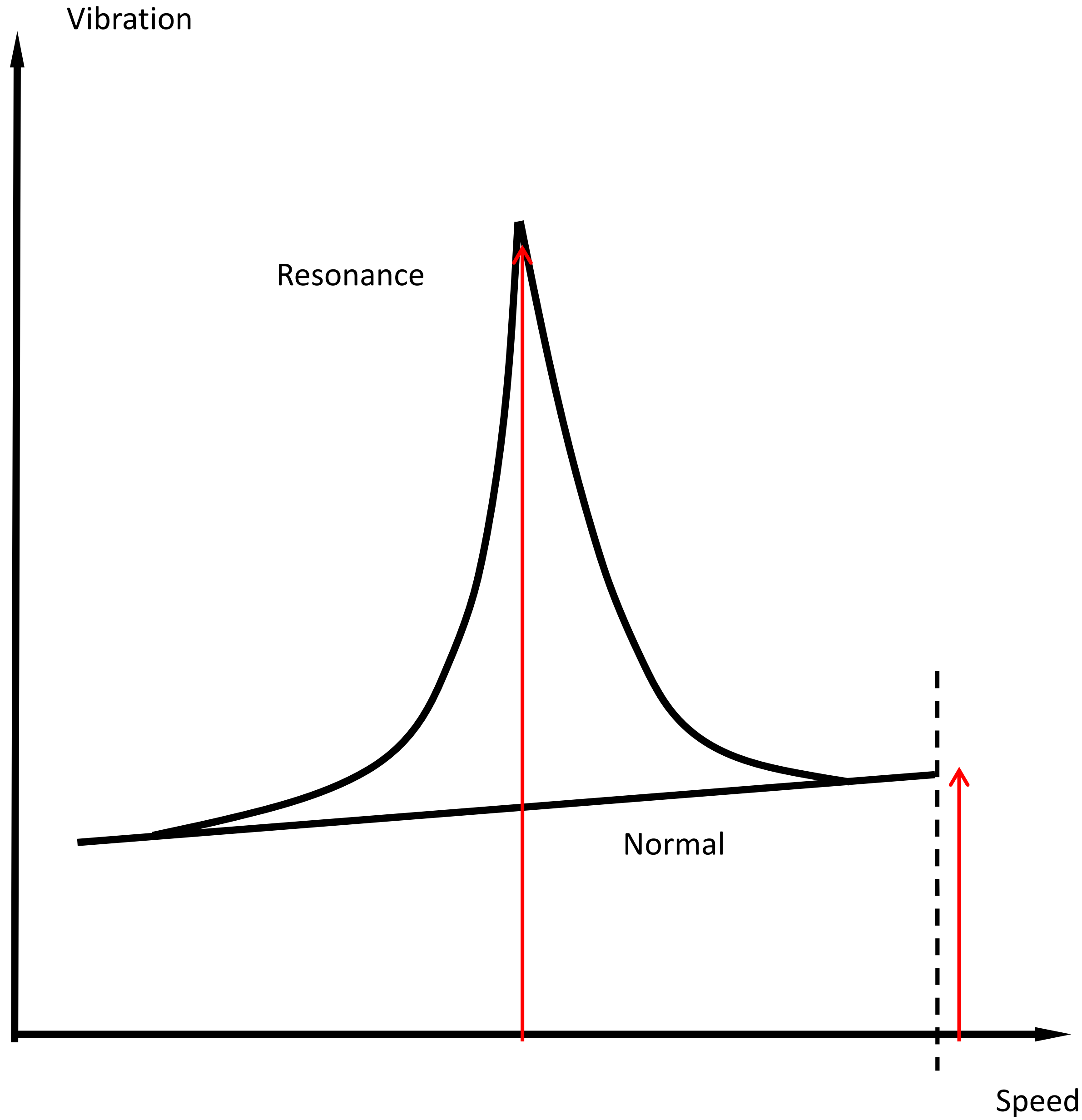


Three steps into basic torque pulsation understanding

How do three different errors manifest themselves?

