Mitigation of Diesel Generator Vibrations in Nuclear Applications

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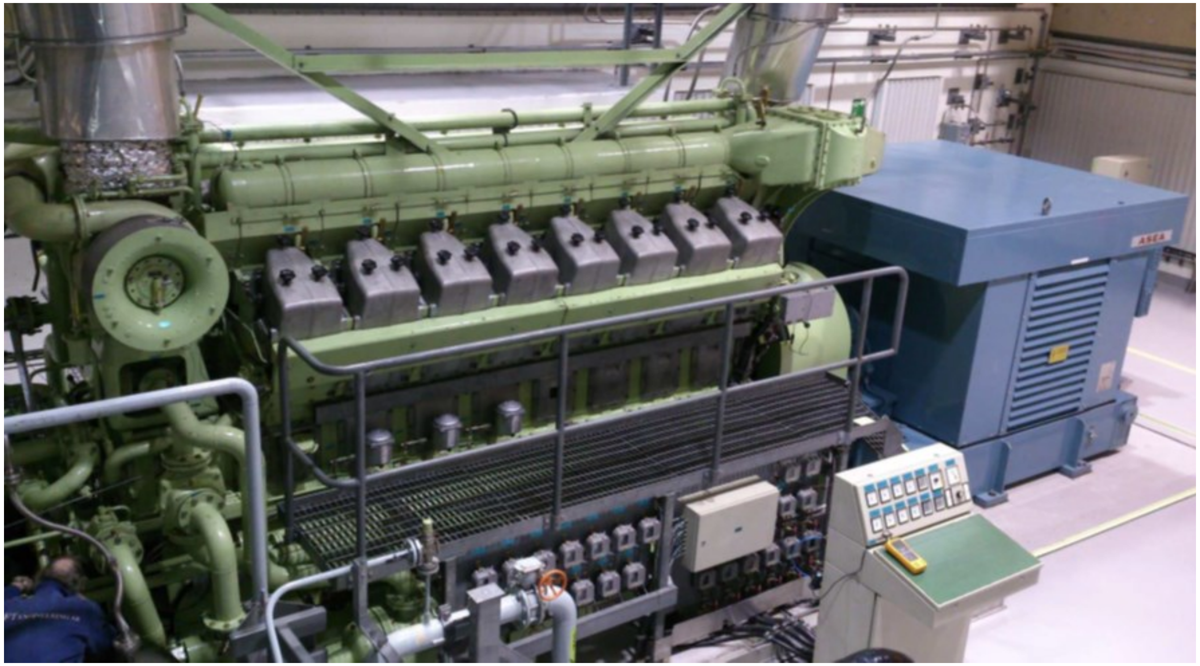
- Sources of excitation
- DIAM-matrices

Introduction

- Goal of this project was to
  - Gather practical information on EDG vibrations into a report
  - Develop a systematic problem solving tool for EDGs, the DIAM-matrices
  - The report doubles as a manual for the DIAM-matrices



NOHAB/Wärtsilä F216V emergency diesel generator in Forsmark 3 (Forsmark, 2014)

Vibration problems in EDGs

- A lot of vibration problems in EDGs
- Problem examples:
  - Loosening and breaking of bolts, pipe supporting, machine feet
  - Cracks in welds and pipes
  - Damaged gears, impellers, pistons, couplings…
  - Exessive vibration of piping, electrical components, turbochargers, pumps, base frame, the whole EDG and the foundation…
- Vibration problems cause major economical losses at nuclear power plants
  - Increased maintenance costs
  - Downtime

Vibration problems in EDGs

- Excitations are always present in an EDG
- Strongest excitations originate from the diesel engine, but excitations are also created in the generator and locally in auxiliary components
- Excessive vibration may occur when
  - Natural frequencies of components are shifted due to loosening, wear, structural changes etc. leading to resonance/ dynamic amplification
  - Excitation forces grow stronger or new excitations appear due to faulty condition

Sources of excitation

Diesel engine excitations

- Excitations are caused by mass and gas forces inside the engine
- Mass forces
  - due to rotating and reciprocating masses
  - Continuous in the period of 1 crackshaft cycle
  - Excitations are created at harmonic orders 1, 2, 3, 4…
  - Rigid body, bending mode and torsional vibrations
- Gas forces
  - due to compression and combustion pressure waves inside the cylinders
  - Continuous in the period of 2 full crackshaft cycles (4-stroke engine)
  - Excitations at sub harmonic orders ½, 1, 1½, 2…
  - Crankshaft torsional and axial vibrations, engine block vibrations

Harmonic order of running speed

$$f = order\# \frac{rpm}{60}$$

Sources of excitation

Diesel engine excitations

- Engine excitations (reciprocating forces and moments) are transmitted to the rest of the EDG through the base frame -> are felt everywhere in the EDG
- Each engine type causes a different excitation spectrum

Sources of excitation

Diesel engine excitations

- Firing frequency is typically the strongest engine excitation frequency
  - Caused by the firing of cylinders
  - Firing of each cylinder causes a torque pulse to the crankshaft
  - The engine block is twisted to opposite direction -> force couple transmitted to the base frame

