CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

Department of production machines and equipment

Master thesis

Single-purpose grinder spindle quality control and assurance within small series production

Text appendices

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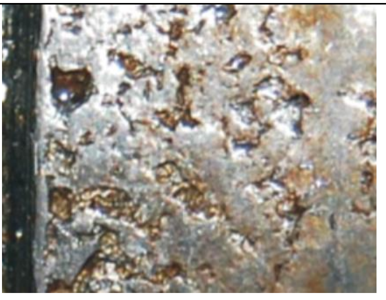
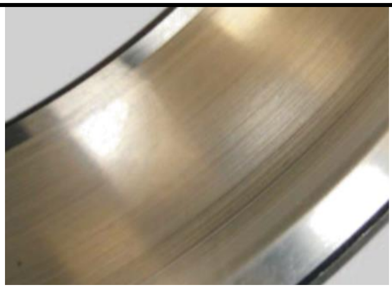
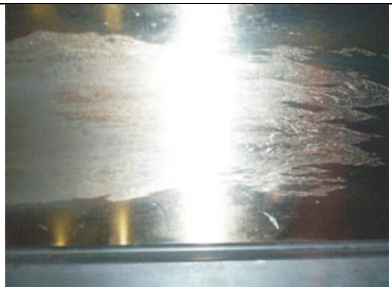
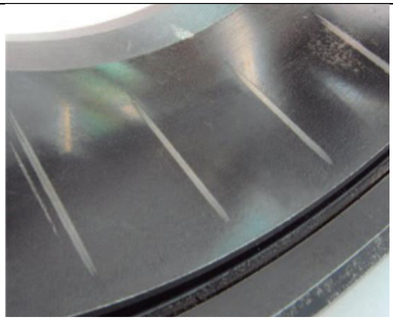
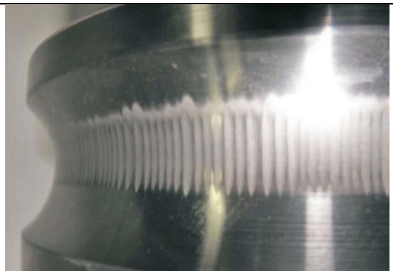
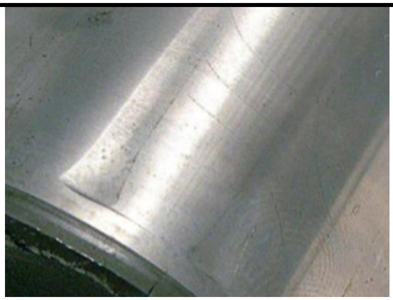
Appendix 1. Failure submodes chains of causation

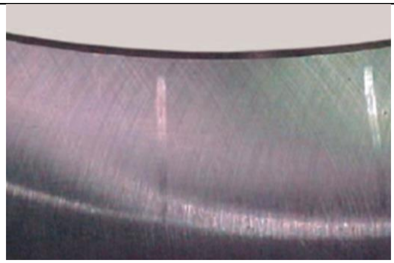
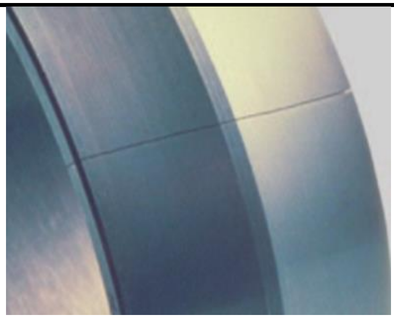
Failure submode	**Visual example [14]**	**Damage description**	**<= „caused by ↓“**	**<= „caused by ↓“**	**<= „caused by ↓“**	**<= „caused by ↓“**
A1. Fatigue subsurface failure mode (FM)		Microcracks below the raceway surface	Cyclic stresses underneath the raceway surface	Long bearing operation (bearing life expiration)		
A2. Fatigue surface FM		Distress of the surface, small cracks	Shear stresses at the surface	Metal-to-metal contact	Inadequate lubrication	
					Ingress of contaminants	

B1. Abrasive wear FM		Dull or polished surfaces	Particles moving over surfaces	Metal-to-metal contact	Inadequate lubrication Ingress of contaminants	
B2. Adhesive wear FM		Material transfer from one surface to another	Frictional heat	Breakthrough of lubrication film	Sliding of rolling elements (passage of a rolling element (RE) from the unloaded zone to a loaded zone)	Light loads Inadequate lubrication Speed differences Inadequate fits

C1. Moisture corrosion FM		Oxidation of the surfaces	Presence of moisture/ corrosive liquids/air	Inadequate sealing Inadequate handling/storage		
C2.1 Fretting corrosion FM		Oxidation and wear of surface asperities under oscillating movements between mating surfaces	Micro-movements between loaded surfaces: cyclic loads when REs are passing by	Inadequate fits Bent shaft Imperfections in the contact surfaces		

C2.2 False brinelling FM		Shallow depressions in raceway/RE places of contact	Combination of corrosion and wear	Cyclic vibration on a non-rotating bearing	Inadequate storage (on end)	
D1. Electric erosion by excessive voltage FM		Discoloured areas where the material has been tempered, re-hardened, or melted, craters	Heating of the material to tempering/ melting levels	High current density over a small contact surface	Passage of electric current from one rin to another via REs	Ineffective insulation
D2. Electric erosion by current leakage FM		Shallow craters, washboard-patterned flutes	Heating of the material to tempering levels	Electric current passage (density is not as high as it is at D1 FM)	Frequency variations	

E1. Overload plastic deformation FM		Permanent deformation – depressions at REs distance	Static or shock overloads (true brinelling)	Improper force application	Improper mounting procedure	
E2. Plastic deformation from indentation from debris FM		Particles indented into raceway/ REs surfaces	Stresses in the surfaces	Destruction of the raceway geometry, impairment of lubrication	Over-rolled particles in the raceway-RE contact areas	Ingress of contaminants

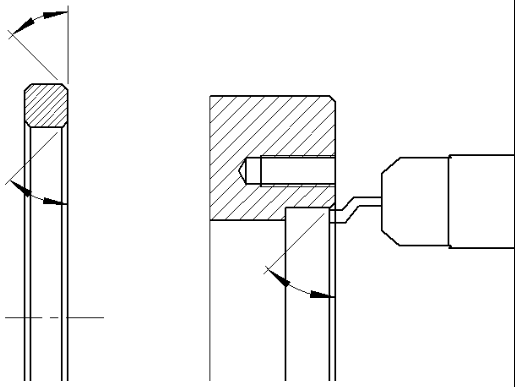
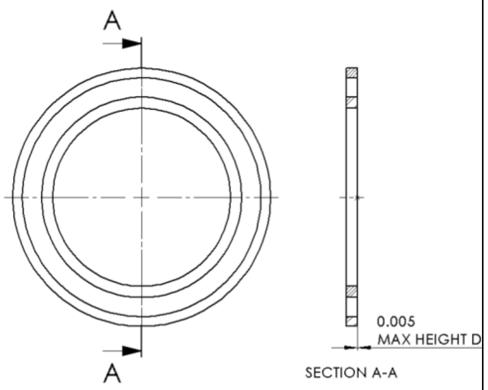
E3. Indentation by handling FM		Dents by hard, sharp objects	Localized overloads	Improper handling		
F1. Forces fracture FM		Fracture	Stress concentration in excess of the material's tensile strength	Rough treatment (impact) Excessive drive-up on a tapered seat or sleeve	Improper mounting procedure	

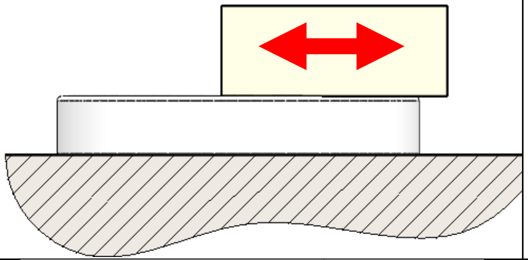
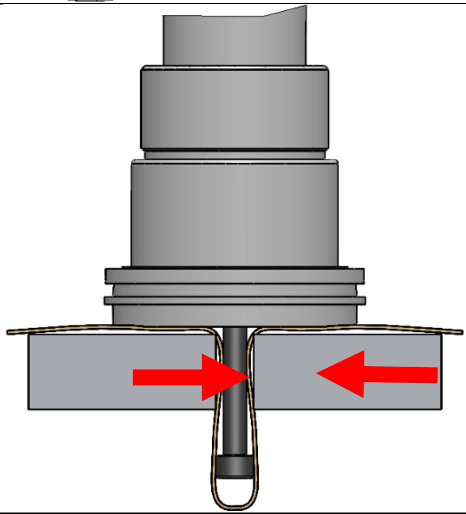
F2. Fatigue fracture FM		Propagating crack	Frequently exceeding the fatigue strength limit of the material (premature fatigue) under bending	High hoop stresses, Herzian stresses	Reduction of bearing’s internal clearance	Inadequate fit (too tight)
F3. Thermal cracking FM		Cracks perpendicular to the direction of sliding motion	Frictional heat	Sliding of two surfaces heavily against each other	Inadequate lubrication Inadequate fit (either too tight or too loose)	

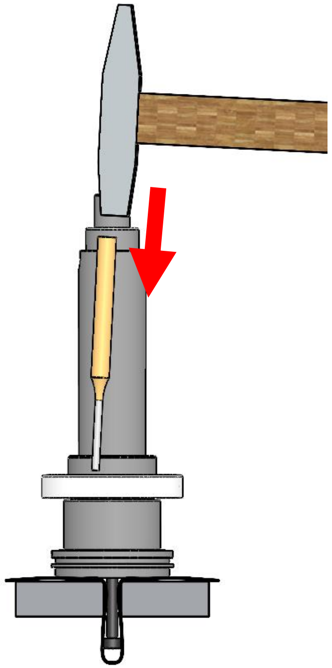
Appendix 2. .Vibration measurement devices overview

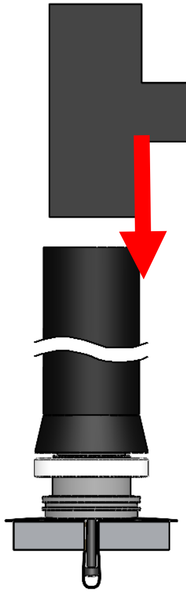
Device Name	Supplier	Number of channels	Frequency measurement range [Hz]	ISO overall vibration	FFT	Fault detection	HFRT	Balancing
Vibrometer Fluke 805	Prueftechnik	1	10-1000 ; 4000-2000	+	-	-	-	-
Vibrio M	Adash	1	500-16000	+	+	+	-	-
FAG Detector II	FAG	1	2000-20000	+	+	+	+	-
QuickCollect Sensor	SKF	1	3-5000	+	+	-	+	-
VIBSCANNER 2	Prueftechnik	3	Z:0-50000 X;Y: 0-10000	+	+	+	-	-
VIBXPERT II	Prueftechnik	2	0.5-51200	+	+	+	-	+
Fluke 810	Prueftechnik	4	5-20000	+	+	+	+	-
Microlog Analyzer AX	SKF	4	0.16-80000	+	+	-	+	+
SCHENK SmartBalancer	SCHENK	2	5-5000	+	+	+	-	+

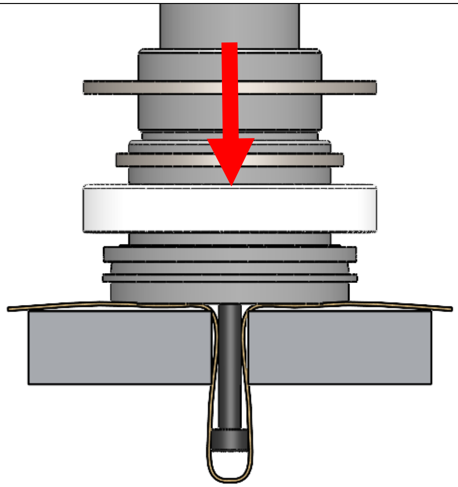
Appendix 3. Spindle assembly mounting procedure

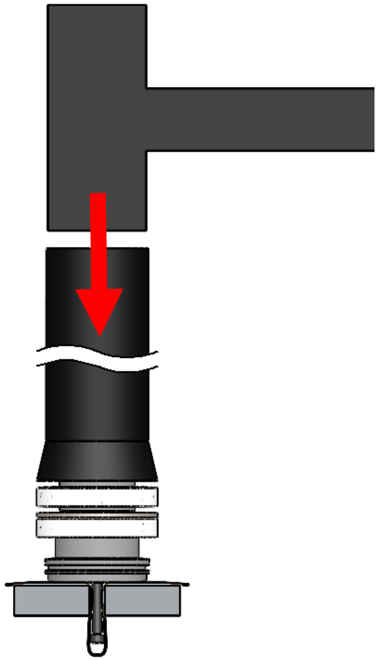
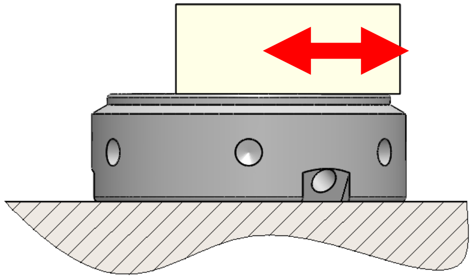
Step No.	Illustration	Instruction	Tools needed	Notes
1.		Sharp edges of spindle pipe and bearing spacer rings are chamfered.	• manual deburring tool	
2.		The height of bearing spacer rings is measured.	• micrometer	• Height difference affects the preload.