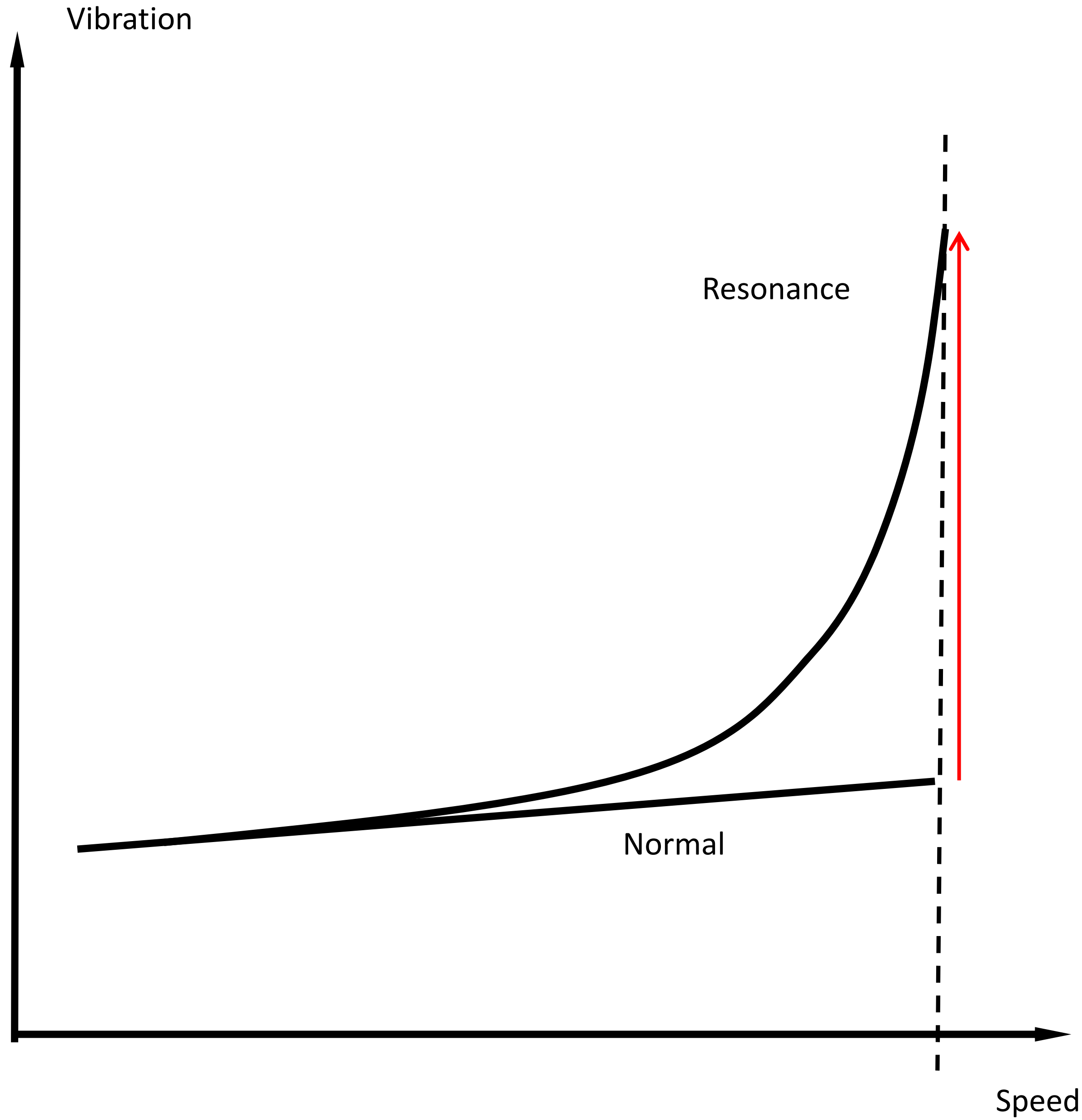
Resonance

Vibration high passing a speed when starting up

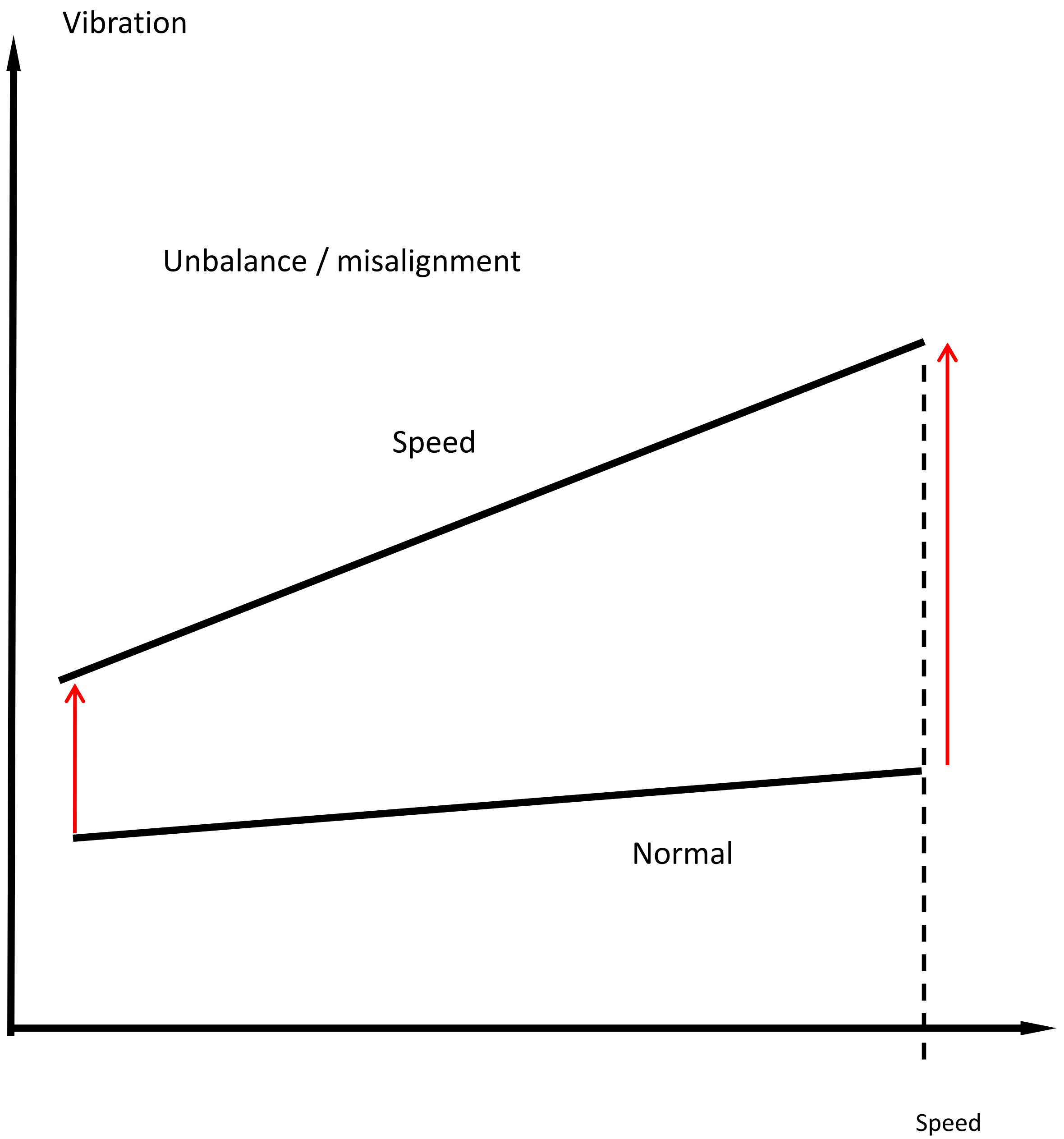


Resonance

Vibration worst at full speed

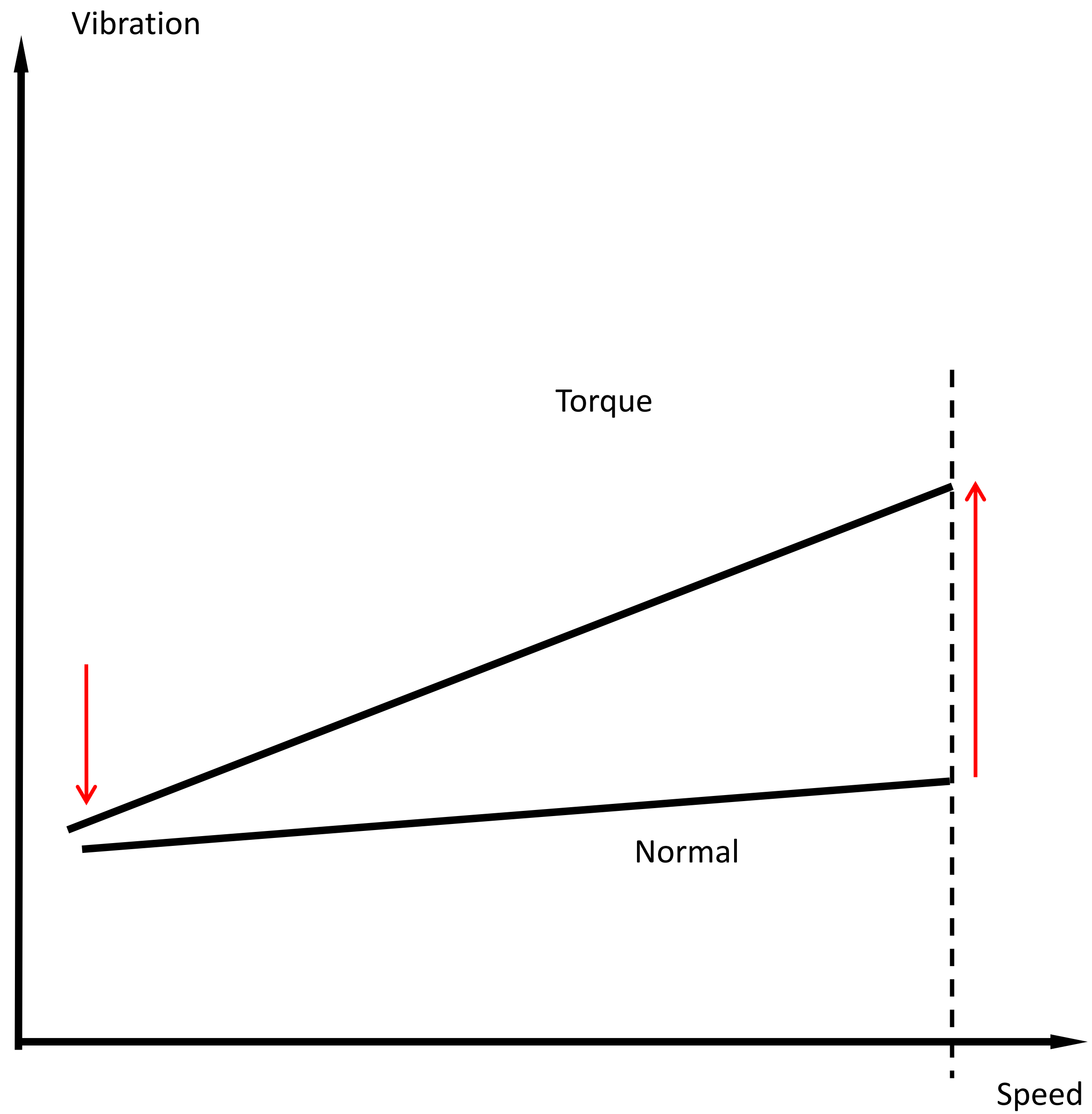


Unbalance
or
Misalignment



Torque
Vibration

Increasing from very low to high at full speed in an almost linear fashion



Where the torque actually comes from

All EDG diesel engines are four stroke engines
just as all modern car engines are.