Firing frequency for 4-stroke engines

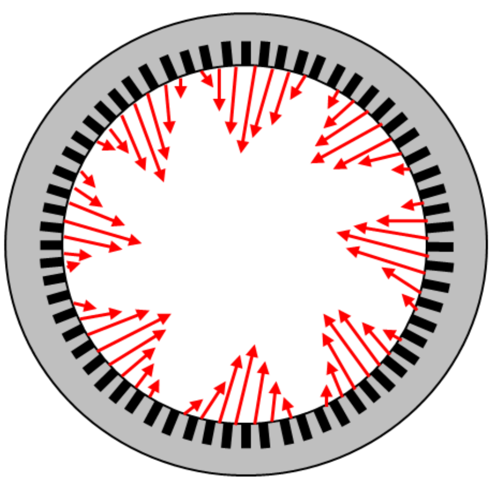
$$f = \frac{N_{cyl}}{2}\frac{rpm}{60}$$

N_{cyl} = number of cylinders in one cylinder bank

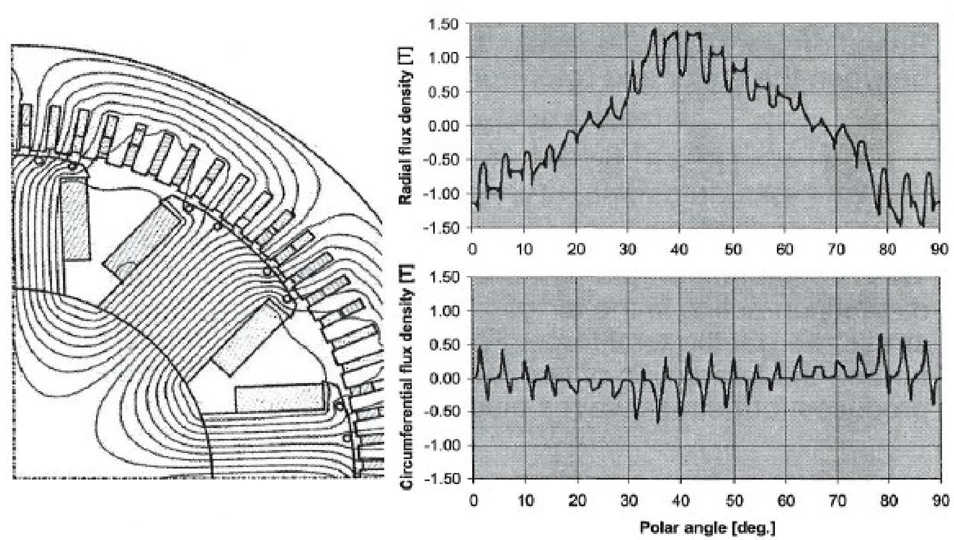
Sources of excitation

Generator excitations

- The rotating magnetic field causes rotating magnetic force waves
  - Fundamental variation of the magnetic field 50 Hz (line frequency)
  - Fundamental variation of the force waves 100 Hz (pole pass frequency=twice line frequency)
  - A broad spectrum of excitations are present 50, 100, 150, 200 Hz…



Magnetic force distribution.



Magnetic field in the air gap. (Arkkio, A. 2007)

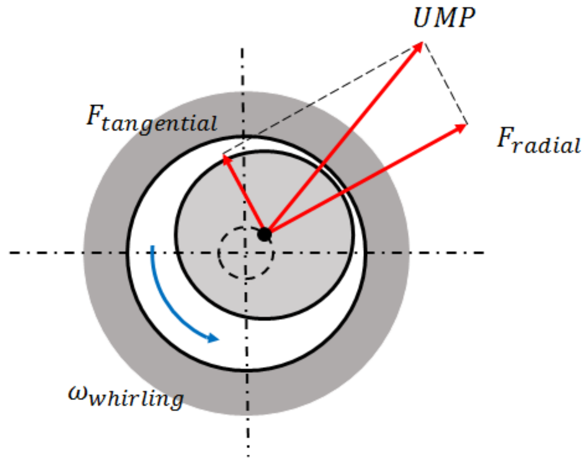
Sources of excitation

Generator excitations

- Ideally the rotor and stator core are concentric

  Radial force components cancel each other out, tangential force components create load for the engine

- In practice the rotor is more or less eccentric
  - Radial forces become non-zero -> Unbalanced magnetic pull (UMP)
  - UMP increases in nonlinear fashion with increasing eccentricity -> increases excitations
  - Typically about 10% eccentricity is permitted



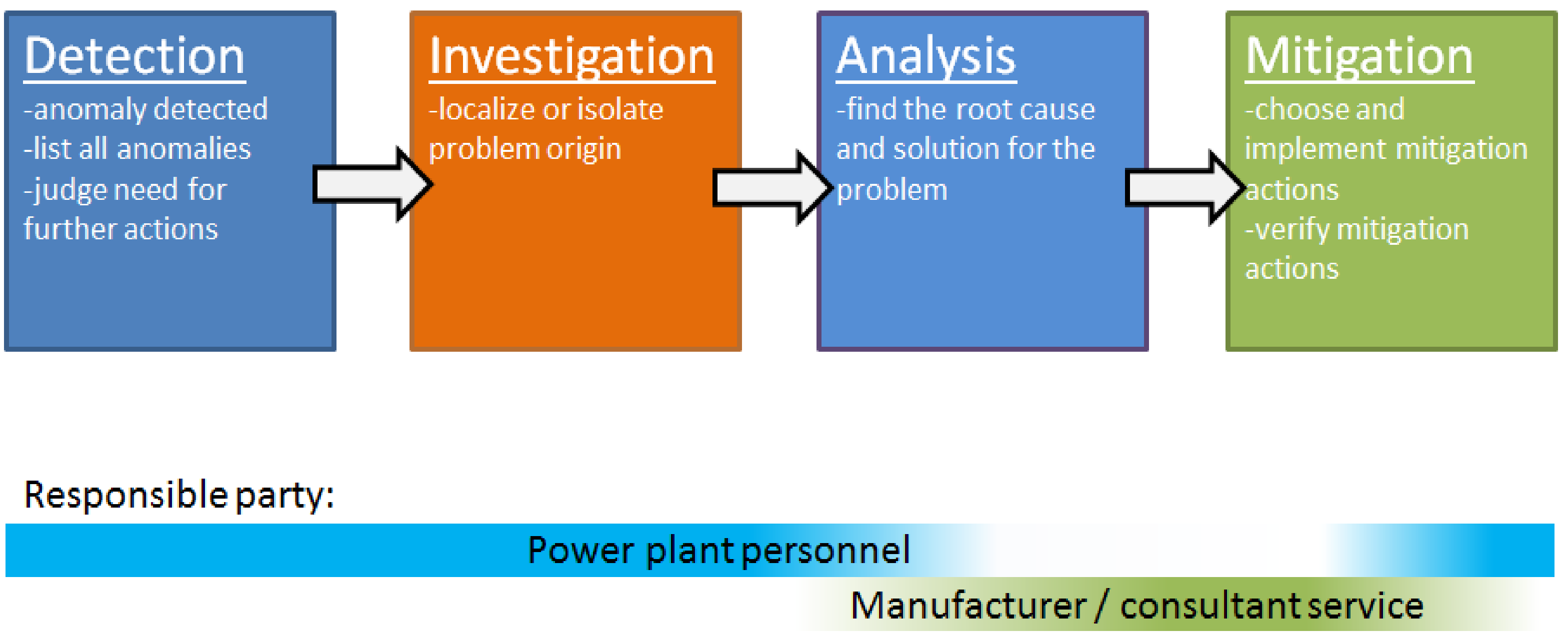
Sources of excitation

Other excitation sources

- Engine misfiring
- Critical speeds
- Unbalance
- Misalignment
- Mechanical looseness
- Rotor rub
- Governor hunting
- Gear meshing
- Pump vane excitation
- Bearing defects
- Etc.