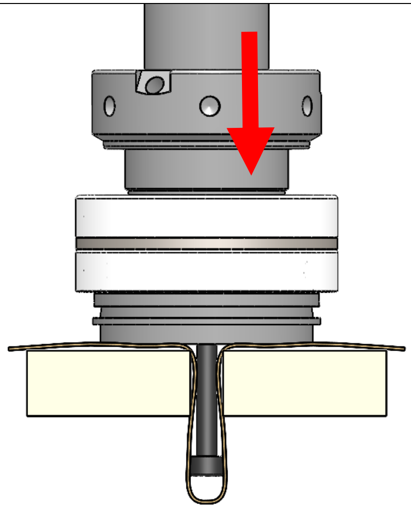
3.		• Surfaces of bearings, • corresponding abutment on spindle • spacer rings are rubbed.	• abrasive stone	• The components should be abraded on a flat plate.
4.		The shaft is clamped on a bench vise.	• bench vise • 2x M5 screw • rag	• Two screws are put into the threaded holes on the front face of the shaft and then clamped between the vise jaws, fixing the shaft upside down. • rag should be put between the spindle and the vise faces.

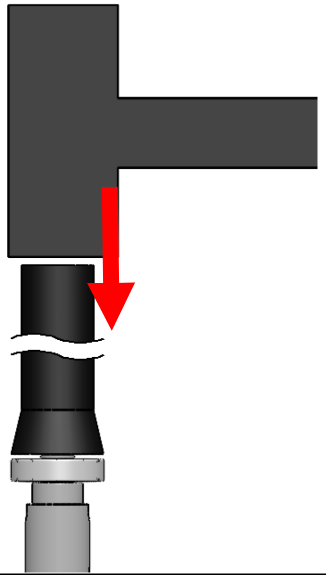
5.		Bearing 1 is placed to the bearing 55 diameter by hammering the inner ring through a pin punch.	• hammer • pin punch	• The angular contact ball bearing orientation has to be checked. • Gentle mounting with a pin punch and a hammer is more preferable for mounting the first bearing than an impact sleeve, because it is better for immediate visual control. • Impacts are applied to diametrally opposite points of the ring. • It is important to route the impacts to the inner ring and not to the cover – otherwise there is a high risk of damage of fragile ceramic bearing balls.

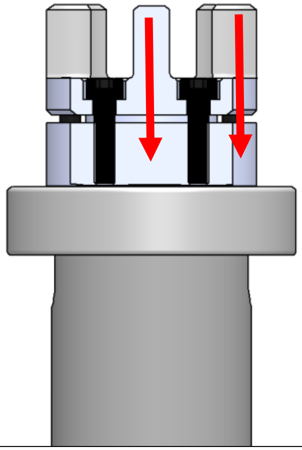
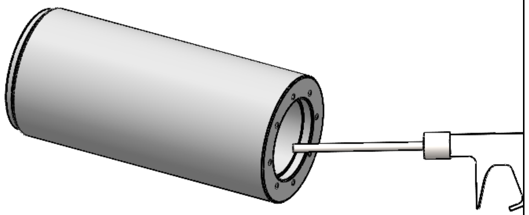
6.		Bearing 1 is hammered using a blowback-proof hammer through an impact sleeve.	• impact sleeve • blowback-proof hammer	• This step is performed after the first angular contact ball bearing is fitted on the diameter. • Blowback-proof hammer is able to absorb a part of the impact energy and protect the bearing from potential damage.

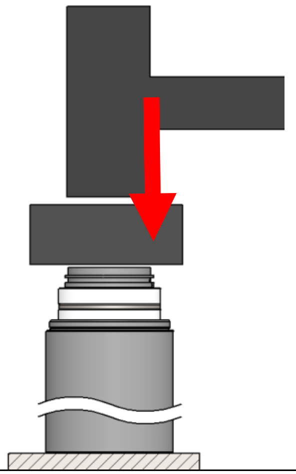
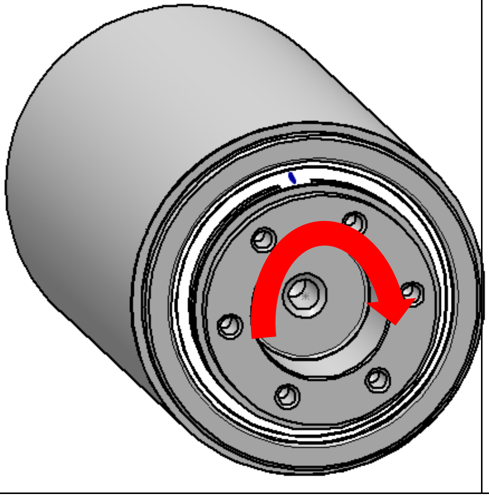
7.		The spacer rings are placed to the bearing 55 diameter.	• -	• This step is performed after there is enough space on the diameter for mounting a second bearing.

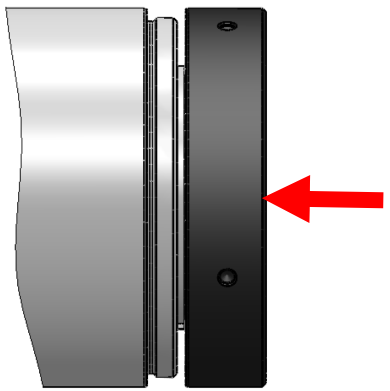
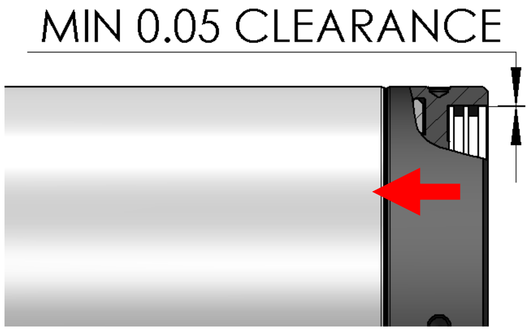
8.		The second angular contact ball bearing is placed to the bearing 55 diameter.	• impact sleeve • blowback-proof hammer • block with a flat surface	• The concentricity of the outer bearing spacer ring with bearings is checked and, if needed, aligned using an appropriate block with a flat surface. • Before the first bearing reaches its fitting surface, the surfaces of the bearing and the shaft have to be visually inspected to double-check its cleanliness.
9.		The bearing nut's fitting surface is rubbed.	An abrasive stone	• The component should be abraded on a flat plate.

10.		• The bearing nut's set screws are loosened. • The nut is screwed and tightened.	• -	

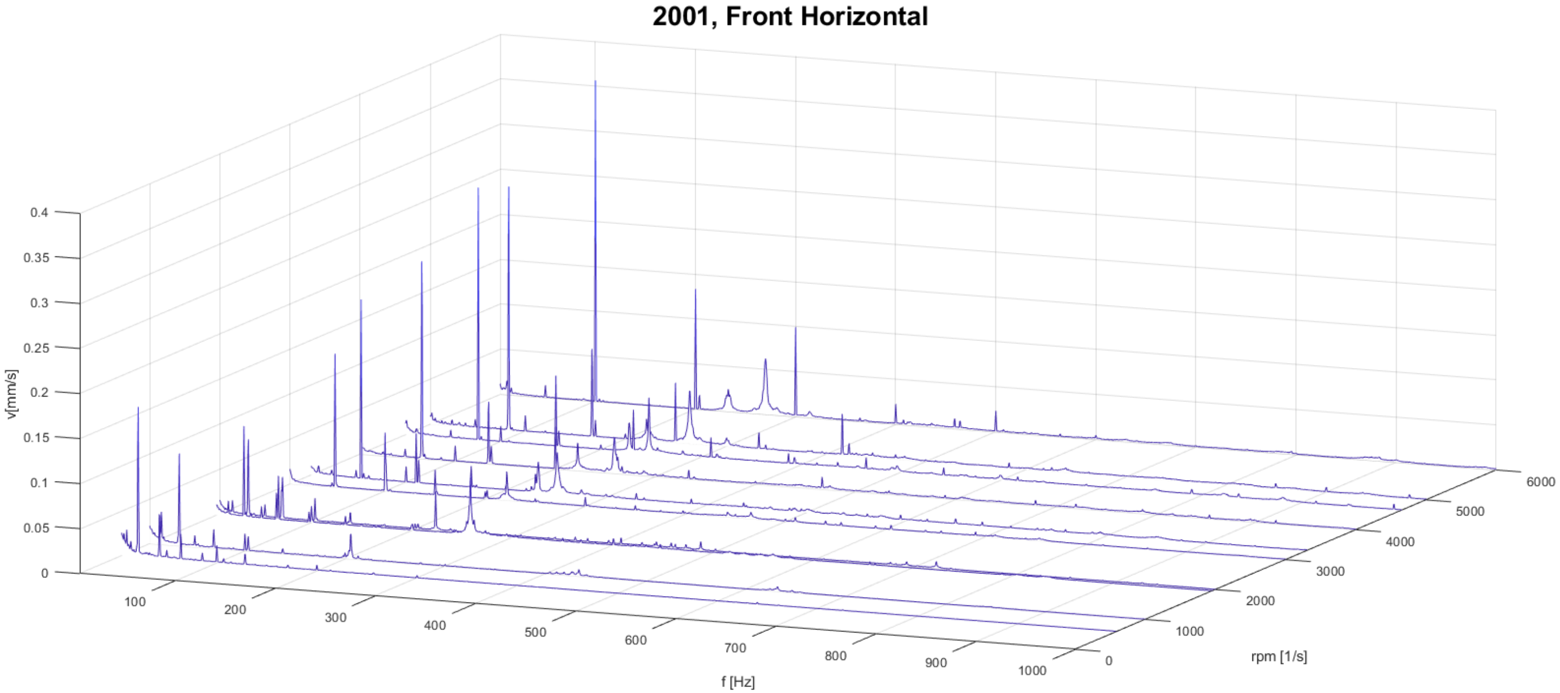
11.		The radial ball bearing is mounted.	• impact sleeve • blowback-proof hammer	• according to the same principles as in the step 8.

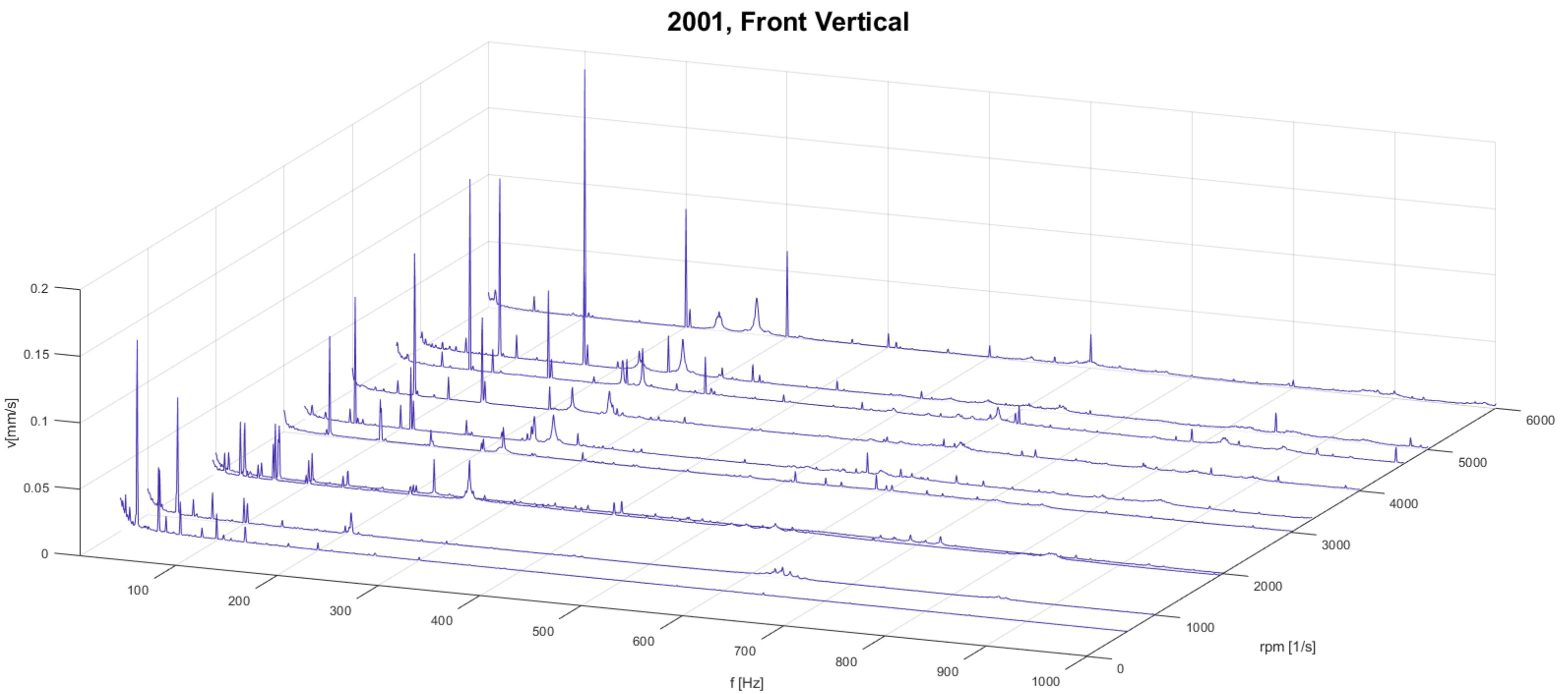
12.		The coupling is mounted and fixed.		• It is important to control the tightening force, as the wall of the coupling is very thin in places of screws' counterbores and it can crack relatively easily. • Every tightened screw has to be diametrically opposite to the previous one.
13.		The spindle pipe is cleaned from chips and oil.	• air gun • acetone-based cleaner	