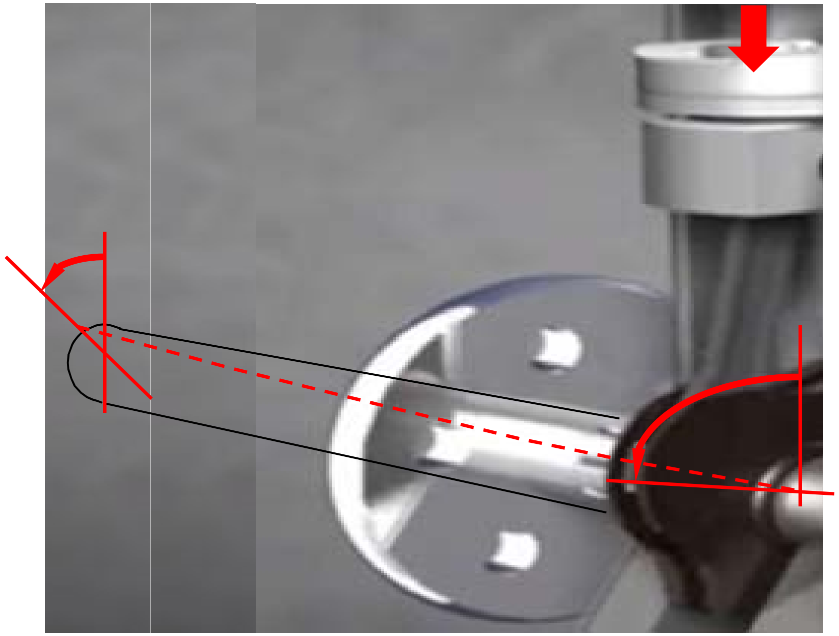
The four stroke engine fundamental property
A combustion occurs only every
second complete turn of a crank

The diesel engine is special

The combustion force to the crank will **twist**

the shaft one direction and just as strongly

the engine block will twists in the other direction



Large torsional rocking force opposed to the rotation

The pulsation has the frequency of half the speed

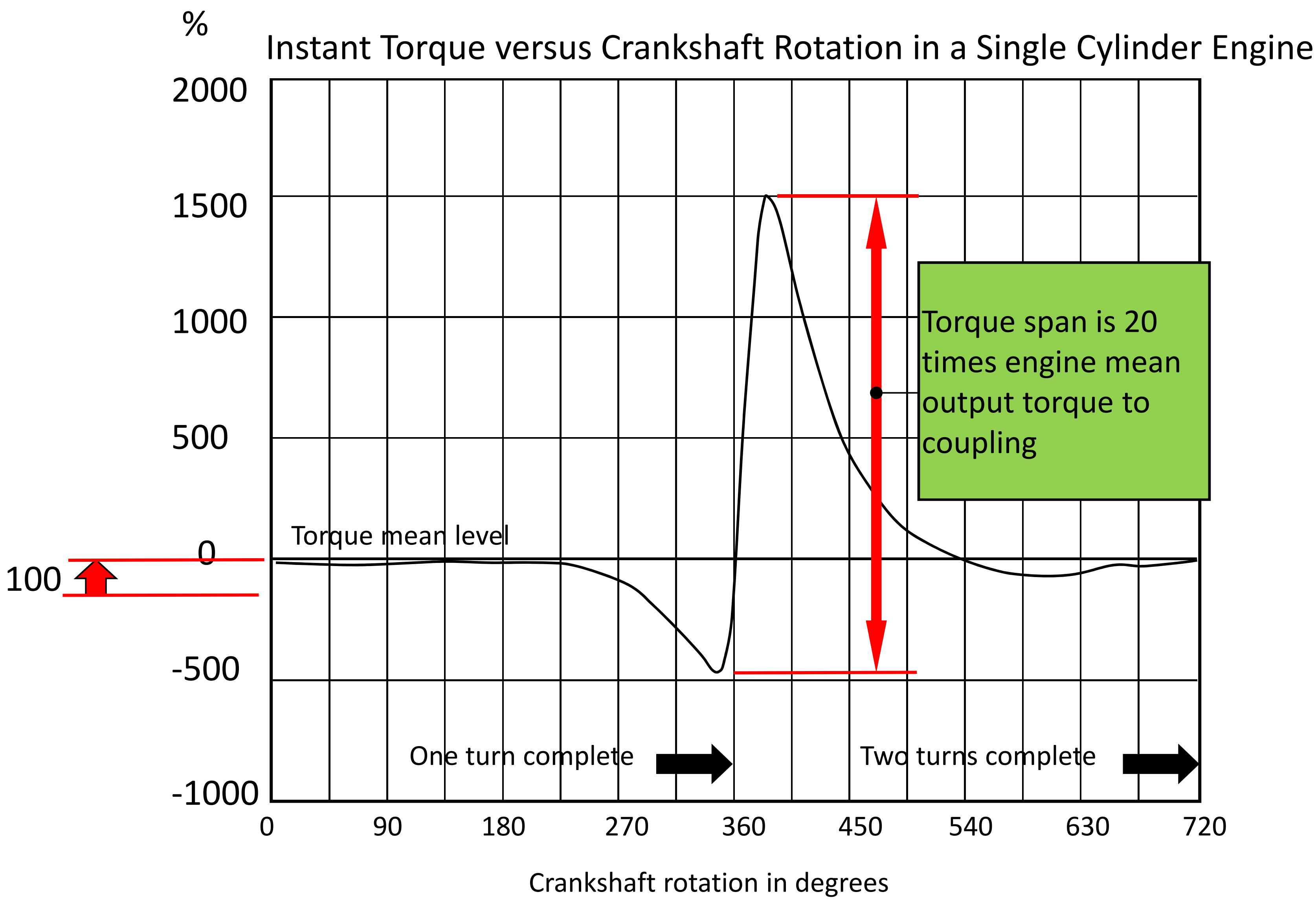
Example:
1500 RPM (25 Hz) running
a 4-pole generator to create 50 Hz
Pulsation is 12.5 Hz

The torque acts along two paths

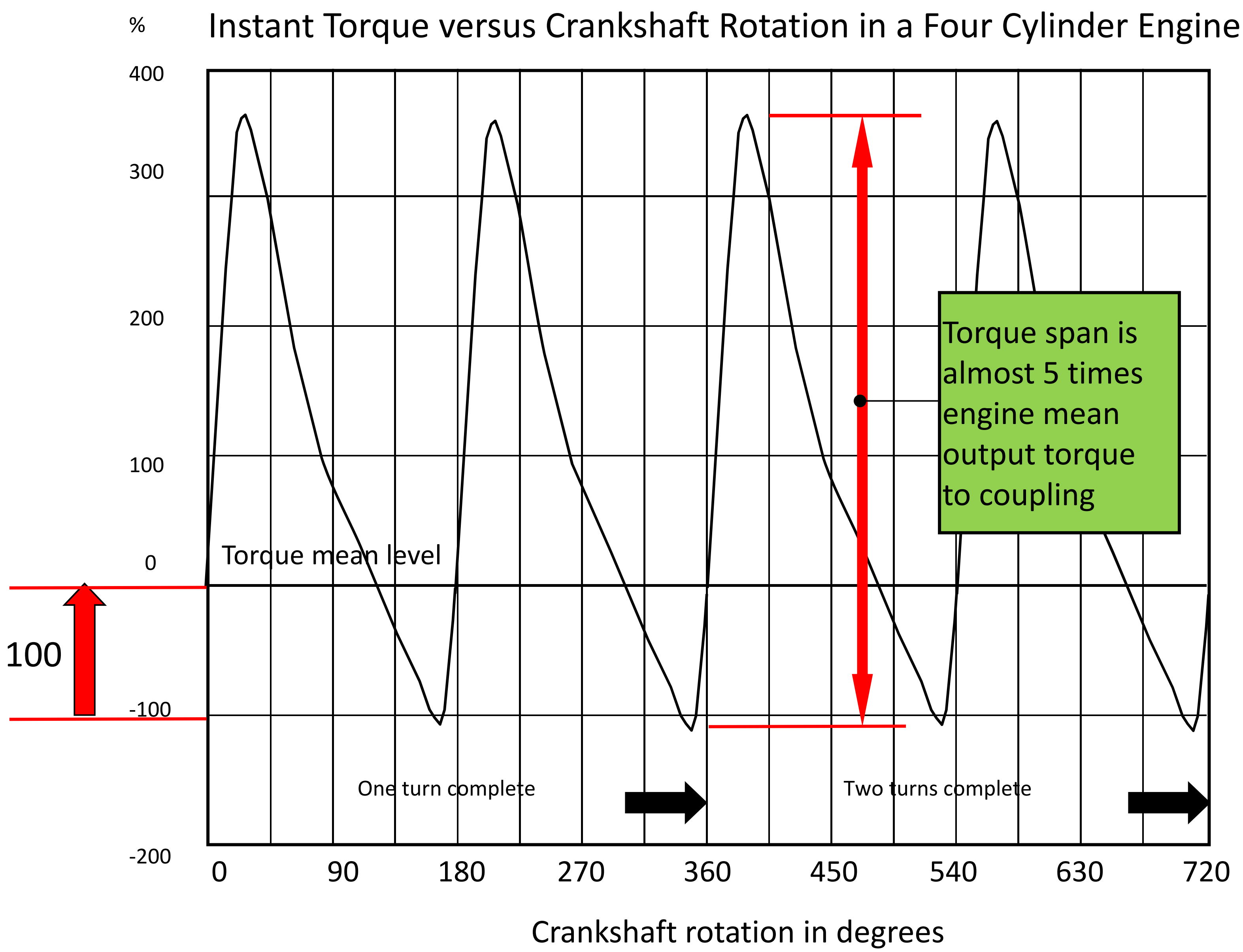
1. Shaft rotation damped through
the inertia of one or even two flywheels