DIAM-matrices

- DIAM-matrices are an Excel-based table tool that provides a systematic walkthrough to solving vibration problems
- Problem solving procedure is divided into steps of Detection, Investigation, Analysis and Mitigation



DIAM-matrices

- Original idea by Paul Smeekes
- DIAM-matrices for pipe vibration – Mikko Merikoski
- DIAM-matrices for turbine and generator vibrations – Rainer Nordmann
- DIAM-matrices for EDG vibrations – Antti Kangasperko

DIAM-matrices

Basic idea

- The matrices are primary targeted for users who are not diesel vibration experts
- The matrices are based on correlation values between different observations/findings and possible problems
- Values range from 0-5
  - 5: very strong correlation
  - 1: very weak correlation
  - 0: no correlation
- Correlation values are used to calculate how ”probably” the vibration problem is caused by each phenomena
- The correlation values are <u>estimates</u>
  - Values are to be tuned with experts

DIAM-matrices

Detection phase

- Begins when abnormal machine behaviour, an anomaly, is detected during EDG testing
  - Increased vibration amplitude, increased boost pressure, abnormal cylinder temperature, abnormal sounds, visible vibration, leaks, etc.
- When an anomaly is marked into the matrix as found, it is included in the probability calculation
- Other possible anomalies should be looked for to get more accurate initial probabilities for phenomena causing the problem

DIAM-matrices

Detection matrix

<---- Mark here "x" if not used in the plant

<---- Mark here "x" if detected

			Anomalies detectable by sensors								Anomalies detectable by human senses													Anomaly location														
	Phenomenon (Anomaly description)	Section	6.1.1.1 Vibration amplitude monitoring	6.1.1.2 Vibration frequency monitoring	6.1.1.3 Boost pressure monitoring	6.1.1.4 Cylinder pressure monitoring	6.1.1.5 Electric power monitoring	6.1.1.6 Unstable engine running speed	6.1.1.7 Coolant temperature increase	6.1.1.8 Oil monitoring	6.1.1.9 Narrowband noise	6.1.1.10 Broadband noise	6.1.1.11 Continuous noise	6.1.1.12 Transient noise	6.1.1.13 Amplitude modulating noise	6.1.1.14 Intermittent noise	6.1.1.15 Low frequency noise (<100Hz)	6.1.1.16 High frequency noise (>100Hz)	6.1.1.17 Crack	6.1.1.18 Leakage	6.1.1.19 Wear dust or wear marks	6.1.1.20 Component failure	6.1.1.21 Visible vibration	Diesel engine + mounted components	Generator + mounted components	Base frame	Coupling	Bearing housing	Rotating auxiliary component	Piping	Not applicable or uncertain	Commonness	Severity	Product of probabilities, if no blanks	Relative probabilities	Commonness & Severity weighted probability	Commonness	Severity
Diesel engine	Mass forces	4.1.1									1	2		2			4		4	2	2	3	4	5	4	5	5	3	4		1	5	2	0				
	Gas forces	4.1.2										3	5	3			5	2	5	3	3	4	5	5	4	5	5	3	4		1	5	3	0				
	Crankshaft torsional critical speed	4.1.5	5	3				2	1	2	1	3	2	5			2	3	5	2	4	5	1	2	1	1					1	1	5	0				
	Misfiring	4.1.7	4	5	5	5	4	5	2	1		3				5	5		2		3	4	4	5	3	5					1	3	3	0				
	Diesel knock	4.1.8	1	2	1	4	1	2	1	3		2		1				3			2	1	1	3							1	1	2	0				
	Piston slap	4.1.9	2	3				1	2	5	3	1		5			4				5		1	4	1	1					1	2	1	0				
	Governor hunting	4.1.11	3	4	2		2	5	1			1	3		5	3	3				2	1	3	5	2	3					1	2	1	0				
Generator	Magnetic forces	4.2.1									3	1	3		2			4	3	1	1	1	2	2	5	3		3			1	5	1	0				
	Static eccentricity	4.2.3	3	1			3		1	2	3	1	1		3		1	2	4		2	3	1	3	5	4		4			1	3	4	0				
	Dynamic eccentricity	4.2.4	4	1			3		1	3	3	1	1		3		1	2	2		2	2	3	3	5	3		5			1	2	3	0				
	Stator end winding looseness	4.2.5	1	2			1				1			1	1		1	2	3		4	3			2						1	4	2	0				
Rotating elements	Rotating unbalance	4.3.1	5	3					1	2	2				3		1		2	1	2	2	3	3	4	3		5			1	5	3	0				
	Misalignment	4.3.2	3	4					2	2	1	1			4	1	1		3	2	3	3	1	2	3	2		4			1	5	3	0				
	Mechanical looseness	4.3.3	4	5					3	4	1	3		4	3	4	3	3	1	1	4	3	4	4	3	3		3			1	5	2	0				
	Rotor rub	4.3.4	3	5			1	2	4	5	3	2		3	1	3		4	1	4	5	2	2	2	3	1		4			1	3	3	0				
	Lateral critical speed	4.3.5	5	3					2	3	1						1		1		1	1	4	1	1	3		5			1	1	3	0				
	Oil whirl	4.3.6	2	3					1	2										1	1		1	1				2			1	1	2	0				
	Oil whip	4.3.6	5	4					2	3	1			2					2	1	1	2	4	1				2			1	1	4	0				
	Roller bearing defect	4.3.7	1	3					1	1		3						3			1							5			1	5	1	0				
	Gear meshing	4.3.8	3	4				1	3	4	1	2		3				3	2		4	2	1	3		1		3			1	2	4	0				
	Vane or blade excitation	4.3.9	3	3	3				1	3	4		3	1	3		2	5	2	4	2	2	2	1	1	1		3			1	3	2	0				
Other	Structural resonance	3.3	5	4					1	1	3						3	1	5	2	4	5	5	5	5	4	3	2	4	5	1	5	5	0				
	Measurement fault	5.1.4	4	5																				3	3	3	3	3	3	3	1	5	1	0				