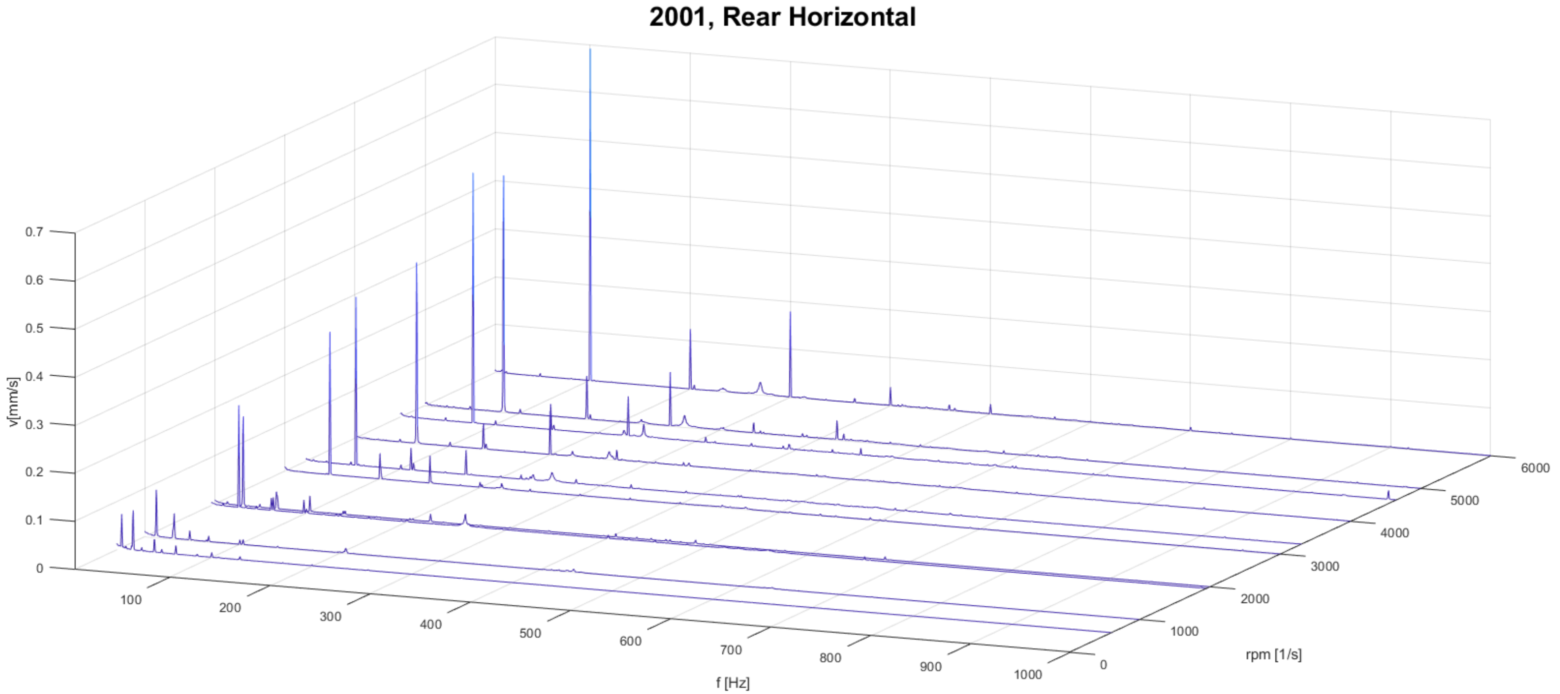
14.		The shaft with bearings on it is inserted into the spindle pipe by hammering through a silon block.	• hammer • silon block	• The spindle pipe is put on its rear face. • The bearings' fitting surfaces on spindle pipe are checked. • until the first angular contact ball bearing hits the surface. In this very moment, the impact sound recognizably changes, signalizing hammering has to be stopped.
15.		A small mark is added on the first angular contact ball bearing's outer ring and a check if it does not rotate while rotating the spindle by hand or by pushing on it with a reasonable force using a punch pin is performed.	• punch pin	

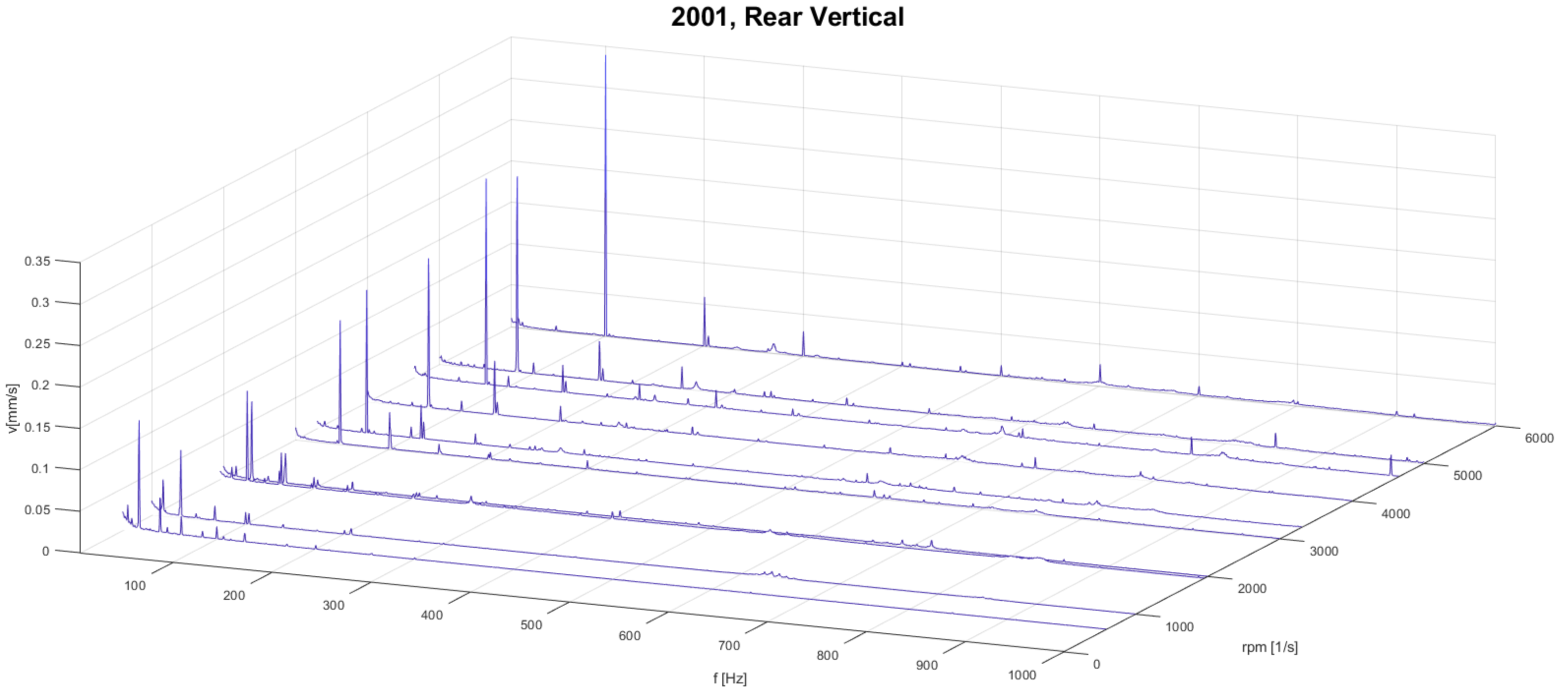
16.		The front bearing nut is mounted.		
17.	 	The front labyrinth seal is mounted.		• One has to make sure that there is a 0.05 mm clearance between the outer diameter of the seal and the nut using a feeler gauge. Otherwise, these faces might come into contact during spindle operation, because of the thermal expansion of the parts. It manifests itself as an additional motor load, which is quantified by measuring the consumed current, and displayed in machine's HMI. • Approximate value of load is 5% on 5000 rpm (however, there could be more reasons for increased motor load than just this one).