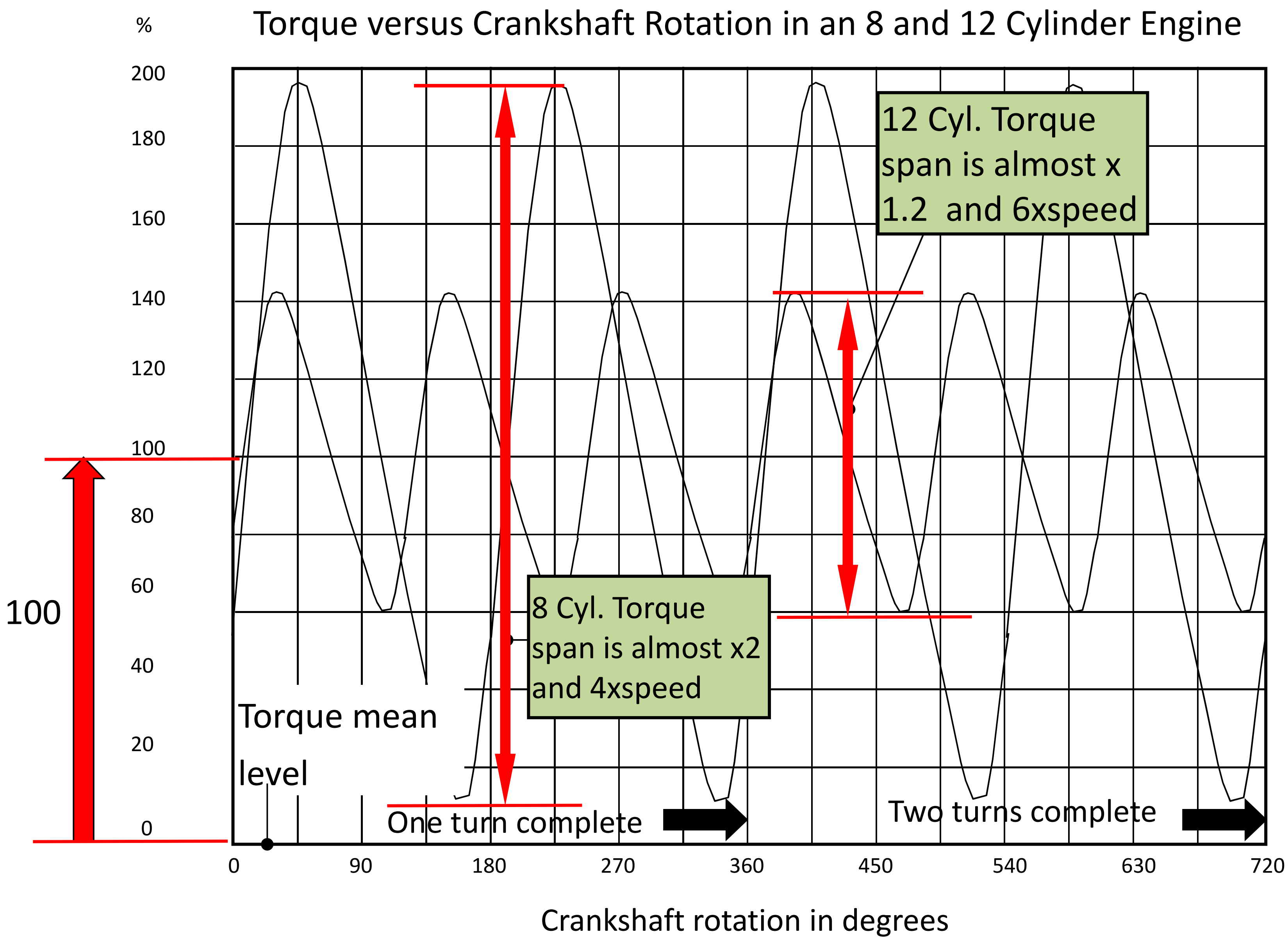
2. The engine block reaction is
damped through its inertia and
“fixation” to the base frame

A Single Cylinder Diesel



Fire order 1 3 4 2


Instant Torque versus Crankshaft Rotation in a Four Cylinder Engine
%
400
300
200
100
0
-100
-200
Torque mean level
100
Torque span is almost 5 times engine mean output torque to coupling
One turn complete
Two turns complete
0
90
180
270
360
450
540
630
720
Crankshaft rotation in degrees


Torque versus Crankshaft Rotation in an 8 and 12 Cylinder Engine
%
200
180
160
140
120
100
80
60
40
20
0
100
12 Cyl. Torque span is almost x 1.2 and 6xspeed
8 Cyl. Torque span is almost x2 and 4xspeed
Torque mean level
One turn complete
Two turns complete
0
90
180
270
360
450
540
630
720
Crankshaft rotation in degrees

The EDG has all normal machine vibrations
and
the torque pulsation

The torque pulsation is twisting the driveline and stators
with opposing direction with a force approx.
twice the mean power kWe.
When transformed into kNm pulses it has a frequency
locked to the firing frequency of the engine.

What happens with more number of cylinders?

What order of force are we considering?

2500 kWe at 1000 RPM is about 20 kNm.

How much weight is 20 kNm at the outer
end of a one meter lever fixed in one end?

20 000 Newton is approx. 2 ton.

So the torque impulse corresponds to double that.
2 ton-meter or 20 kNm brings respect.

Unbalance can often be handled with balancing efforts.

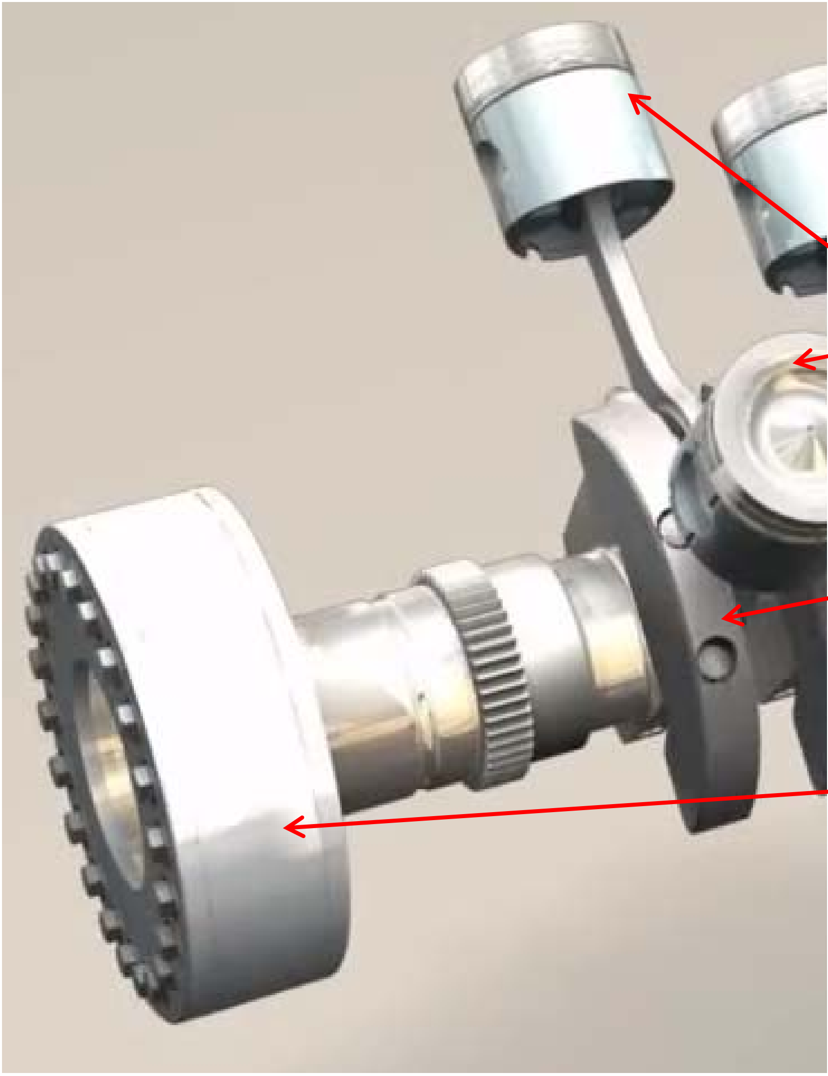
This force must be ”converted” to a steady torque to the generator.