DIAM-matrices

FS DYNAMICS

Detection matrix – structure

Correlation values

List of possible anomalies

location

Findings are marked to the yellow row

List of possible phenomena that can cause vibrations

<---- Mark here "x" if not used in the plant

<---- Mark here "x" if detected

			Anomalies detectable by sensors								Anomalies detectable by human senses													Anomaly location														
	Phenomenon	Section (Anomaly description)	Vibration amplitude monitoring 6.1.1.1	Vibration frequency monitoring 6.1.1.2	Boost pressure monitoring 6.1.1.3	Cylinder pressure monitoring 6.1.1.4	Electric power monitoring 6.1.1.5	Unstable engine running speed 6.1.1.6	Coolant temperature increase 6.1.1.7	Oil monitoring 6.1.1.8	Narrowband noise 6.1.1.9	Broadband noise 6.1.1.10	Continuous noise 6.1.1.11	Transient noise 6.1.1.12	Amplitude modulating noise 6.1.1.13	Intermittent noise 6.1.1.14	Low frequency noise (<100Hz) 6.1.1.15	High frequency noise (>100Hz) 6.1.1.16	Crack 6.1.1.17	Leakage 6.1.1.18	Wear dust or wear marks 6.1.1.19	Component failure 6.1.1.20	Visible vibration 6.1.1.21	Diesel engine + mounted components	Generator + mounted components	Base frame	Coupling	Bearing housing	Rotating auxiliary component	Piping	Not applicable or uncertain	Commonness	Severity	Product of probabilities, if no blanks	Relative probabilities	Commonness & Severity weighted probability	Commonness	Severity
Diesel engine	Mass forces	4.1.1									1	2		2			4		4	2	2	3	4	5	4	5	5	3	4		1	5	2	0				
Diesel engine	Gas forces	4.1.2										3	5	3			5	2	5	3	3	4	5	5	4	5	5	3	4		1	5	3	0				
Diesel engine	Crankshaft torsional critical speed	4.1.5	5	3				2	1	2	1	3	2	5			2	3	5	2	4	5	1	2	1	1					1	1	5	0				
Diesel engine	Misfiring	4.1.7	4	5	5	5	4	5	2	1		3				5	5		2		3	4	4	5	3	5					1	3	3	0				
Diesel engine	Diesel knock	4.1.8	1	2	1	4	1	2	1	3		2		1				3			2	1	1	3							1	1	2	0				
Diesel engine	Piston slap	4.1.9	2	3				1	2	5	3	1		5			4				5		1	4	1	1					1	2	1	0				
Diesel engine	Governor hunting	4.1.11	3	4	2		2	5	1			1	3		5	3	3				2	1	3	5	2	3					1	2	1	0				
Generator	Magnetic forces	4.2.1									3	1	3		2			4	3	1	1	1	2	2	5	3		3			1	5	1	0				
Generator	Static eccentricity	4.2.3	3	1			3		1	2	3	1	1		3		1	2	4		2	3	1	3	5	4		4			1	3	4	0				
Generator	Dynamic eccentricity	4.2.4	4	1			3		1	3	3	1	1		3		1	2	2		2	2	3	3	5	3		5			1	2	3	0				
Generator	Stator end winding looseness	4.2.5	1	2			1				1			1	1		1	2	3		4	3			2						1	4	2	0				
Rotating elements	Rotating unbalance	4.3.1	5	3					1	2	2				3		1		2	1	2	2	3	3	4	3		5			1	5	3	0				
Rotating elements	Misalignment	4.3.2	3	4					2	2	1	1			4	1	1		3	2	3	3	1	2	3	2		4			1	5	3	0				
Rotating elements	Mechanical looseness	4.3.3	4	5					3	4	1	3		4	3	4	3	3	1	1	4	3	4	4	3	3		3			1	5	2	0				
Rotating elements	Rotor rub	4.3.4	3	5			1	2	4	5	3	2		3	1	3		4	1	4	5	2	2	2	3	1		4			1	3	3	0				
Rotating elements	Lateral critical speed	4.3.5	5	3					2	3	1						1		1		1	1	4	1	1	3		5			1	1	3	0				
Rotating elements	Oil whirl	4.3.6	2	3					1	2										1	1		1	1				2			1	1	2	0				
Rotating elements	Oil whip	4.3.6	5	4					2	3	1			2					2	1	1	2	4	1				2			1	1	4	0				
Rotating elements	Roller bearing defect	4.3.7	1	3					1	1		3						3			1							5			1	5	1	0				
Rotating elements	Gear meshing	4.3.8	3	4				1	3	4	1	2		3				3	2		4	2	1	3		1		3			1	2	4	0				
Rotating elements	Vane or blade excitation	4.3.9	3	3	3				1	3	4		3	1	3		2	5	2	4	2	2	2	1	1	1		3			1	3	2	0				
Other	Structural resonance	3.3	5	4					1	1	3						3	1	5	2	4	5	5	5	5	4	3	2	4	5	1	5	5	0				
Other	Measurement fault	5.1.4	4	5																				3	3	3	3	3	3	3	1	5	1	0				