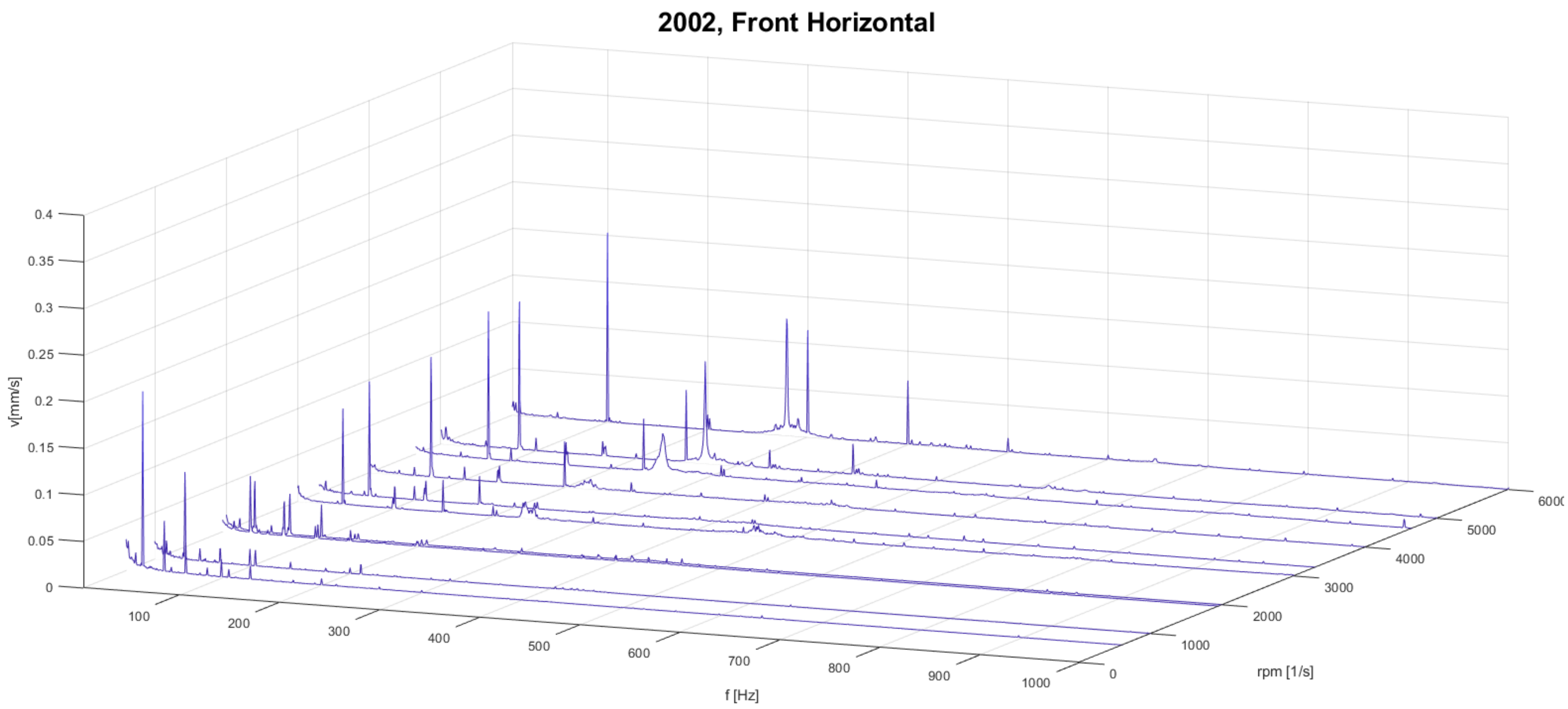
Appendix 4. Waterfall plots

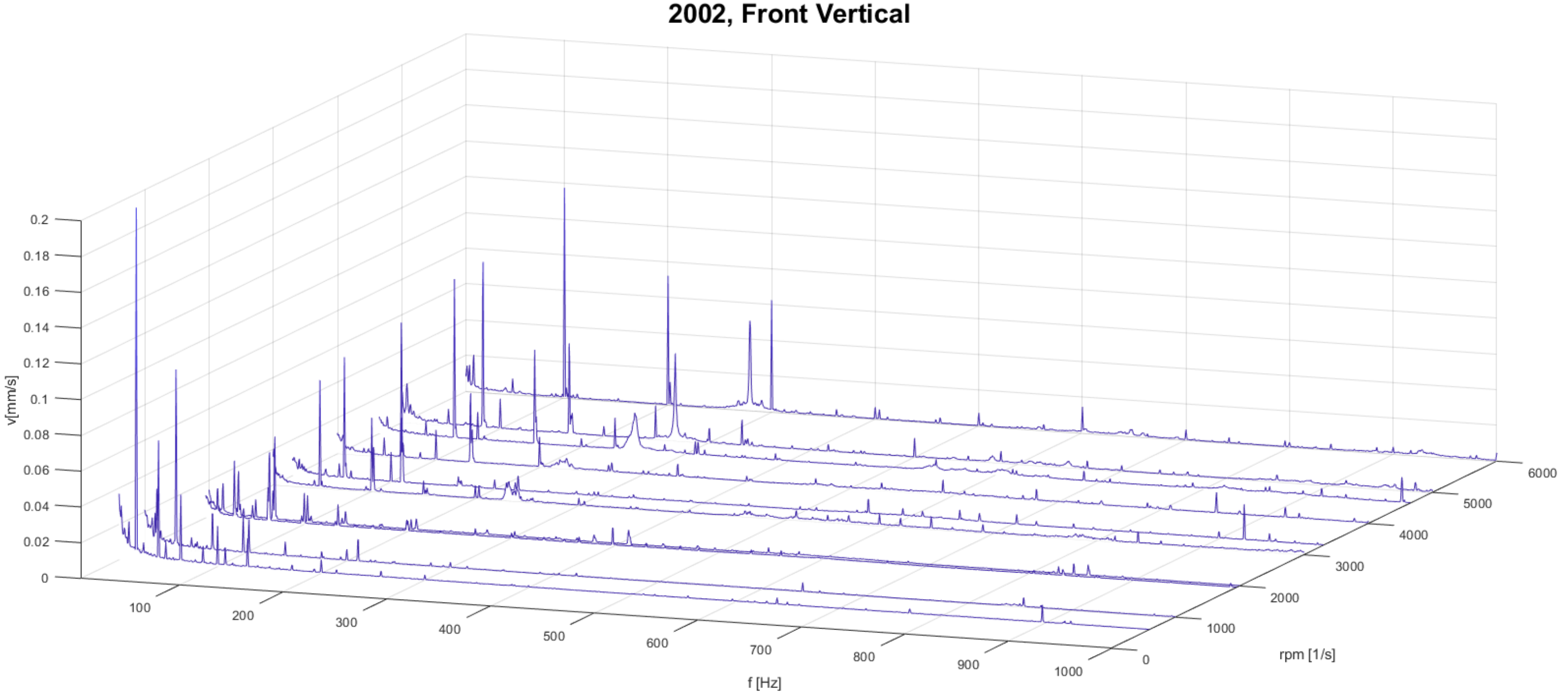


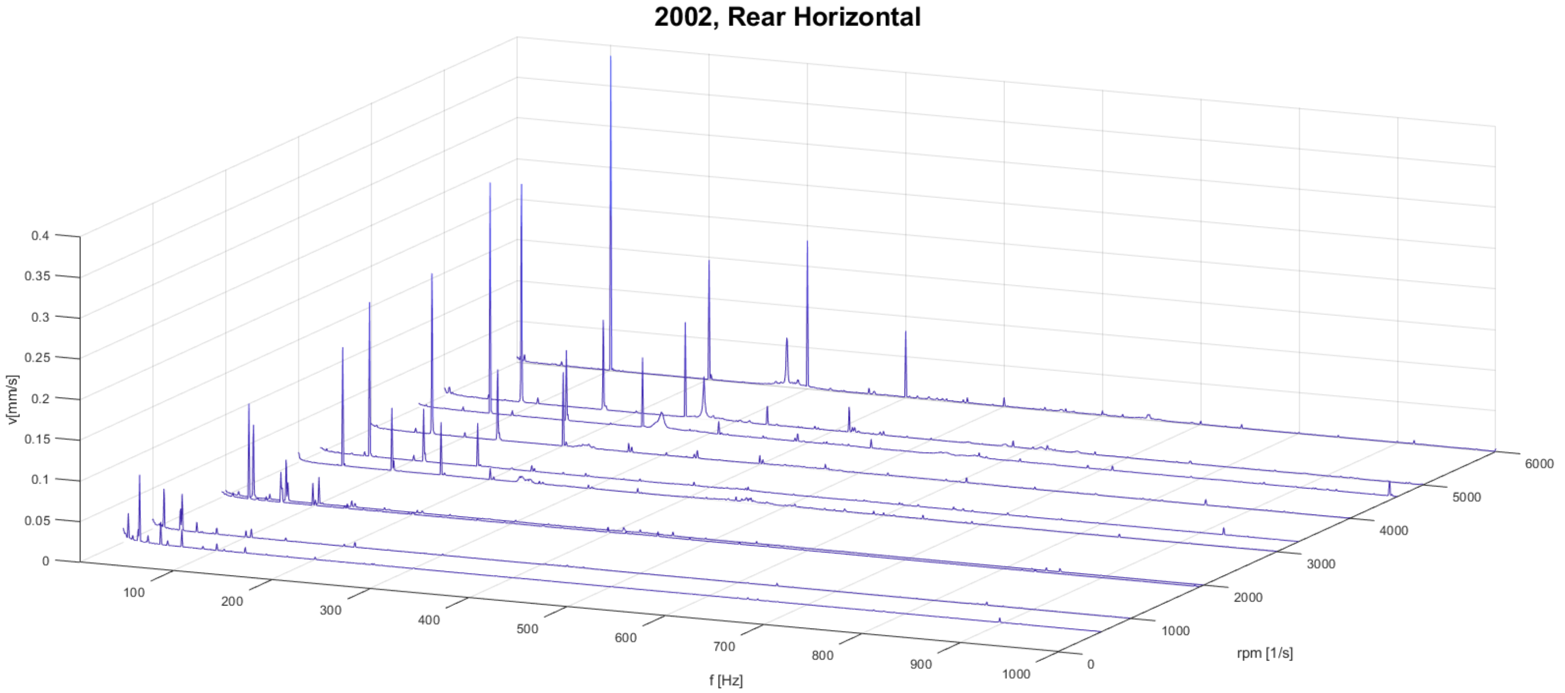

2001, Front Vertical
v[mm/s]
0.2
0.15
0.1
0.05
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

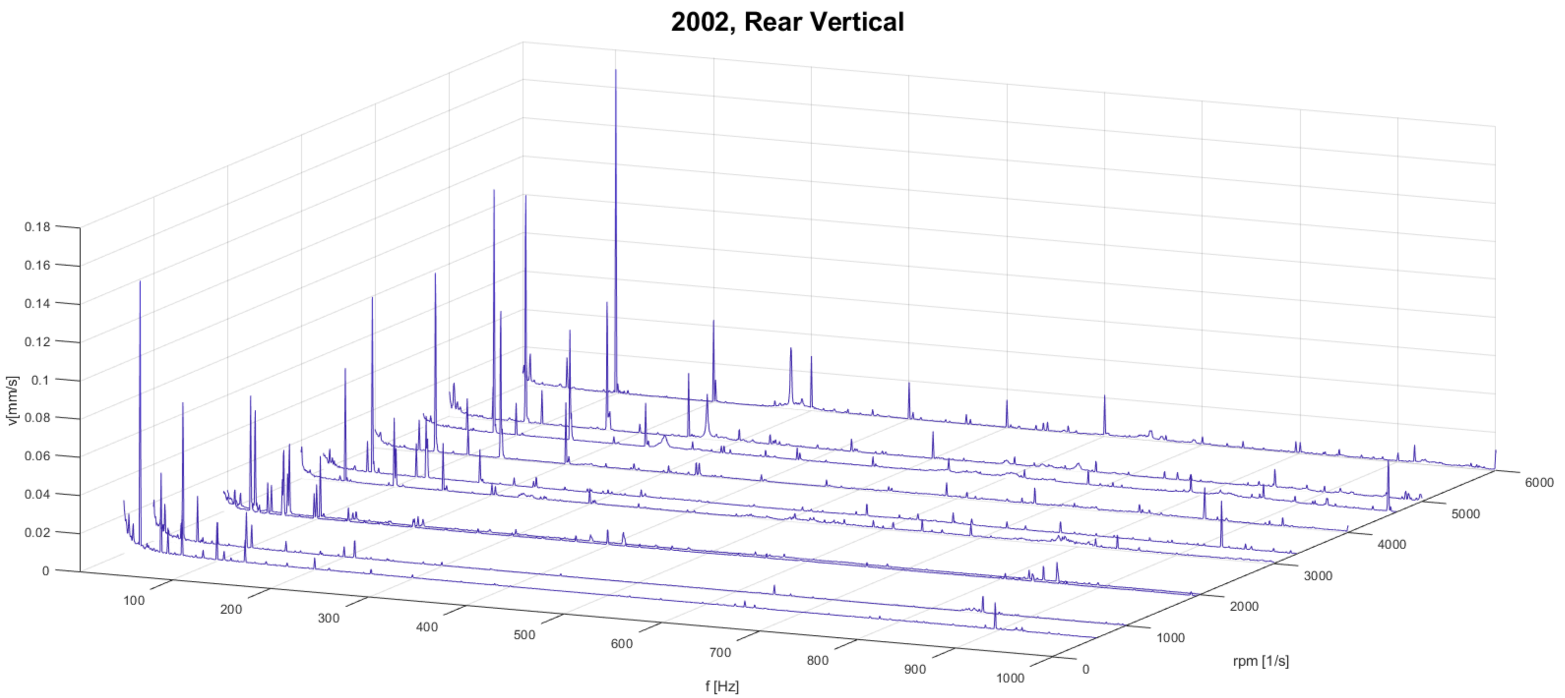

2001, Rear Horizontal
v[mm/s]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
f [Hz]
100
200
300
400
500
600
700
800
900
1000
rpm [1/s]
0
1000
2000
3000
4000
5000
6000

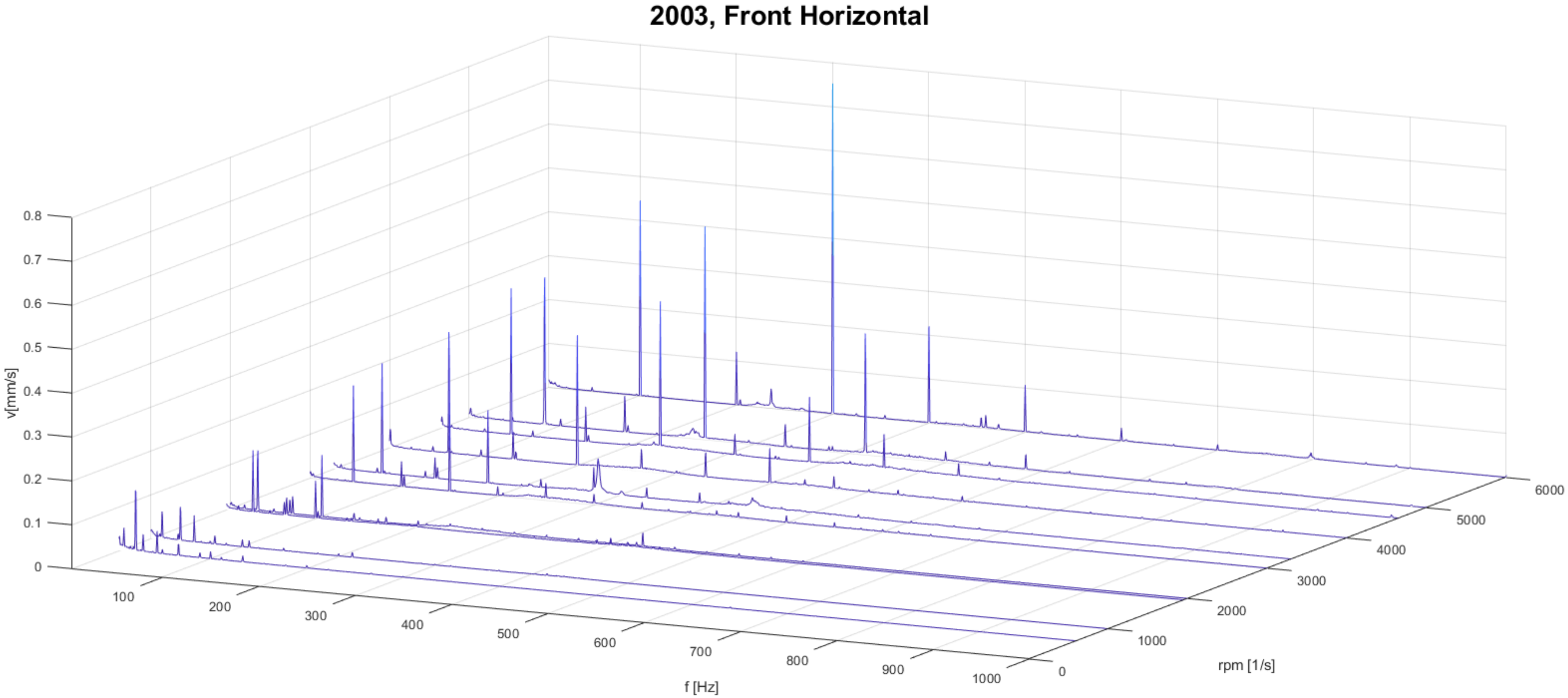

2001, Rear Vertical
v[mm/s]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
f [Hz]
100
200
300
400
500
600
700
800
900
1000
rpm [1/s]
0
1000
2000
3000
4000
5000
6000

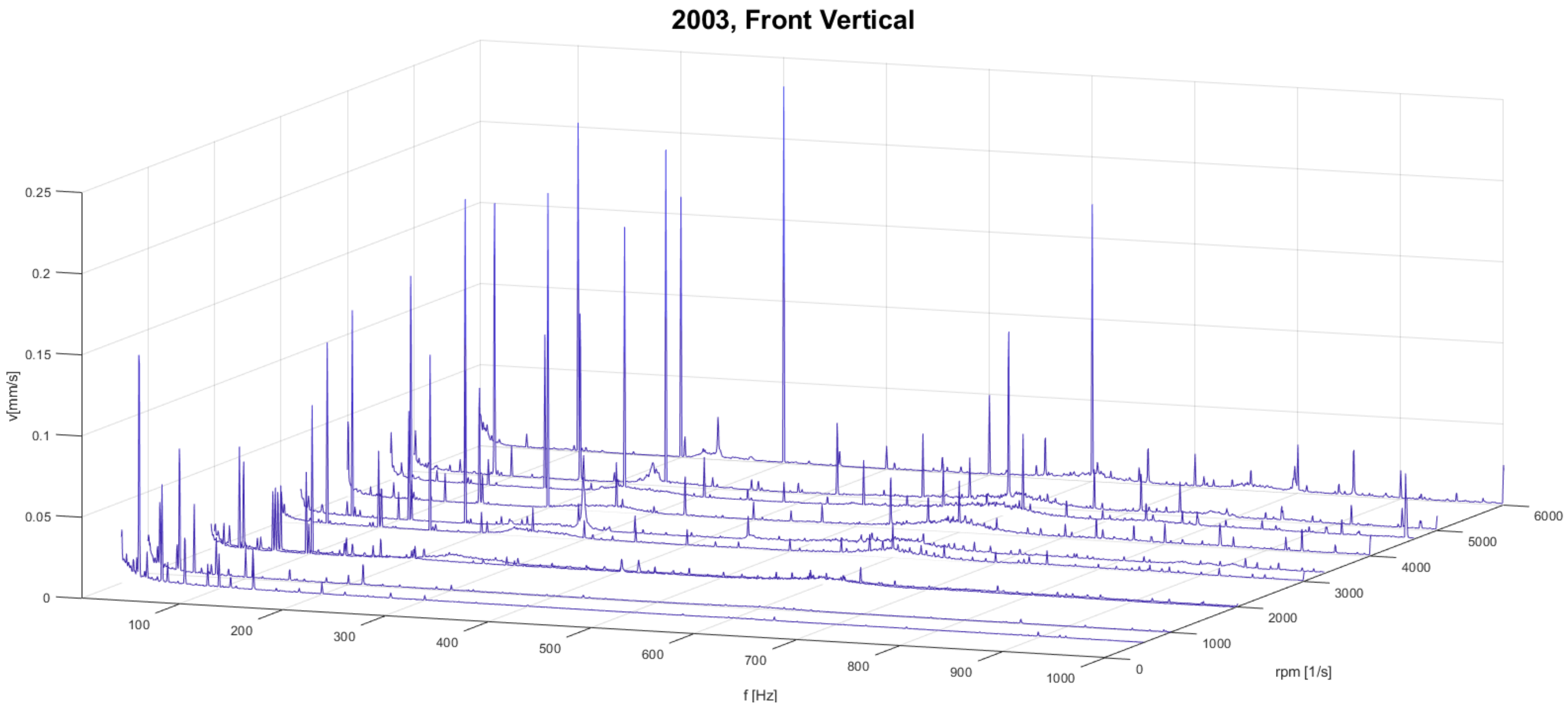

2002, Front Horizontal
v[mm/s]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
rpm [1/s]