Splitting the torque in 16 chocks over time is an improvement

Torsional damper MTU info homepage 2015 Flywheel

Engine rotor with pistons in an 16V4000

Torque Pulsation Damper

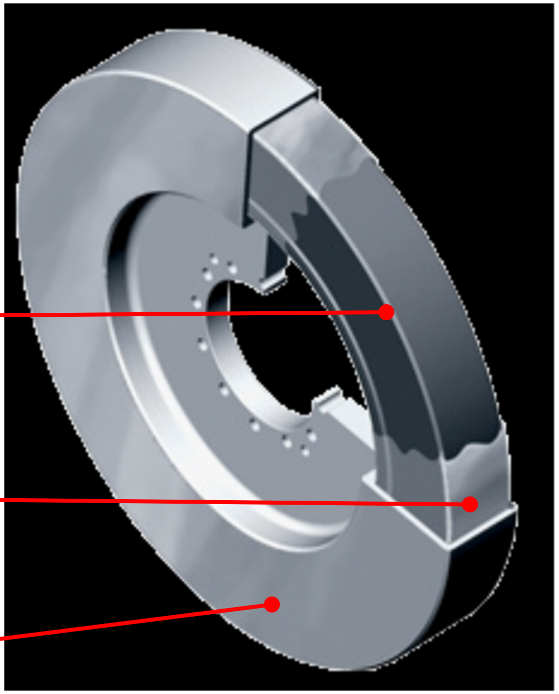


Piston pairs at each crank

Counter weights

Torque Damper at
the crankshaft
free end

Torque Pulsation Damper



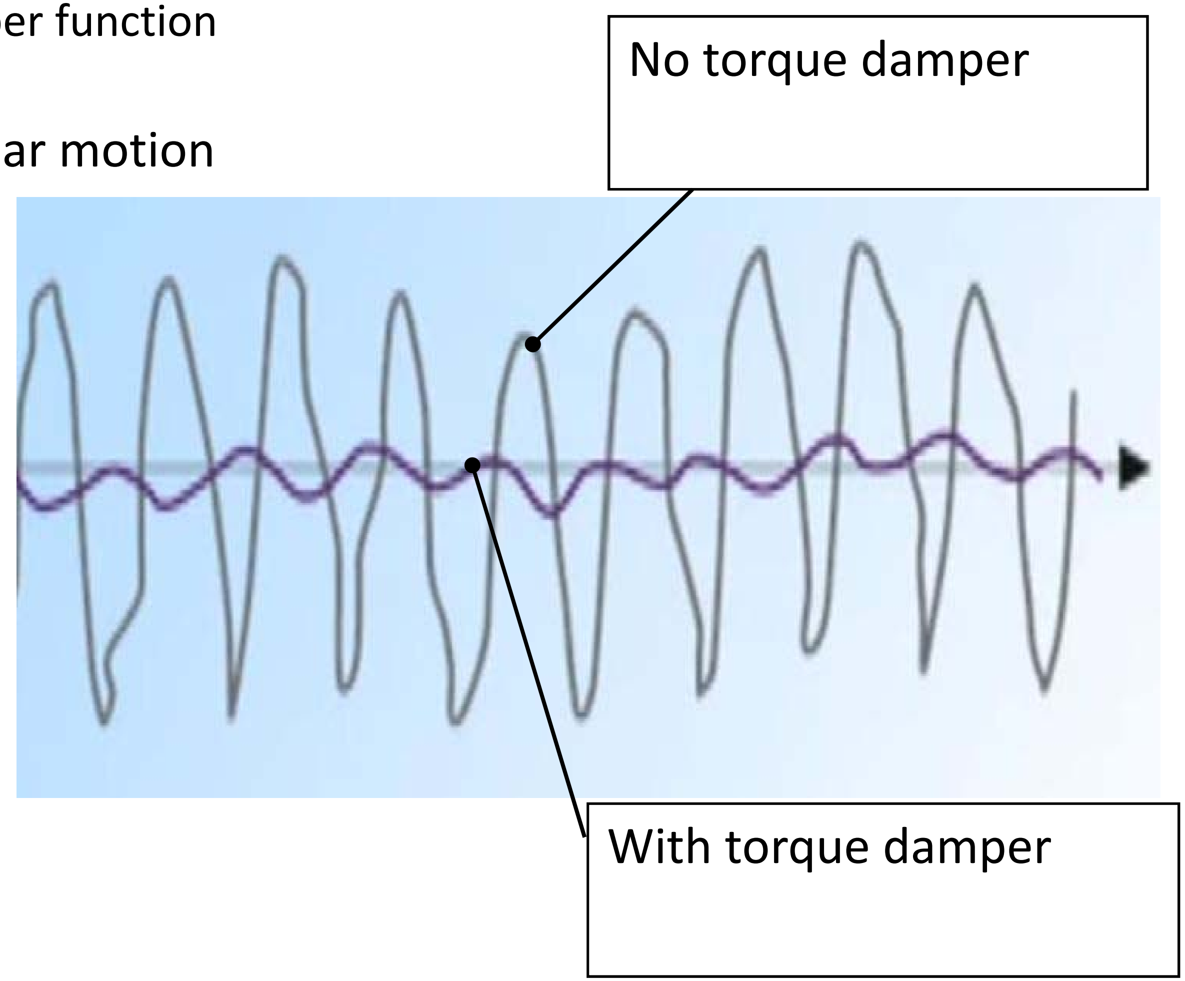
Massive steel ring