DIAM-matrices

Possible phenomena highlighted with green

Discovered anomalies now marked

Probabilities for phenomena

<---- Mark here "x" if not used in the plant

<---- Mark here "x" if detected

			Anomalies detectable by sensors								Anomalies detectable by human senses													Anomaly location														
			x									x				x								x														
	Anomaly description		Vibration amplitude monitoring	Vibration frequency monitoring	Boost pressure monitoring	Cylinder pressure monitoring	Electric power monitoring	Unstable engine running speed	Coolant temperature increase	Oil monitoring	Narrowband noise	Broadband noise	Continuous noise	Transient noise	Amplitude modulating noise	Intermittent noise	Low frequency noise (<100Hz)	High frequency noise (>100Hz)	Crack	Leakage	Wear dust or wear marks	Component failure	Visible vibration	Diesel engine + mounted components	Generator + mounted components	Base frame	Coupling	Bearing housing	Rotating auxiliary component	Piping	Not applicable or uncertain	Commonness	Severity	Product of probabilities, if no blanks	Relative probabilities	Commonness & Severity weighted probability	Commonness	Severity
	Phenomenon	Section	6.1.1.1	6.1.1.2	6.1.1.3	6.1.1.4	6.1.1.5	6.1.1.6	6.1.1.7	6.1.1.8	6.1.1.9	6.1.1.10	6.1.1.11	6.1.1.12	6.1.1.13	6.1.1.14	6.1.1.15	6.1.1.16	6.1.1.17	6.1.1.18	6.1.1.19	6.1.1.20	6.1.1.21															
Diesel engine	Mass forces	4.1.1									1	2		2			4		4	2	2	3	4	5	4	5	5	3	4	5	1	5	2	0				
	Gas forces	4.1.2										3	5	3			5	2	5	3	3	4	5	5	4	5	5	3	4	5	1	5	3	0				
	Crankshaft torsional critical speed	4.1.5	5	3				2	1	2	1	3	2	1	3		2	3	5	2	4	5	1	2	1	1	4		1	1	1	1	5	60	8 %	3 %	2 %	12 %
	Misfiring	4.1.7	4	5	5	5	4	5	2	1	1	3	1	1	3	5	5		2		3	4	4	5	3	5	5		4	3	1	3	3	300	39 %	31 %	33 %	37 %
	Diesel knock	4.1.8	1	2	1	4	1	2	1	3		2		1				3			2	1	1	3			1			1	1	1	2	0				
	Piston slap	4.1.9	2	3				1	2	5	3	1		5			4				5		1	4	1	1	1			1	1	2	1	32	4 %	1 %	2 %	1 %
	Governor hunting	4.1.11	3	4	2		2	5	1			1	3		5	3	3				2	1	3	5	2	3	5		2	1	1	2	1	45	6 %	1 %	3 %	2 %
Generator	Magnetic forces	4.2.1									3	1	3		2			4	3	1	1	1	2	2	5	3	3	3	1	2	1	5	1	0				
	Static eccentricity	4.2.3	3	1			3		1	2	3	1	1		3		1	2	4		2	3	1	3	5	4	2	4	2	3	1	3	4	9	1 %	1 %	1 %	1 %
	Dynamic eccentricity	4.2.4	4	1			3		1	3	3	1	1		3		1	2	2		2	2	3	3	5	3	3	5	2	3	1	2	3	12	2 %	1 %	1 %	1 %
	Stator end winding looseness	4.2.5	1	2			1				1			1	1		1	2	3		4	3			2						1	4	2	0				
Rotating elements	Rotating unbalance	4.3.1	5	3					1	2	2				3		1		2	1	2	2	3	3	4	3	2	5	5	4	1	5	3	0				
	Misalignment	4.3.2	3	4					2	2	1	1			4	1	1		3	2	3	3	1	2	3	2	5	4	4	4	1	5	3	6	1 %	1 %	1 %	1 %
	Mechanical looseness	4.3.3	4	5					3	4	1	3		4	3	4	3	3	1	1	4	3	4	4	3	3	3	3	4	4	1	5	2	144	19 %	16 %	27 %	12 %
	Rotor rub	4.3.4	3	5			1	2	4	5	3	2		3	1	3	1	4	1	4	5	2	2	2	3	1	1	4	4	3	1	3	3	12	2 %	1 %	1 %	1 %
	Lateral critical speed	4.3.5	5	3					2	3	1						2	3	1		1	1	4	1	1	3	3	5	4	4	1	1	3	0				
	Oil whirl	4.3.6	2	3					1	2	3						2	2		1	1		1	1				4	1	1	1	1	2	0				
	Oil whip	4.3.6	3	4					2	3	3	1	3	2		1	2	2	2	1	1	2	4	1				5	2	1	1	1	4	6	1 %	0 %	0 %	1 %
	Roller bearing defect	4.3.7	1	3					1	1		3						3			1						1	5	2		1	5	1	0				
	Gear meshing	4.3.8	3	4				1	3	4	1	2		3				3	2		4	2	1	3		1	2	3	3	2	1	2	4	0				
	Vane or blade excitation	4.3.9	3	3	3				1	3	4		3	1	3			5	2	4	2	2	2	1	1	1		3	4	4	1	3	2	0				
Other	Structural resonance	3.3	5	4					1	1	5	2	3				3	1	5	2	4	5	5	5	5	4	3	2	4	5	1	5	5	150	19 %	43 %	28 %	30 %
	Measurement fault	5.1.4	4	5																				3	3	3	3	3	3	3	1	5	1	0				

DIAM-matrices

Investigation phase

- Investigation phase begins when it has been concluded that the anomaly requires further actions
- Based on the detection findings, the matrix recommends checks, test and measurements that may be helpful in locating the problem origin
  - For example: vibration matches with at a certain known excitation frequency, vibration increases with engine speed, vibration matches with hammer test frequencies, vibration dissappears when electricity is turned off…
  - main excitation frequencies are calculated automatically if technical data is added to the front sheet
- Investigation phase is split to three matrices
  - Investigation objectives: suggests what to look for
  - Investigation methods: suggests which tests and instruments are effective for the present purpose
  - Investigation findings: findings are marked here for probability calculation

DIAM-matrices

Investigation objectives

What to look for, problem characteristics, frequencies etc.