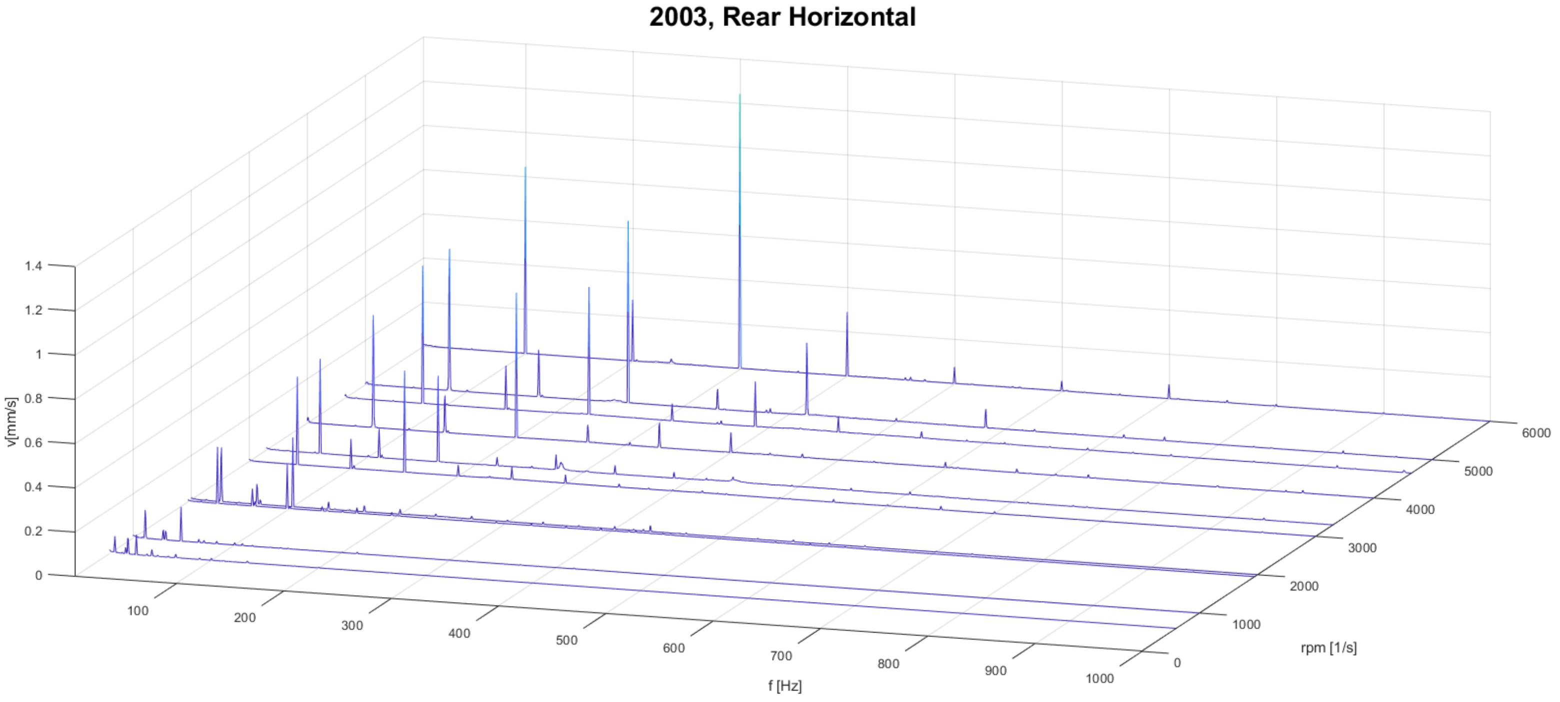

2002, Front Vertical
v[mm/s]
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

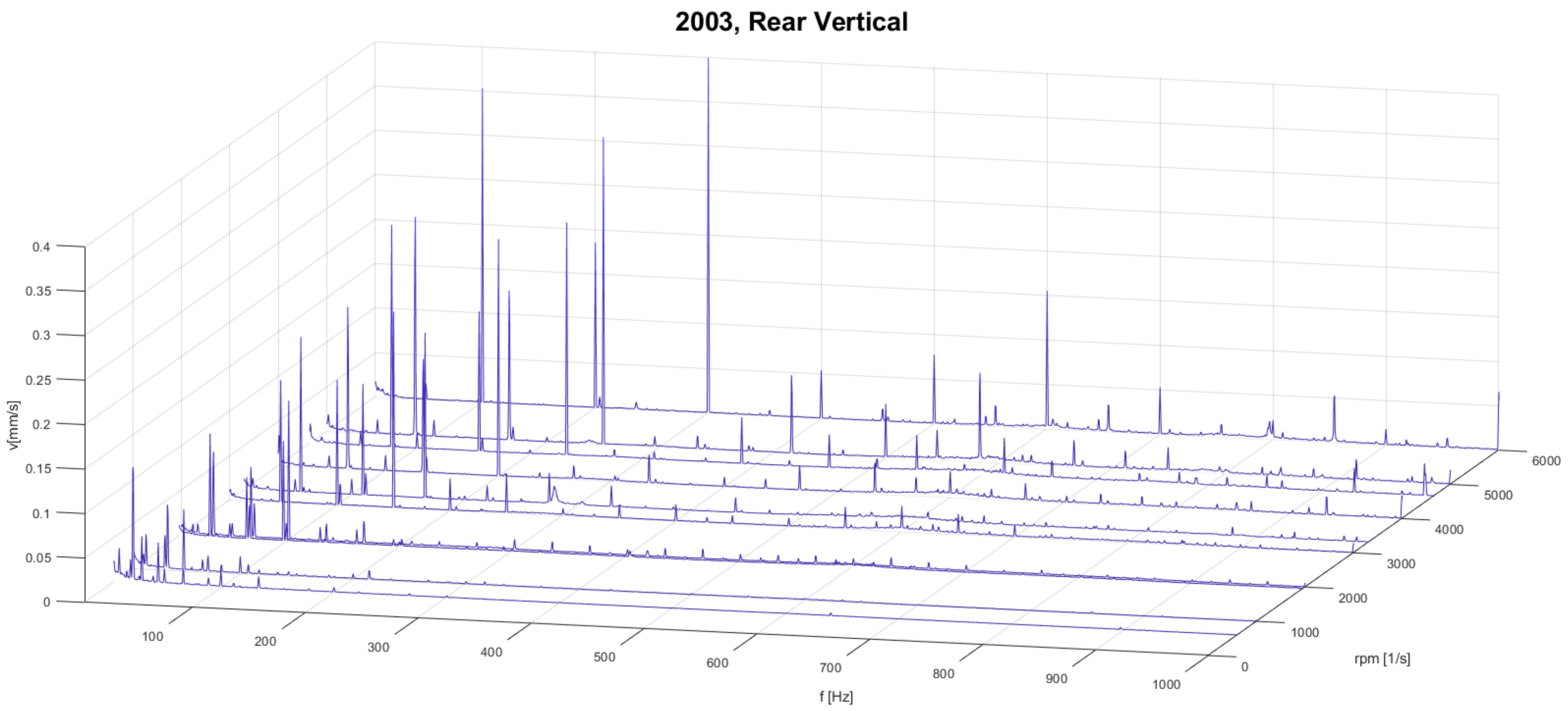

2002, Rear Horizontal
v[mm/s]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
f [Hz]
100
200
300
400
500
600
700
800
900
1000
rpm [1/s]
0
1000
2000
3000
4000
5000
6000

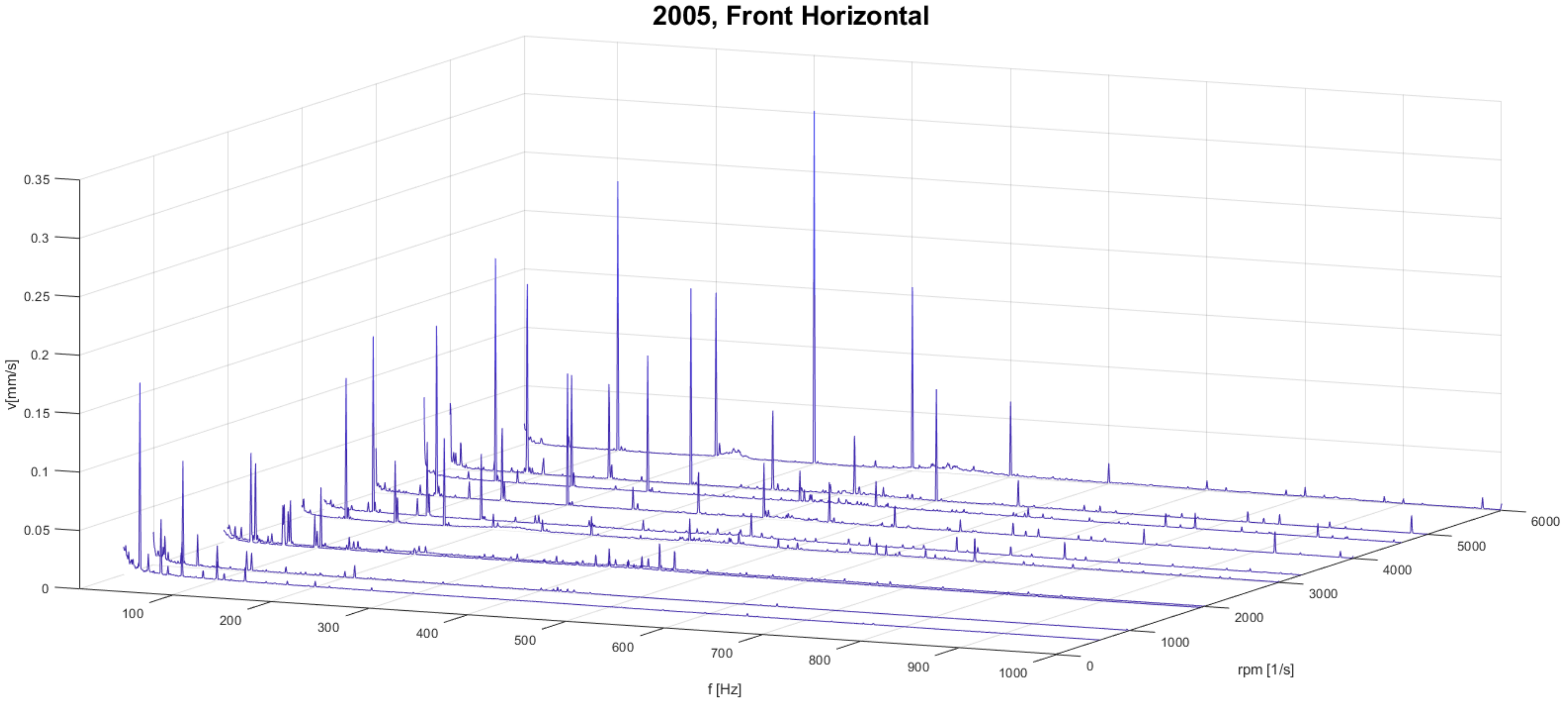

2002, Rear Vertical
v[mm/s]
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