Silicone fluid in very small radial and axial gap

Container fixed on the crankshaft end

Damper function

Angular motion

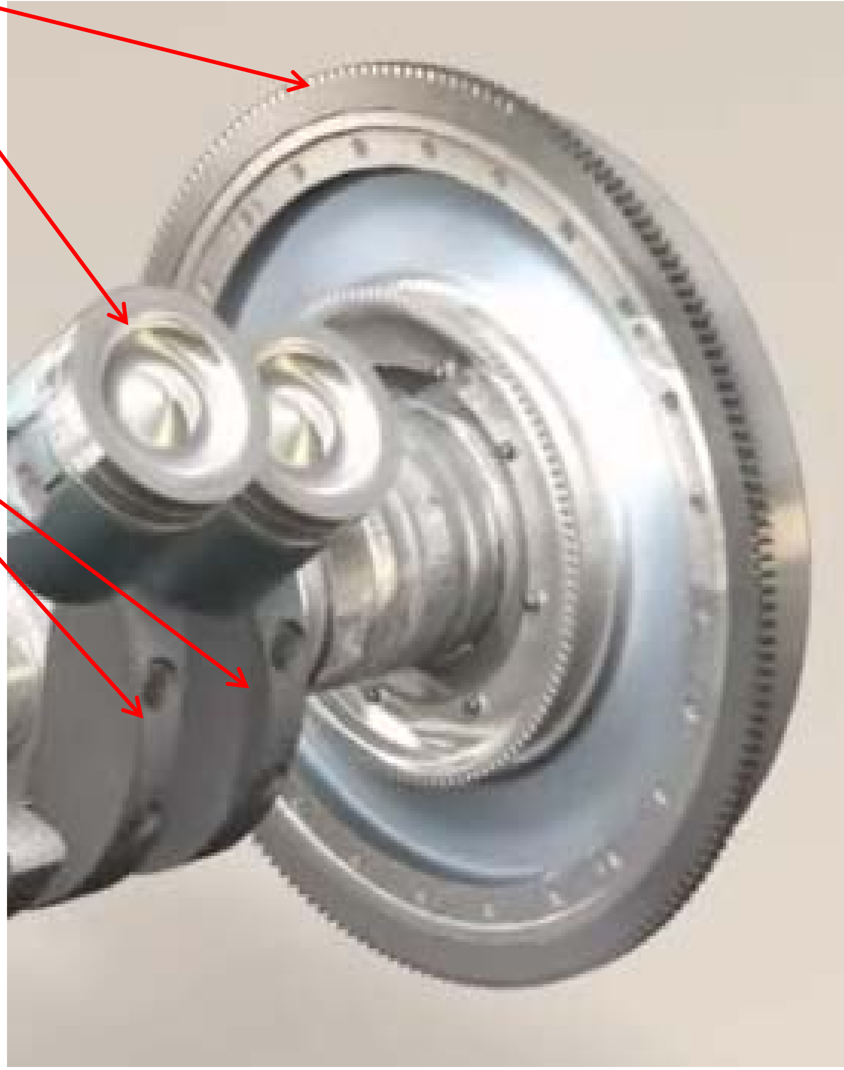


The flywheel, the pistons and counter weights all add inertia

Flywheel

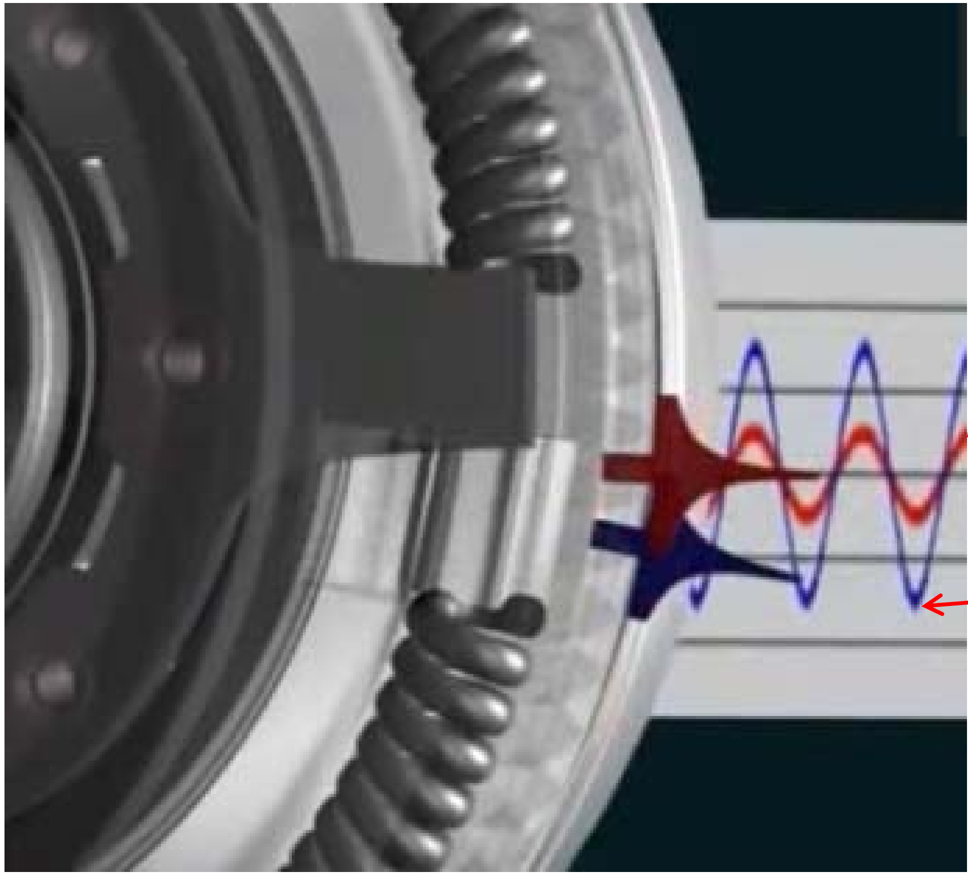
Piston pairs at each crank

Counter weights



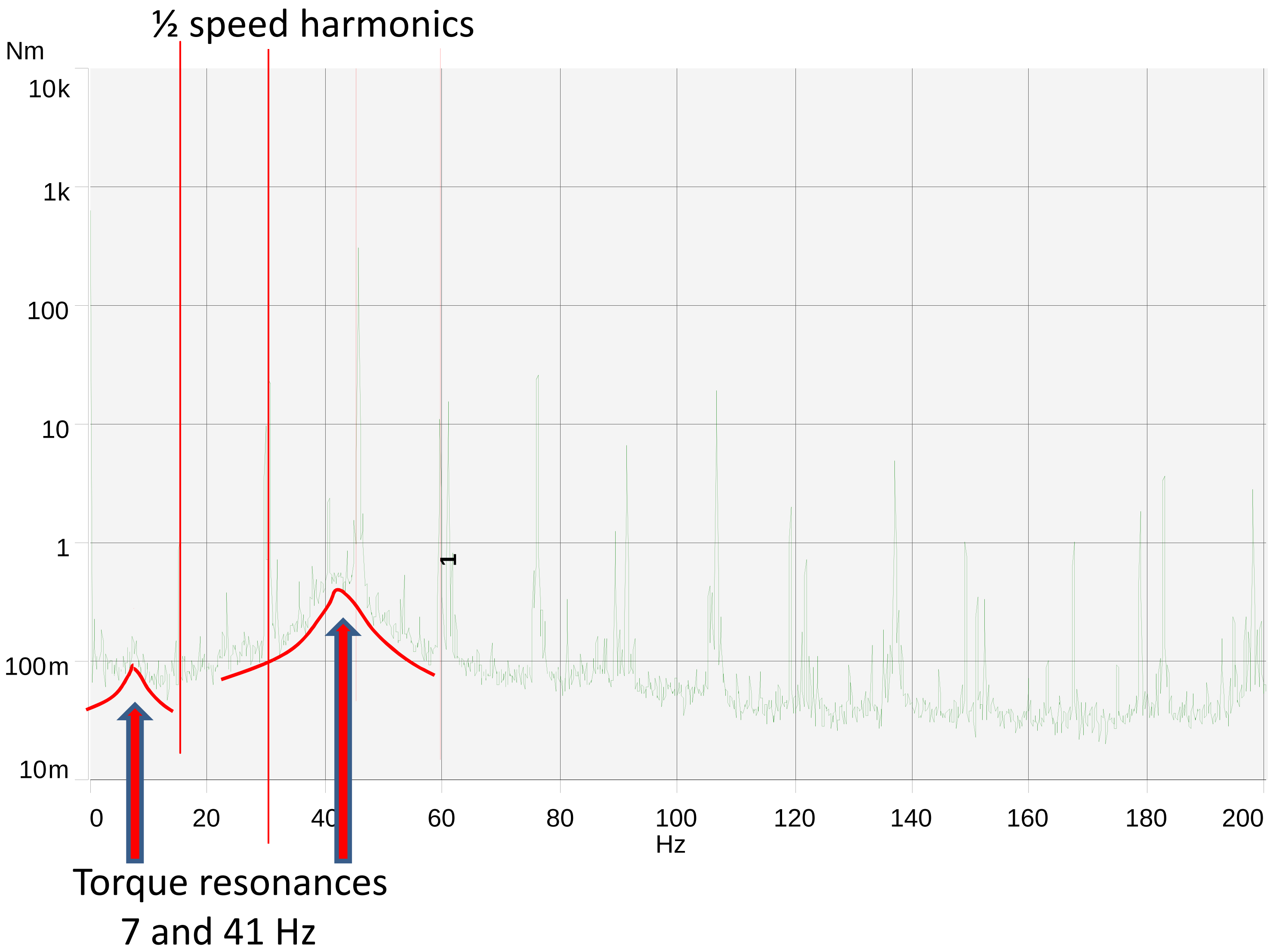
DMF Dual Mass Flywheel adds a damping to the size single Flywheel