Major Investigation objectives

Other Investigation objectives

Possible phenomena according to the Detection matrix

Same phenomena as in detection phase

Investigation objective		Vibration increases with engine speed	Vibration increases with generator load	Vibration disappears when electric power is turned off	Strong vibration only on certain speeds	Vibration disappears when mounting foot is loosened	Vibration disappears when the governor is prevented	Crankshaft torsional vibrations	Vibration at blade pass frequency	Vibration at hammer test frequencies	Vibration at 6,25 Hz (engine half order)	Vibration at 12,5 Hz (engine first order)	Vibration at 25 Hz (engine second order)	Vibration at 37,5 Hz (firing frequency)	Vibration at 50 Hz (line frequency)	Vibration at 100 Hz (2x line frequency)	Vibration at 200 Hz (4x line frequency)	Vibration at 1250 Hz (slot pass frequency)	Vibration at 0,43...0,48 x rpm (auxiliary components)	Vibration at 1x rpm (auxiliary components)	Vibration at 2x rpm (auxiliary components)	Harmonics of running speed present	Subharmonics of running speed present	Frequency is modulating	Disturbances in time waveform	Unexplainable measurement results		Product of probabilities in detection	Relative probabilities in detection	Commonness in detection	Severity in detection	Commonness & Severity weighted probability in detection
Easiness		4	4	4	4	3	3	1	2	3	5	5	5	5	5	5	5	5	4	4	4	4	4	5	5	4						
Objectives, sum		81	11	11	139	6	23	131	30	150	150	7	9	0	0	5	0	15	3	46	45	80	118	51	119	74						
Objectives, %		6	1	1	11	0	2	10	2	12	12	1	1			0		1			3	6	9	4		6	87 %					
Easiness weighted %		7	1	1	11	0	1	3	1	9	15	1	1			0		2			4	7	10	5		6	84 %					
Phenomenon	Section																															
Mass forces	4.1.1	5						2		1		5	5	1	1							5						0				
Gas forces	4.1.2	3	5					2	3	1	2			5	1							5	4					0				
Crankshaft torsional critical speed	4.1.5				3			5		3												2	1		1			60	8 %	2 %	12 %	3 %
Misfiring	4.1.7							3	1	1	5												2	1	1	2		300	39 %	33 %	37 %	31 %
Diesel knock	4.1.8							1	1	1														1	1			0				
Piston slap	4.1.9	5						1		1			2									1	1		3			32	4 %	2 %	1 %	1 %
Governor hunting	4.1.11						5	1		1														1		3		45	6 %	3 %	2 %	1 %
Magnetic forces	4.2.1		4	5						1					3	3	3	2			3	1	1					0				
Static eccentricity	4.2.3		5	5		4				1						5						1	1					9	1 %	1 %	1 %	1 %
Dynamic eccentricity	4.2.4	2	5	5						1		3										1	1					12	2 %	1 %	1 %	1 %
Stator end winding looseness	4.2.5		5	5	1					1					2	3	2					2	1		1			0				
Rotating unbalance	4.3.1	5								1		5								5								0				
Misalignment	4.3.2	2				4				1			4							4	3	3			2			6	1 %	1 %	1 %	1 %
Mechanical looseness	4.3.3	4			3					1										3	3	4	3	1	5			144	19 %	27 %	12 %	16 %
Rotor rub	4.3.4	3						2		1		3										3	3	2				12	2 %	1 %	1 %	1 %
Lateral critical speed	4.3.5				4					3																		0				
Oil whirl	4.3.6							1		1		1							5									0				
Oil whip	4.3.6				4			1		1									5									6	1 %	0 %	1 %	0 %
Roller bearing defect	4.3.7	1								1															4			0				
Gear meshing	4.3.8	2						2		1												3	3		5			0				
Vane or blade excitation	4.3.9	2						2	4	1												3	3		4			0				
Structural resonance	3.3				5					5								1										150	19 %	28 %	30 %	43 %
Measurement fault	5.1.4																							1		5		0				

Same probabilities as in detection phase

DIAM-matrices

Investigation methods

What to look for, problem characteristics, frequencies etc.

Checks, tests, measurements

- Major Investigation objectives
- Other Investigation objectives
- x Used investigation methods
- Possible investigation findings
- Do the markings here

Group	Investigation method	Section	Vibration increases with engine speed	Vibration increases with generator load	Vibration disappears when electric power is turned off	Strong vibration only on certain speeds	Vibration disappears when mounting foot is loosened	Vibration disappears when the governor is prevented	Crankshaft torsional vibrations	Vibration at blade pass frequency	Vibration at hammer test frequencies	Vibration at 6,25 Hz (engine half order)	Vibration at 12,5 Hz (engine first order)	Vibration at 25 Hz (engine second order)	Vibration at 37,5 Hz (firing frequency)	Vibration at 50 Hz (line frequency)	Vibration at 100 Hz (2x line frequency)	Vibration at 200 Hz (4x line frequency)	Vibration at 1250 Hz (slot pass frequency)	Vibration at 0,43...0,48 x rpm (auxiliary components)	Vibration at 1x rpm (auxiliary components)	Vibration at 2x rpm (auxiliary components)	Harmonics of running speed present	Subharmonics of running speed present	Frequency is modulating	Disturbances in time waveform	Unexplainable measurement results	Recommendation based on the objectives, sum	Recommendation taking into account selected methods	Relative recommendation percentage	Percentage taking into account selected methods
	Objectives																														
	Major objectives																														
	Easiness		4	4	4	4	3	3	1	2	3	5	5	5	5	5	5	5	5	4	4	4	4	4	5	5	4				
	Objectives, sum		81	11	11	139	6	23	131	30	150	150	7	9	0	0	5	0	15	3	46	45	80	118	51	119	74				
	Objectives, %		6	1	1	11	0	2	10	2	12	12	1	1			0		1		0	3	6	9	4		6				
	Easiness weighted %		7	1	1	11	0	1	3	1	9	15	1	1			0		2		0	4	7	10	5		6				
Pre-checks	check for recent structural changes	8.2.1.1																													
Pre-checks	Check for exceptional operating conditions	8.2.1.2																										Perform always			
Pre-checks	Review operating history	8.2.1.3																													
Transducer selection	Accelerometers	5.2.1.1	5	4	3	5	5	5		3	5	5	5	5	5	3	3	3	3	5	5	5	5	5	5	5	5	117	117	12 %	12 %
Transducer selection	Velocity transducers	5.2.1.2	4	3	2	4	4	1		1	4	4	4	4	4	3	3	3	3	4	4	4	4	4	4	4	4	91	91	10 %	10 %
Transducer selection	Proximity probes	5.2.1.3	5	3	3	5	5	2		1	5	5	5	5	5	3	3	3	3	5	5	5	5	5	5	5	5	114	114	12 %	12 %
Transducer selection	Laser vibrometers	5.2.1.4	5	4	3	5	5	2		2	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	116	116	12 %	12 %
Transducer selection	Shaft encoders	5.2.1.5	2	1				5	4	1	1	4	4	4	4	5	2	1	1	1	1	1	1	1	1	1	1	47	47	5 %	5 %
Transducer selection	Strain gauges	5.2.1.6	1	1	1	1	1	5	3	1	1	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	1	40	40	4 %	4 %
Transducer selection	Fiber optic sensors	5.2.1.7	5	5	5	5	5	2		3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	117	117	12 %	12 %
Transducer selection	Dynamic pressure transducers	5.2.1.8								5																4					
Tests and measurements	Engine speed test	8.2.2.1	5			5																						78	78	8 %	8 %
Tests and measurements	Generator load test	8.2.2.2		5																								5	5	1 %	1 %
Tests and measurements	Electric power off test	8.2.2.3			5																							5	5	1 %	1 %
Tests and measurements	Impact hammer test	8.2.2.4									5																	75	75	8 %	8 %
Tests and measurements	Soft foot test	8.2.2.5					5																					3	3	0 %	0 %
Tests and measurements	Governor preventation test	8.2.2.6						5																				11	11	1 %	1 %
Tests and measurements	Time waveform signal analysis	5.3.2																							5	5	3	62	62	7 %	7 %
Tests and measurements	Vibration spectrum analysis	5.3.1								3	3	5	5	5	5	5	5	5	5	5	5	5	4	4	1		2	71	71	7 %	7 %