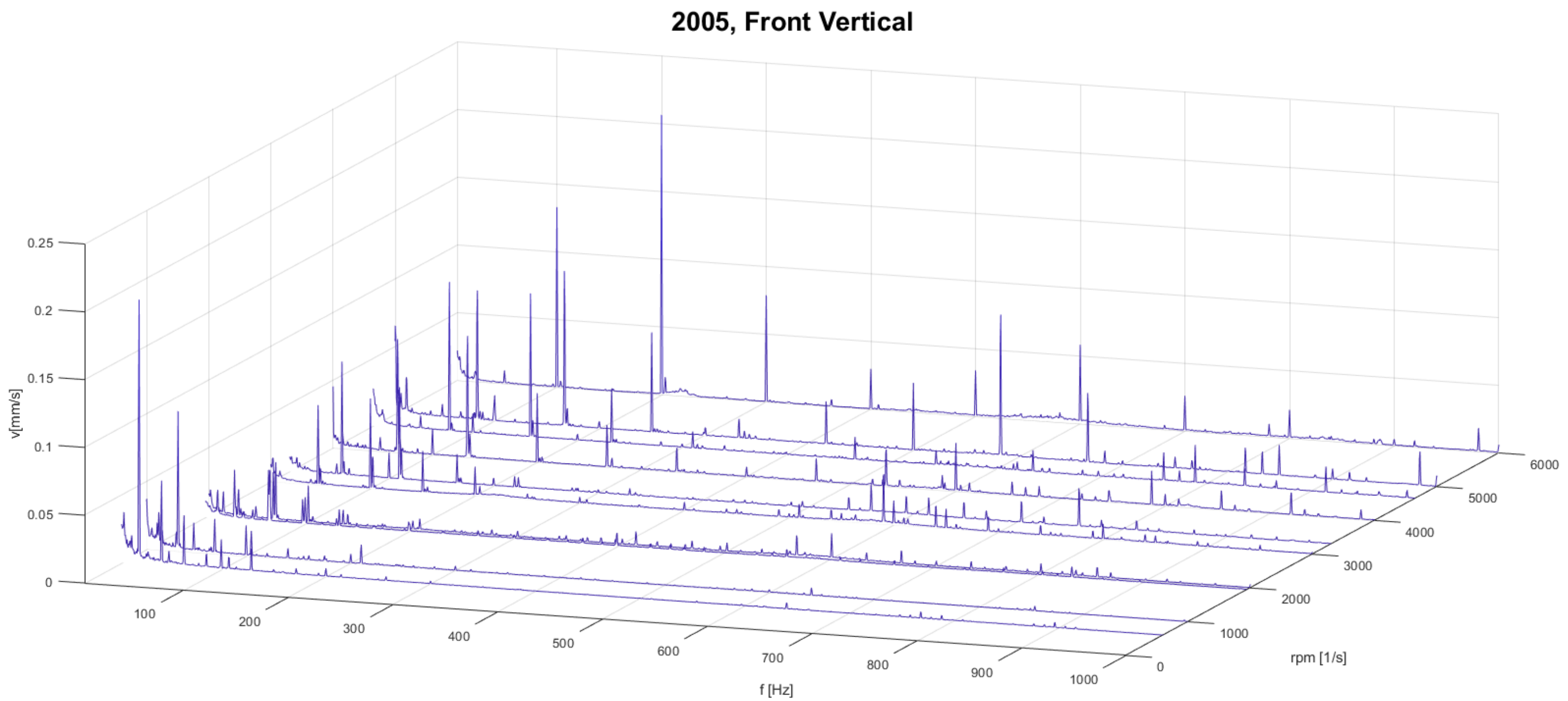

2003, Front Horizontal
v[mm/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

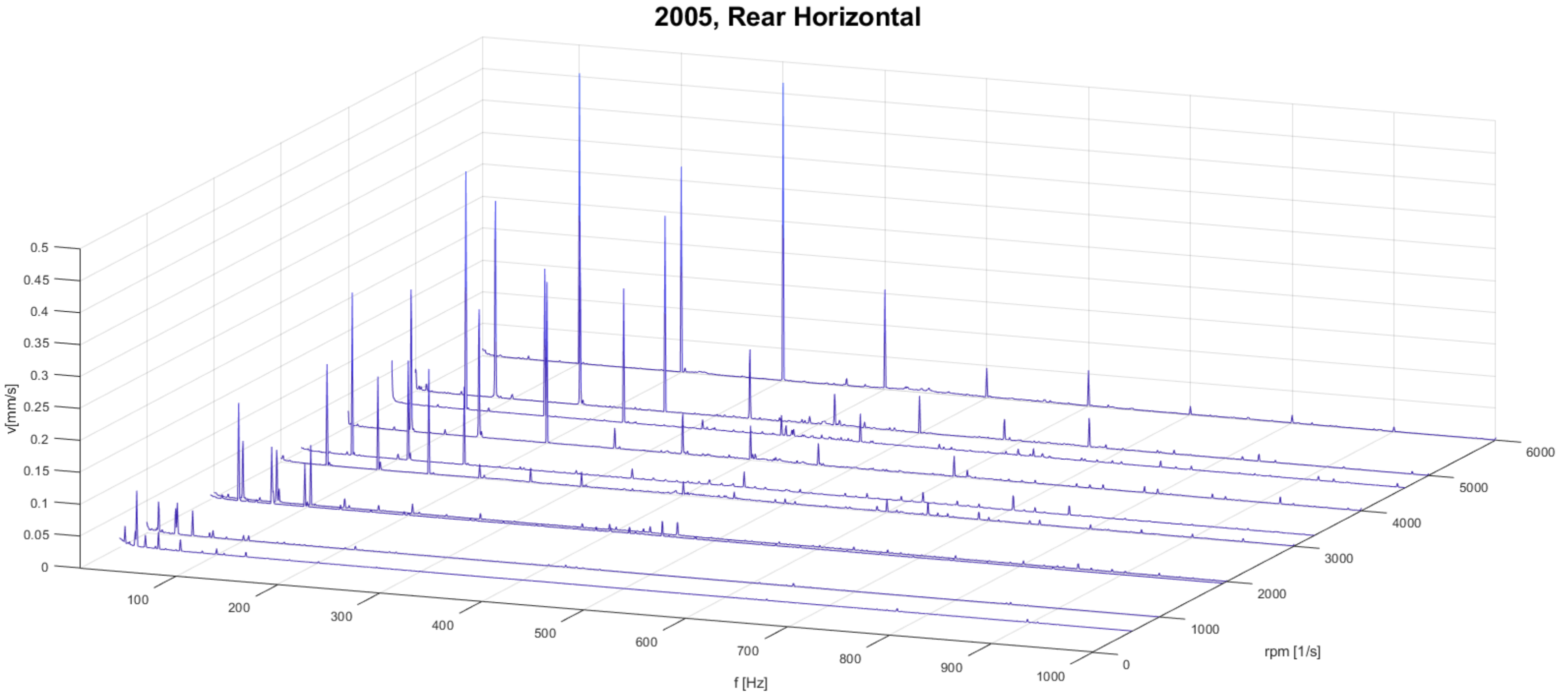

2003, Front Vertical
v[mm/s]
0.25
0.2
0.15
0.1
0.05
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

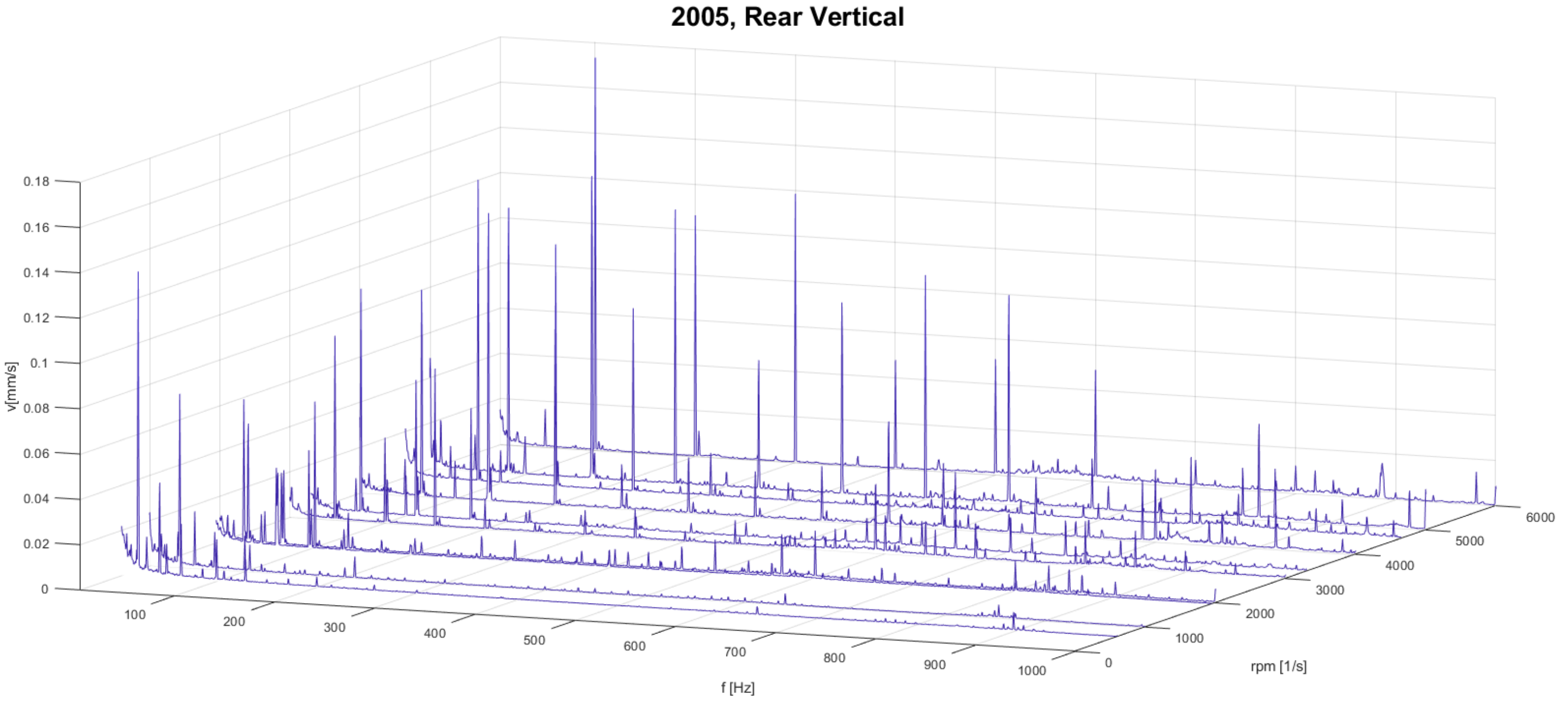

2003, Rear Horizontal
1.4
1.2
1
0.8
0.6
0.4
0.2
0
v[mm/s]
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

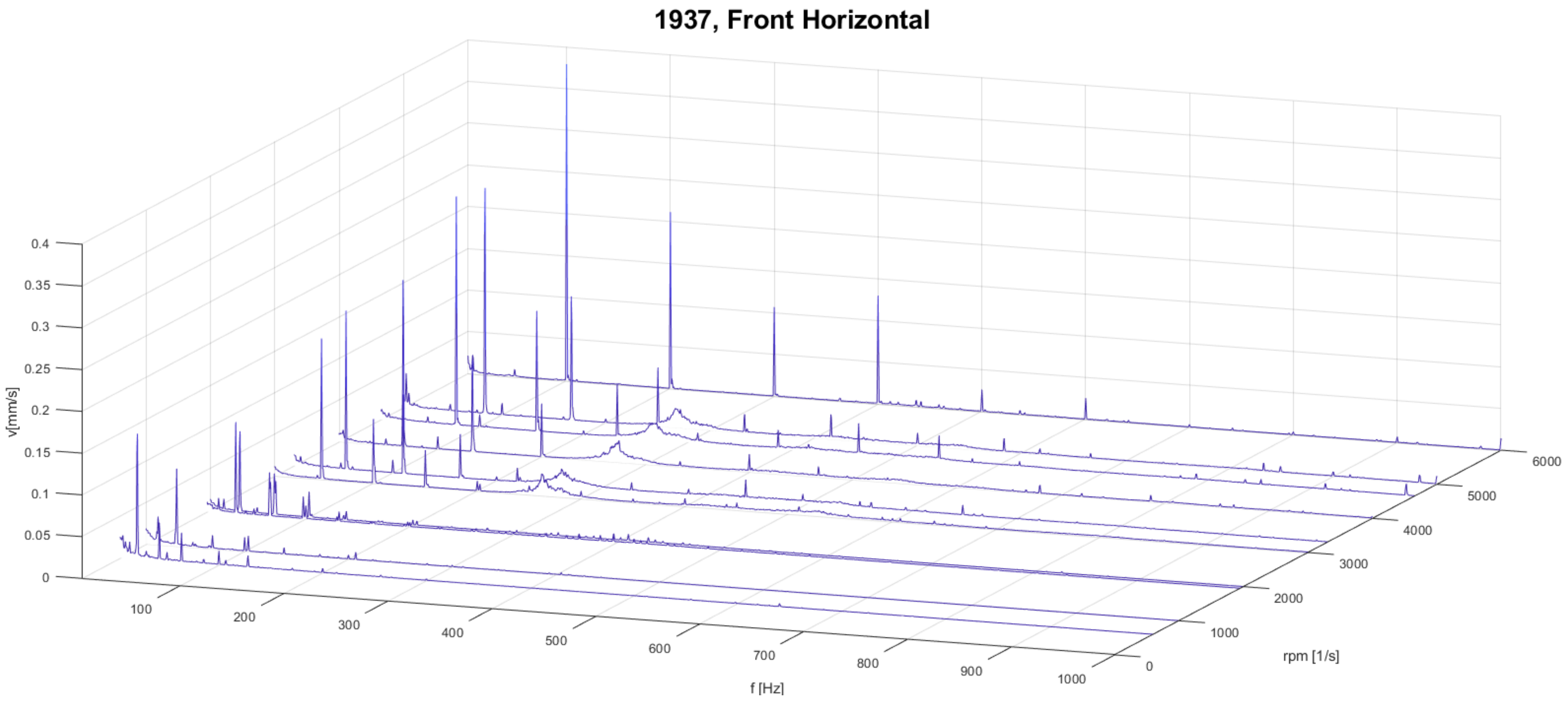

2003, Rear Vertical
v[mm/s]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
f [Hz]
100
200
300
400
500
600
700
800
900
1000
rpm [1/s]
0
1000
2000
3000
4000
5000
6000