Internal tangential spring and silicone oil with shear friction

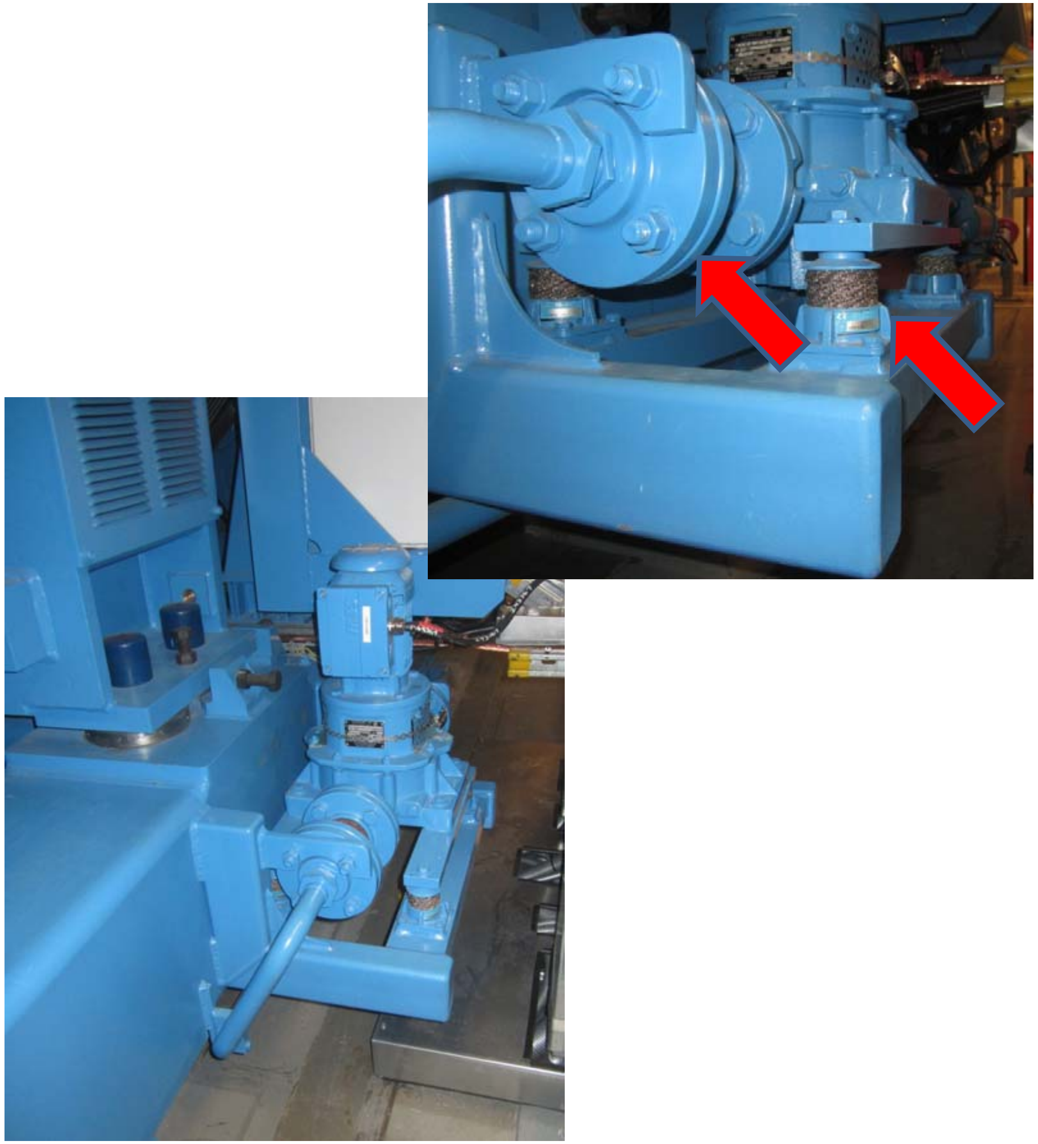


Flywheel with rubber coupling elements adds damping as well as building a low torsional resonance

Torque spectrum example, 12 cylinder diesel running 1800 RPM



An example of a good installation on an EDG



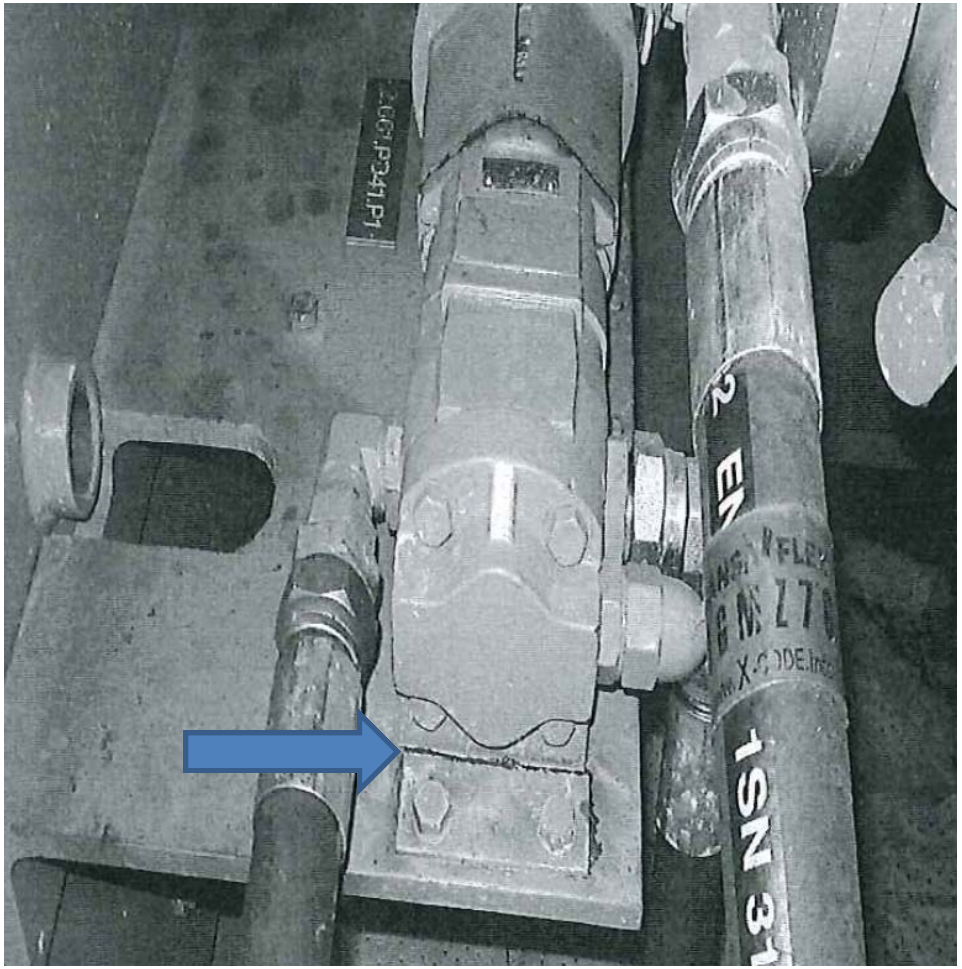
Pump mounted correctly to mitigate vibrations from engine as well as fluid

All six degrees of freedom resonances very low with strong damping as good as soft rubber.

- No age issues.
- No oil and dirt issues
- No wear.
- Cheap

Compensator in rubber, fixed stiff on both sides of rubber. From engine and to pump.

An example of an unacceptable installation on an EDG



Pump mounted incorrectly with no mitigation of vibrations from engine as well as fluid.

Foot broke off.

Experiences used for a recommendation for requirements buying new

Documentation

Qualifying Standard Equipments

Qualifying Prototype Equipments

Is it possible to figure out on beforehand what to specify, test and verify that an offered EDG is a good design?