Investigation objective

How good different instruments and tests are in this case?

DIAM-matrices

Investigation findings

Investigation findings are marked here

Phenomenon	Section	Vibration increases with engine speed	Vibration increases with generator load	Vibration disappears when electric power is	Strong vibration only on certain speeds	Vibration disappears when mounting foot is	Vibration disappears when the governor is	Crankshaft torsional vibrations	Vibration at blade pass frequency	Vibration at hammer test frequencies	Vibration at 6,25 Hz (engine half order)	Vibration at 12,5 Hz (engine first order)	Vibration at 25 Hz (engine second order)	Vibration at 37,5 Hz (firing frequency)	Vibration at 50 Hz (line frequency)	Vibration at 100 Hz (2x line frequency)	Vibration at 200 Hz (4x line frequency)	Vibration at 1250 Hz (slot pass frequency)	Vibration at 0,43...0,48 x rpm (auxiliary components)	Vibration at 1x rpm (auxiliary components)	Vibration at 2x rpm (auxiliary components)	Harmonics of running speed present	Subharmonics of running speed present	Frequency is modulating	Disturbances in time waveform	Unexplainable measurement results	Product of probabilities, if no blanks	Relative probabilities
Investigation findings								x			x												x				<----- Mark h	
Possible findings																												
Objectives																												
Major objectives																												
Mass forces	4.1.1	5						2		1		5	5	1	1							5					0	
Gas forces	4.1.2	3	5					2	3	1	2			5	1							5	4				16	26 %
Crankshaft torsional critical speed	4.1.5				3			5		3												2	1		1		0	
Misfiring	4.1.7							3	1	1	5												3	1	1	2	45	74 %
Diesel knock	4.1.8							1	1	1														1	1		0	
Piston slap	4.1.9	5						1		1			2												3		0	
Governor hunting	4.1.11						5	1		1														1		3	0	
Magnetic forces	4.2.1		4	5						1					3	3	3	2			3	1	1				0	
Static eccentricity	4.2.3		5	5		4				1						5						1	1				0	
Dynamic eccentricity	4.2.4	2	5	5						1		3										1	1				0	
Stator end winding looseness	4.2.5		5	5	1					1					2	3	2					2	1		1		0	
Rotating unbalance	4.3.1	5								1		5								5							0	
Misalignment	4.3.2	2				4				1			4							4	3	3			2		0	
Mechanical looseness	4.3.3	4			3					1										3	3	4	3	1	5		0	
Rotor rub	4.3.4	1						2		1		3										3	3	2			0	
Lateral critical speed	4.3.5				4					3																	0	
Oil whirl	4.3.6							1		1		1							5								0	
Oil whip	4.3.6				4			1		1									5								0	
Roller bearing defect	4.3.7	1								1																	0	
Gear meshing	4.3.8	2						2		1												3	3		5		0	
Vane or blade excitation	4.3.9	2						2	4	1												3	3		4		0	
Structural resonance	3.3				5					5								1									0	
Measurement fault	5.1.4																							1		5	0	

Green: phenomena according to investigation findings

Light blue: phenomena according to detected anomalies

New probabilities based in investigation findings appear here

DIAM-matrices

Analysis phase

- After investigation phase the problem may already be known, at least to some extent
- Sophisticated methods are applied to find the root cause of the problem
  - modal analysis, ODS-animations, Motion amplification, oil analysis, metallurgical failure analysis, simulations…
- External parties (manufacturer, consultants) may have an increasing role in this phase, depending on the readiness of the NPP to carry out the analysis methods
- Matrix shows how good each method is for gaining information from the problem that was discovered
- This matrix sheet is only for information, no input from user required