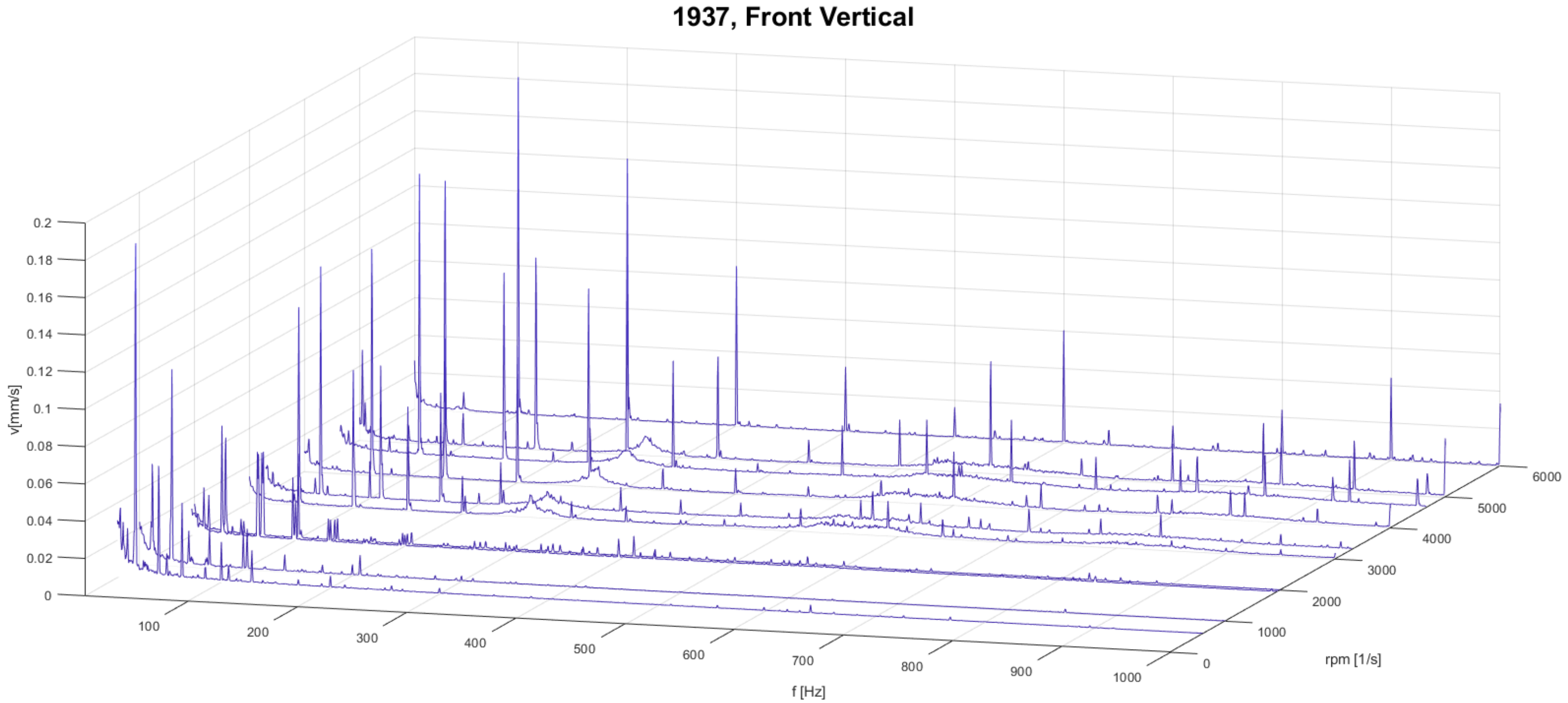

2005, Front Horizontal
v[mm/s]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
f [Hz]
100
200
300
400
500
600
700
800
900
1000
rpm [1/s]
0
1000
2000
3000
4000
5000
6000

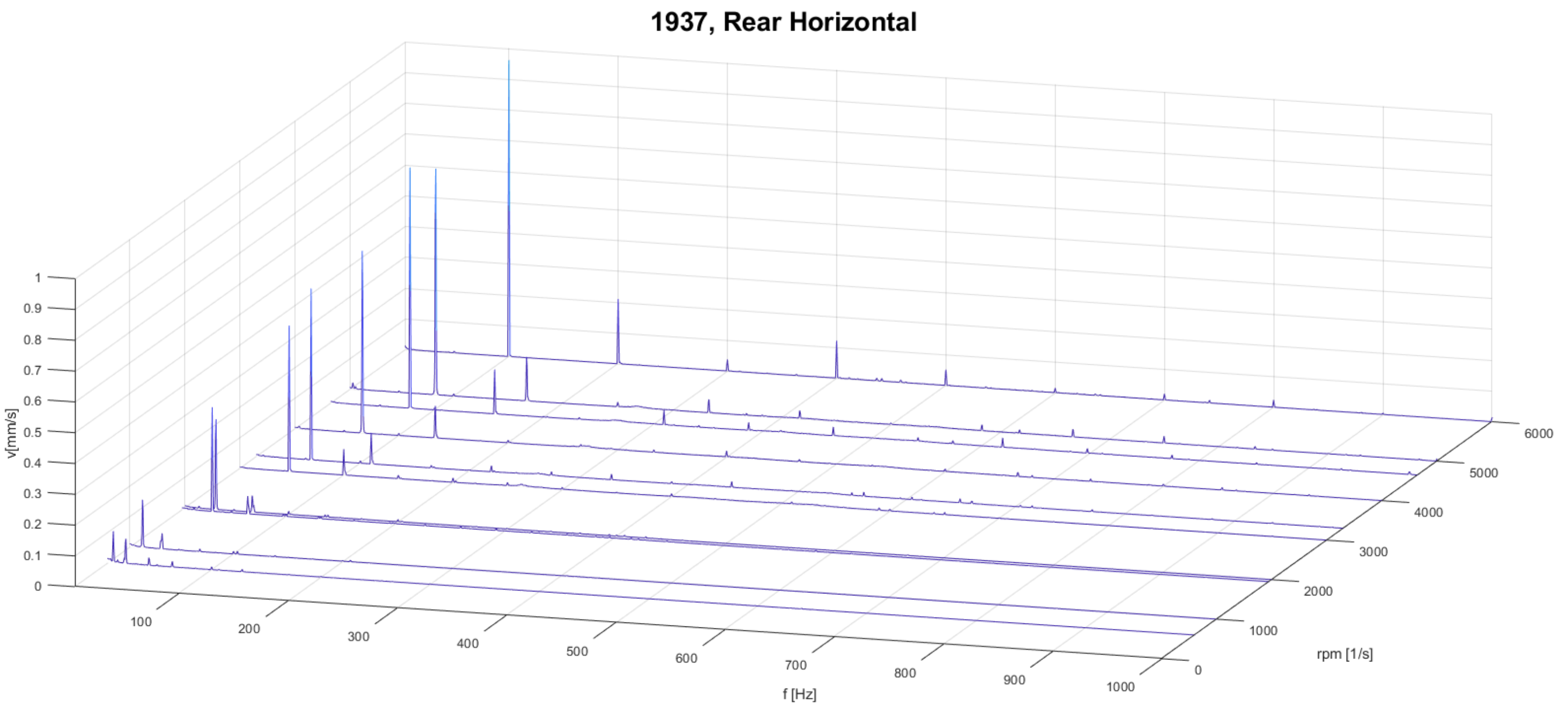

2005, Front Vertical
v[mm/s]
0.25
0.2
0.15
0.1
0.05
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

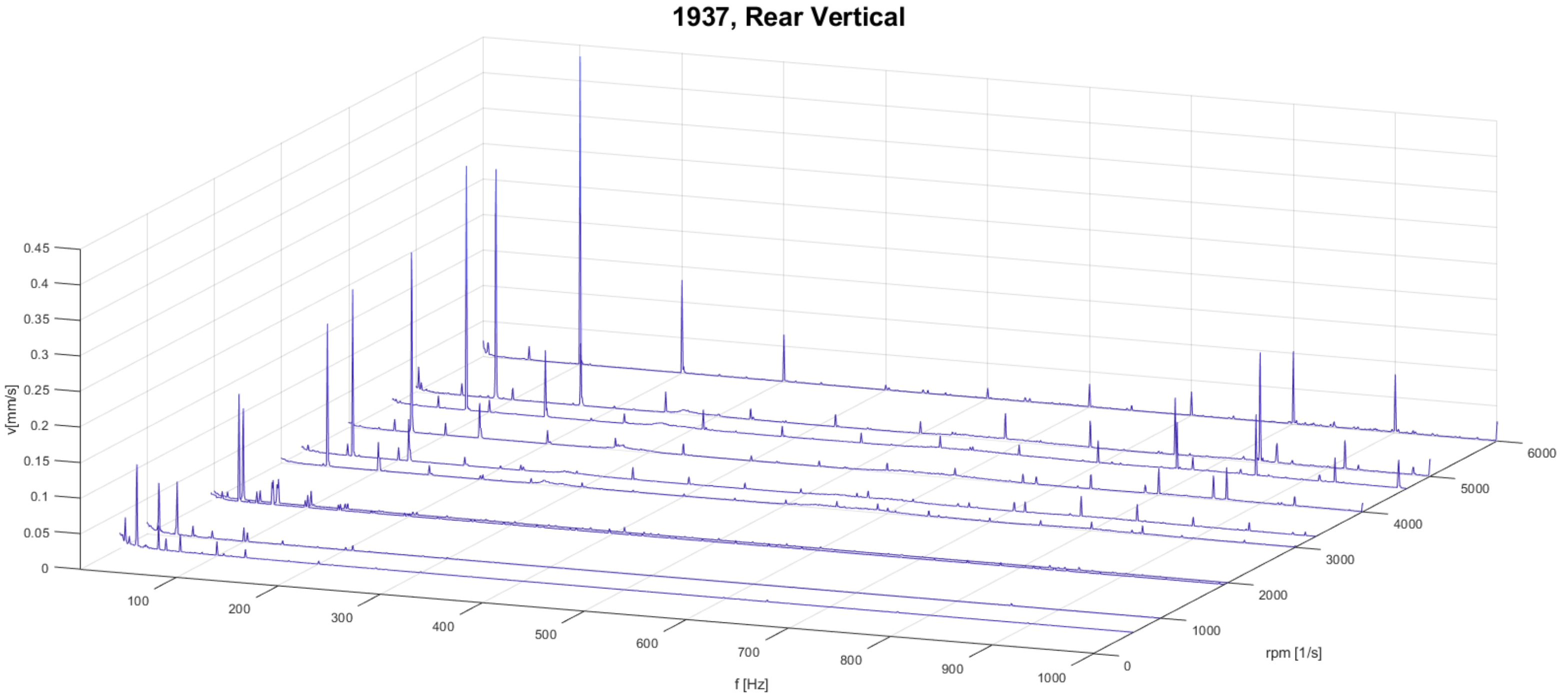

2005, Rear Horizontal
v[mm/s]
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]


2005, Rear Vertical
v[mm/s]
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
f [Hz]
100
200
300
400
500
600
700
800
900
1000
rpm [1/s]
0
1000
2000
3000
4000
5000
6000

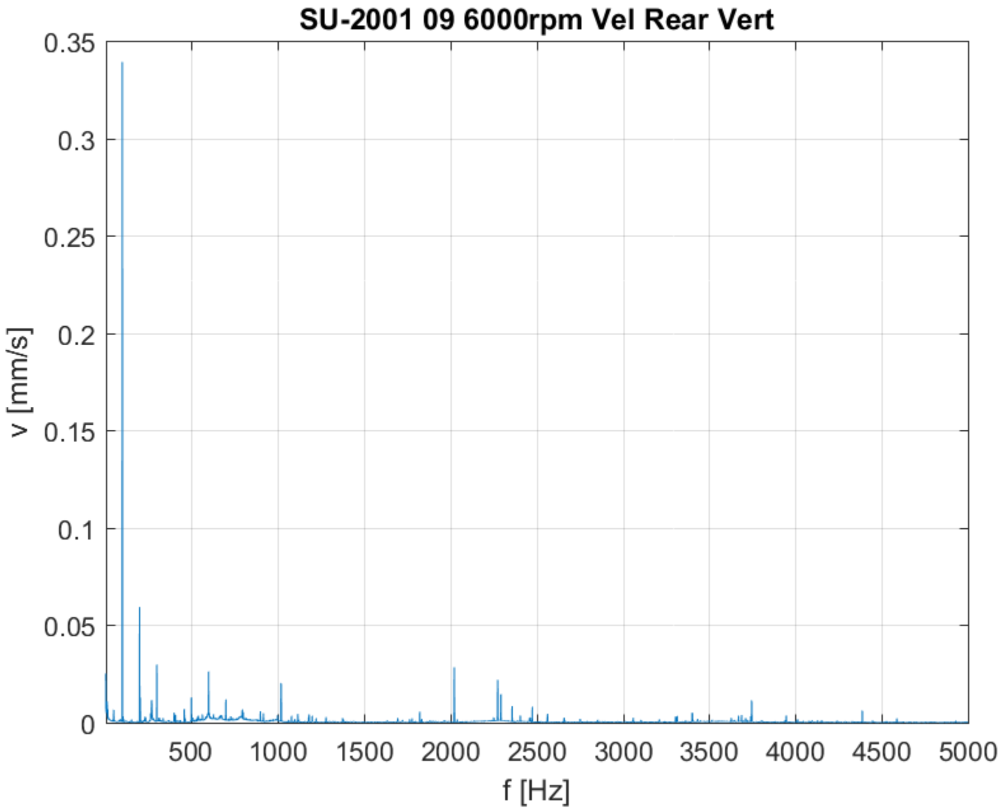

1937, Front Horizontal
v[mm/s]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