Yes it is

Such a good design will as a bonus most probably also be handle to survive any forseable earthquake thanks to ist ruggedness.

Ready to consider requirements for a new EDG?

Requirements regarding

Very Important	•All kinds of Resonances
Important	•Vibration (both Lateral and Torsional)
Good	•Balancing Quality in all rotor parts

Resonances

•Freedom from resonances that can amplify the natural excitation forces typical for the EDG.

•Parts subject to excitation difficult to tune away must have the vibration mitigated.

•Separate machines in the EDG system such as starting air compressors and cooling fans have the same requirements.

Resonance "freedom" in general (lateral, torsional and foundation with the applicable degrees of freedom) shall apply in the range

- +/- 20 % from 1xRPM,
- 2xRPM and
- 1xVane Passage,
- firing torque pulsation frequency
- gear mesh frequency
- 100Hz

Rubber used in all tuning or mitigation elements have a limited service life. Wire mesh elements offer a very long life even warm and under work.

None of the above resonances is allowed to be excited by 1xRPM, 2xRPM, firing order torque pulsation frequency as well as 100 Hz with good margins with age considering the gradually stiffer coupling rubber elements.

Vibration (both Lateral and Torsional)

Vibration Levels on Installed Machine during Operation

Final evaluation on the fully installed machine and supporting machines (starting air compressor and ventilation fans as examples) on site, where all allowed operating conditions can be tested.

Maximum permissible vibration levels shall apply for all allowed continuous operation load condition/ranges.

Vibration Levels on Installed Machine during Operation

Acceptance for deliver, often called Factory Acceptance Test, FAT, shall be done on a machine and supporting machines with a testing situation representative to the on site situation, where all allowed operating conditions can be tested.

Maximum permissible vibration levels shall apply for all allowed continuous operation load condition/ranges. It is only delivery acceptance.

Bearing vibration in mm/s rms (vibration vector 1xRPM, 2xRPM as well as overall level up to at least 2000 Hz).

Full speed on site at all main bearings in three directions, H/V/A.

Idle to full load and during a load which has stabilized thermally.

Direct mechanical path to the bearing.

Each turbo and connected coolers shall be measured.

Representative points should be marked to allow a repeated measurement.

Simple stairs to allow easy measurements is recommended.

Bearing Vibration Limits

ISO 10816 part 3, Zone A for newly installed machine. Measurements in H/V/A.

Frequency range to 2000 Hz. Both measurements of vibration velocity in mm/s rms and vibration displacement in microns rms shall be performed.

Maximum bearing vibrations normally according to ISO 10816-3, Zone A – however maximum 2,8 mm/s rms.

Emergency Diesel Generators and starting air compressor Max: 6 mm/s rms

Torque vibration
The EDG set torsional resonance check with a suitable method.
Also measure.

Long term monitoring
Check strobe flashlight

Pipe and Component Vibrations

Secondary vibrations in pipes (fuel, lubrication, water exhaust), pumps (all in the EDG), coolers (air, ventilation, water), measuring units (such as Pt100 and pressure and flow gauges) with media under pressure, which can cause fire or other damage, should be judged according to the specification below.

Components joining the pipes are normally subject to harder judgment.

Pipe and Component Vibrations

Overall vibration to 2000 Hz in vibration velocity in mm/s rms, and vibration displacement in microns peak.

Limits

Supplier to mitigate if above 7 mm/s rms or above 150 microns peak.

Exceeded limits at pipes

Evaluate risk for fatigue damages.
Verify that the risk for fatigue is very low.
Document the procedure, calculations and verifying stress measurements, and handed over without delay.

Excessive levels at pipes

Exceeding 20 mm/s rms shall not be left in operation more than minutes before shutting down. Evaluate a mitigation activity, such as redesign, tuning, damping.

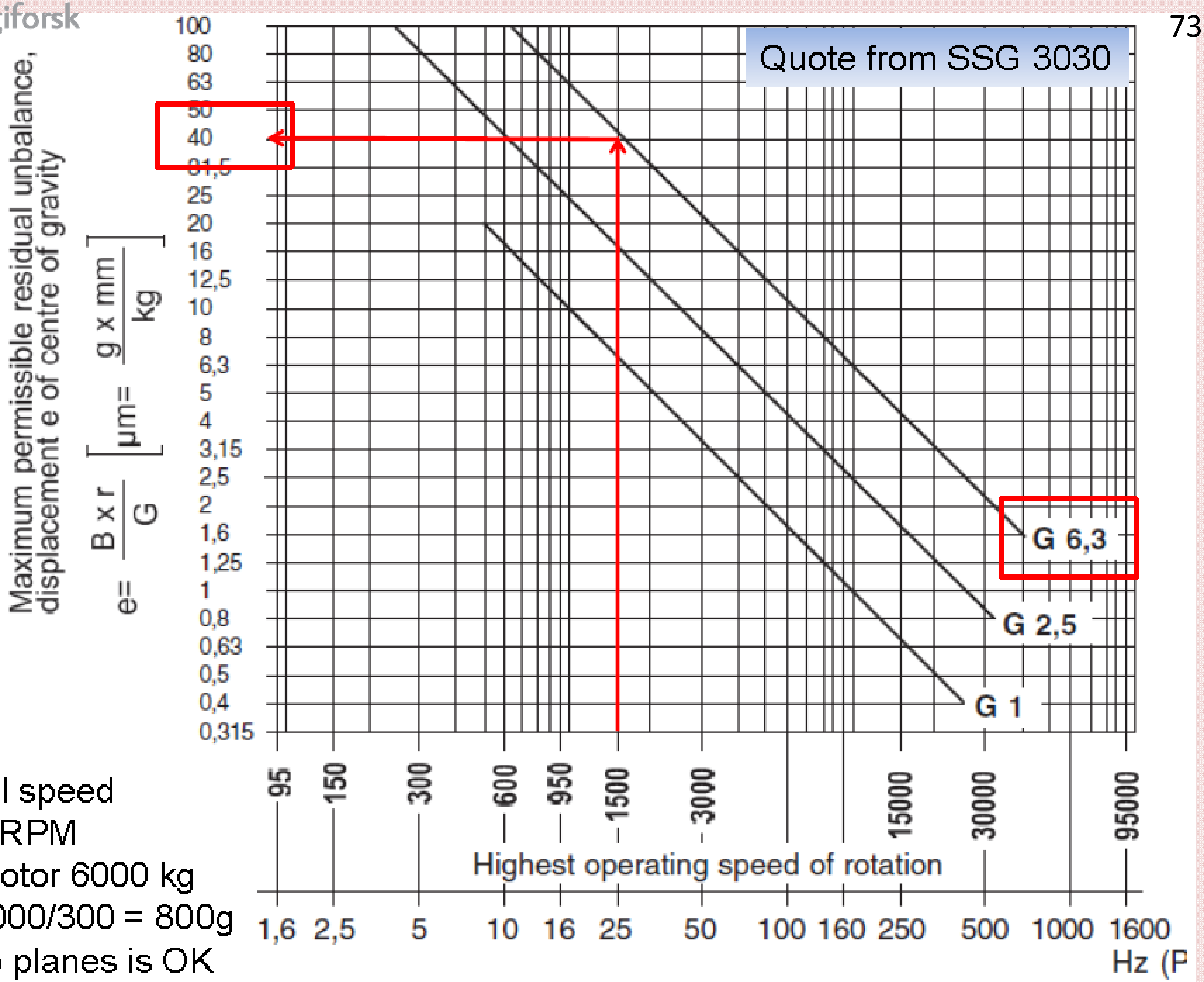
Spectrum

Good resolution and at least 20 seconds average time to 2000 Hz.

The diagnosis in cooperation with the parties and the result of this be documented.

Balancing Condition and Balancing Quality

Energiforsk



Diesel speed
1500 RPM
Gen.rotor 6000 kg
40x6000/300 = 800g
in two planes is OK

Balancing Condition and Balancing Quality

- Rotor complete according to ISO 1940/1 G2.5
- Rotor parts one grade better ISO 1940/1 G1
- For the diesel engine crankshaft G6.3