DIAM-matrices

Analysis matrix

	Analysis method	Recommended tranducers								Analysis methods										
		Accelerometers	Velocity transducers	Proximity probes	Laser vibrometers	Shaft encoders	Strain gauges	Fiber optic sensors	Dynamic pressure transducers	Experimental modal analysis	Operational deflection shape	Operational modal analysis	Motion amplification	Digital image correlation	Infrared thermography	Metallurgical failure analysis	Oil analysis	Simulation	Product of probabilities based on investigation findings	Relative probabilities based on investigation findings
Easiness		4	4	3	3	2	1	5	4	1	2	2	4	2	5	1	1	2		
Recommended method, sum		9,3	7,7	6,1	18,3	30,5	18,3	9,3	30,5	18,3	24,4	24,4	26	12,2	27,3	10,9	10,9	22,8		
Recommended method, %		3	3	2	6	10	6	3	10	6	8	8	8	4	9	4	4	7	100 %	
Easiness weighted %		4	4	2	7	7	2	6	15	2	6	6	12	3	16	1	1	5	100 %	
Phenomenon	Section	5.2.2.1	5.2.2.2	5.2.2.3	5.2.2.4	5.2.2.5	5.2.2.6	5.2.2.7	5.2.2.8	8.3.1.1	8.3.1.2	8.3.1.3	8.3.1.4	8.3.1.5	8.3.1.6	8.3.1.7	8.3.1.8	8.3.1.9		
Mass forces	4.1.1	4	3	2	4	1	1	4		3	4	4	5	1	3	4	5	4	0	
Gas forces	4.1.2	3	2	1	3	5	3	3	5	3	4	4	5	2	3	4	4	3	16	26 %
Crankshaft torsional critical speed	4.1.5	1	1	1	3	5	4	1	1	1	1	1	3	3	1	4	4	5	0	
Misfiring	4.1.7	1	1	1	3	5	3	1	5	3	4	4	4	2	5	1	1	4	45	74 %
Diesel knock	4.1.8	3			3	2	4	3	5	1					2	3	3	5	0	
Piston slap	4.1.9	3	3	1	3		3	3		1	4	1	5		4	3	5	1	0	
Governor hunting	4.1.11	1	1	1	3	5	3	1		1	2	2	3	1	1	3	2		0	
Magnetic forces	4.2.1	3	2		4	3	1	5			2	1	3		1		1	4	0	
Static eccentricity	4.2.3	3	2				2	5		2	5	3	5	2	3	3	3	1	0	
Dynamic eccentricity	4.2.4	3	3	1			2	5		2	5	3	5		1	1	2	2	0	
Stator end winding looseness	4.2.5	3	1		5		2	5		3	1	3	4	2	3	5	1	3	0	
Rotating unbalance	4.3.1	4	3	4	3		1			2	4	2	5	1	1		3	1	0	
Misalignment	4.3.2	4	3	5	3		1						1	3	5	4	3	1	0	
Mechanical looseness	4.3.3	4	3	2	4		1	4		3	4	2	4	2	5	5		2	0	
Rotor rub	4.3.4	4	3	4	3	2	2	4			2		1	2	5	5	4	1	0	
Lateral critical speed	4.3.5	4	3	1	4		1	4		3	1	4	3	1	1		2	4	0	
Oil whirl	4.3.6	4	2				1	3			1		3		2		4	2	0	
Oil whip	4.3.6	4	1				1	3		1	1	1	4		2	2	4	3	0	
Roller bearing defect	4.3.7	5	1		4			4					1		4	5	5		0	
Gear meshing	4.3.8	4	1		4	4	1	4				1	2	3	4	5	5	1	0	
Vane or blade excitation	4.3.9	3	1		3	2	1	3	5			1	3	1	2	1	1	3	0	
Structural resonance	3.3	5			5		2	5		5		4	5	3	1	2		5	0	
Measurement fault	5.1.4	3	3	3	3	3	3	2	2				4		3		5		0	

How recommended each analysis and measurement instrument is in this case? Based on effectiveness and easiness

DIAM-matrices

Mitigation phase

- The root cause of the problem is fully known at this point
- The matrix shows different mitigation methods and how good they are at mitigating each problem type
  - Balancing, aligning, replace component, natural frequency tuning, isolation, mass damper, no damage expected (analysis has shown that it shouldn't break)…
- Mitigation method is verified by vibration measurements after implementation

DIAM-matrices

Mitigation matrix

Best mitigation methods for the found phenomenon

Other mitigation methods

Found phenomenon is marked here

	Mitigation method		Balancing	Aligning	Replace / repair defected component	Improved control sequence	Isolate the source of excitation	Isolate a component from vibrating base	Natural frequency tuning	Vibration dampers	Tuned mass dampers	Active vibration control	No damage expected	Improving fatigue resistance	
	Easiness		2	3	3	3	2	2	1	2	2	1	3	2	
	Recommended method, sum		0	0	3	0	3	3	0	2	1	0	3	3	
	Recommended method, %				17		17	17		11	6		17	17	100 %
	Easiness weighted %				21		14	14		10	5		21	14	100 %
	Phenomenon	Section	6.4.1.1	6.4.1.2	6.4.1.3		6.3.1.4	6.3.1.5	6.3.1.6	6.3.1.8	6.3.1.9	6.3.1.10	6.3.1.11	6.3.1.12	Relative probabilities based on investigation findings
	Mass forces	4.1.1	1				3	3	3	2	2	1	3	3	
	Gas forces	4.1.2					3	3	3	2	1	1	3	3	26 %
	Crankshaft torsional critical speed	4.1.5			3				1	3	3	1	3	1	
x	Misfiring	4.1.7			3		3	3		2	1		3	3	74 %
	Diesel knock	4.1.8											3		
	Piston slap	4.1.9			5					1		1	3		
	Governor hunting	4.1.11				5							3		
	Magnetic forces	4.2.1					1	3	3	1	1	1	3	3	
	Static eccentricity	4.2.3		5				1					3	1	
	Dynamic eccentricity	4.2.4	4	1	2			1		1	1		3	1	
	Stator end winding looseness	4.2.5			4				3	1			3	4	
	Rotating unbalance	4.3.1	5				3	3		2	2	1	3	1	
	Misalignment	4.3.2		5									3		
	Mechanical looseness	4.3.3			4		1	1		1			3		
	Rotor rub	4.3.4	1	4	3								3		
	Lateral critical speed	4.3.5	5				2	2	2	2	2	1	3	1	
	Oil whirl	4.3.6							1			1	3	1	
	Oil whip	4.3.6							1			1	3	1	
	Roller bearing defect	4.3.7			5								3		
	Gear meshing	4.3.8		3	5		3	3	3	2	3	1	3	3	
	Vane or blade excitation	4.3.9			3		4	4	3	2	1	1	3	3	
	Structural resonance	3.3					4	4	5	3	4	3	3	5	
	Measurement fault	5.1.4													

Recommended mitigation methods, based on how effective and easy it is

Thank you for your attention!
Any questions?