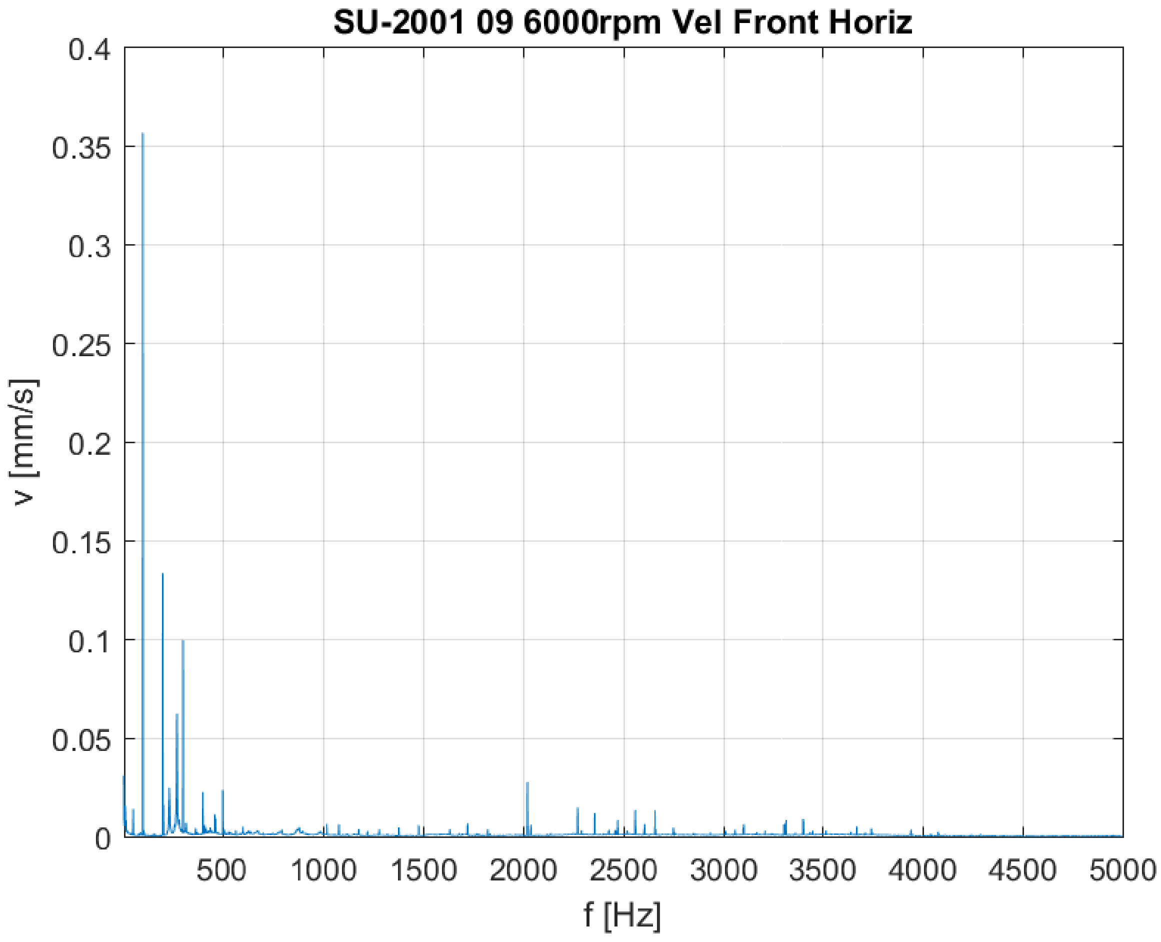

1937, Front Vertical
v[mm/s]
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
f [Hz]
100
200
300
400
500
600
700
800
900
1000
rpm [1/s]
0
1000
2000
3000
4000
5000
6000

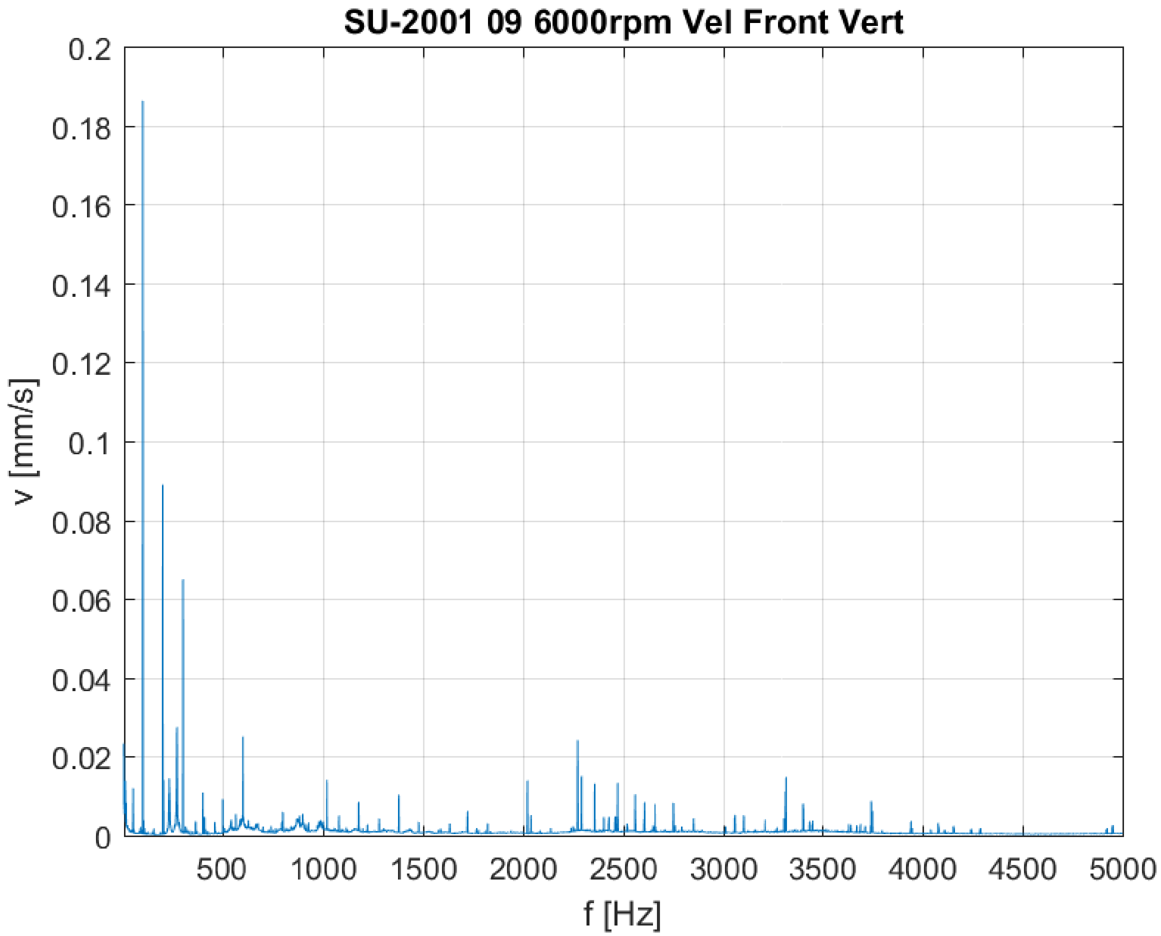

1937, Rear Horizontal
v[mm/s]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

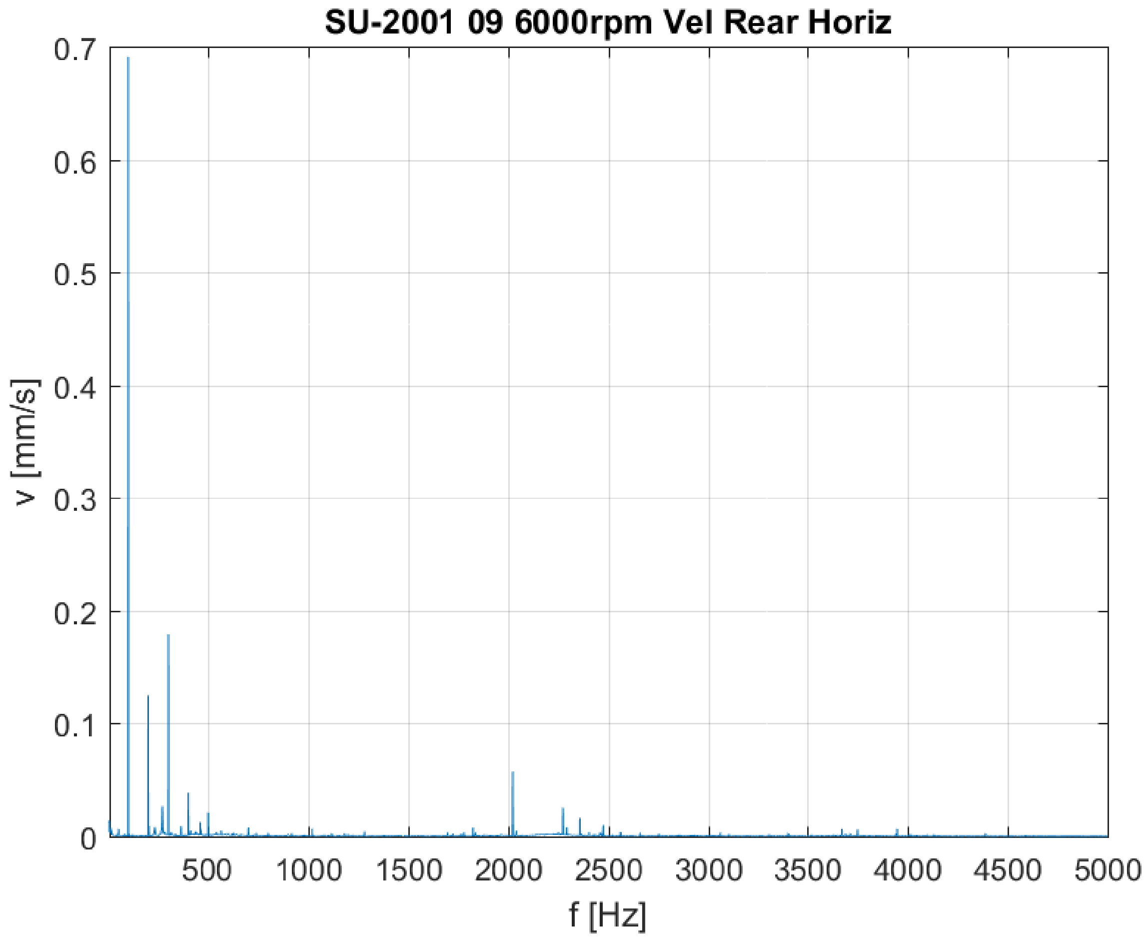

1937, Rear Vertical
v[mm/s]
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
200
300
400
500
600
700
800
900
1000
f [Hz]
0
1000
2000
3000
4000
5000
6000
rpm [1/s]

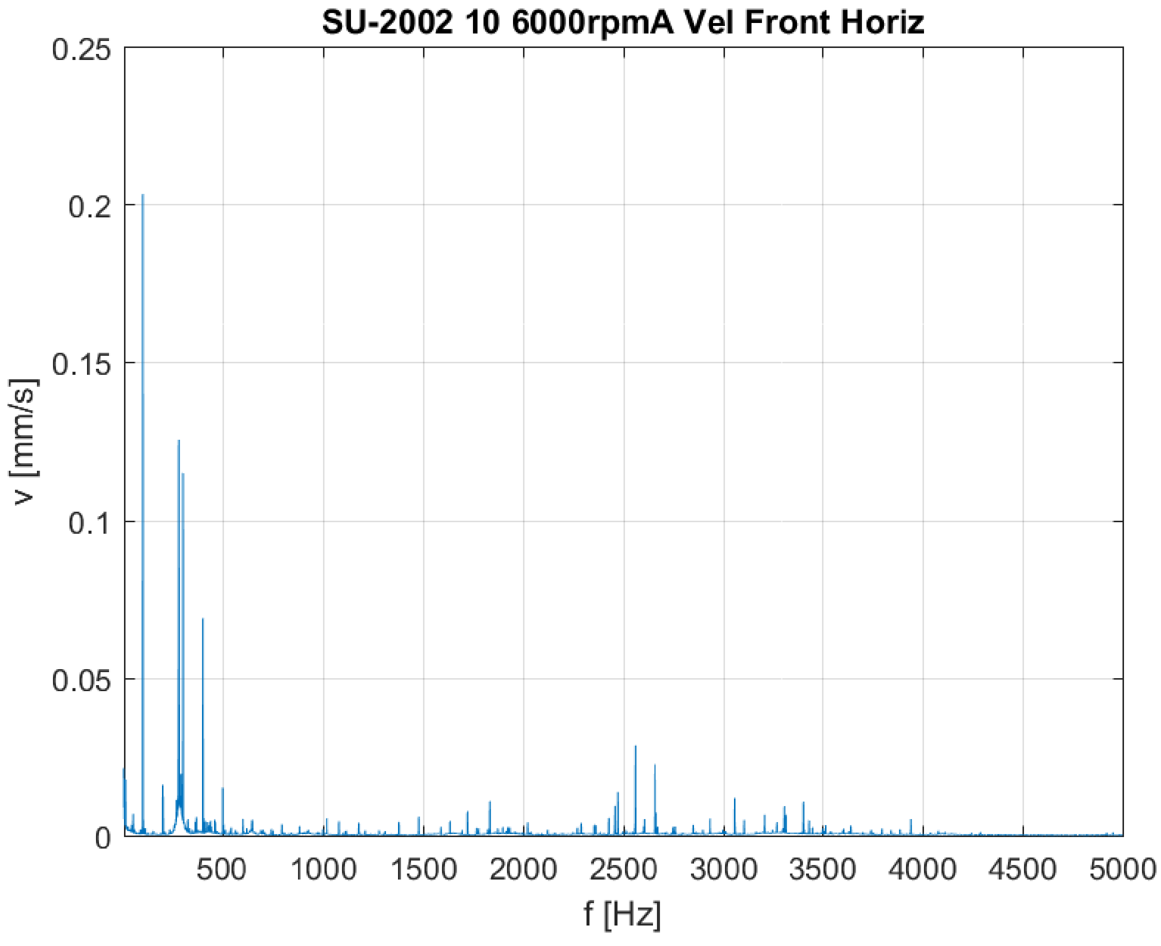
Appendix 5. Selected frequency spectra

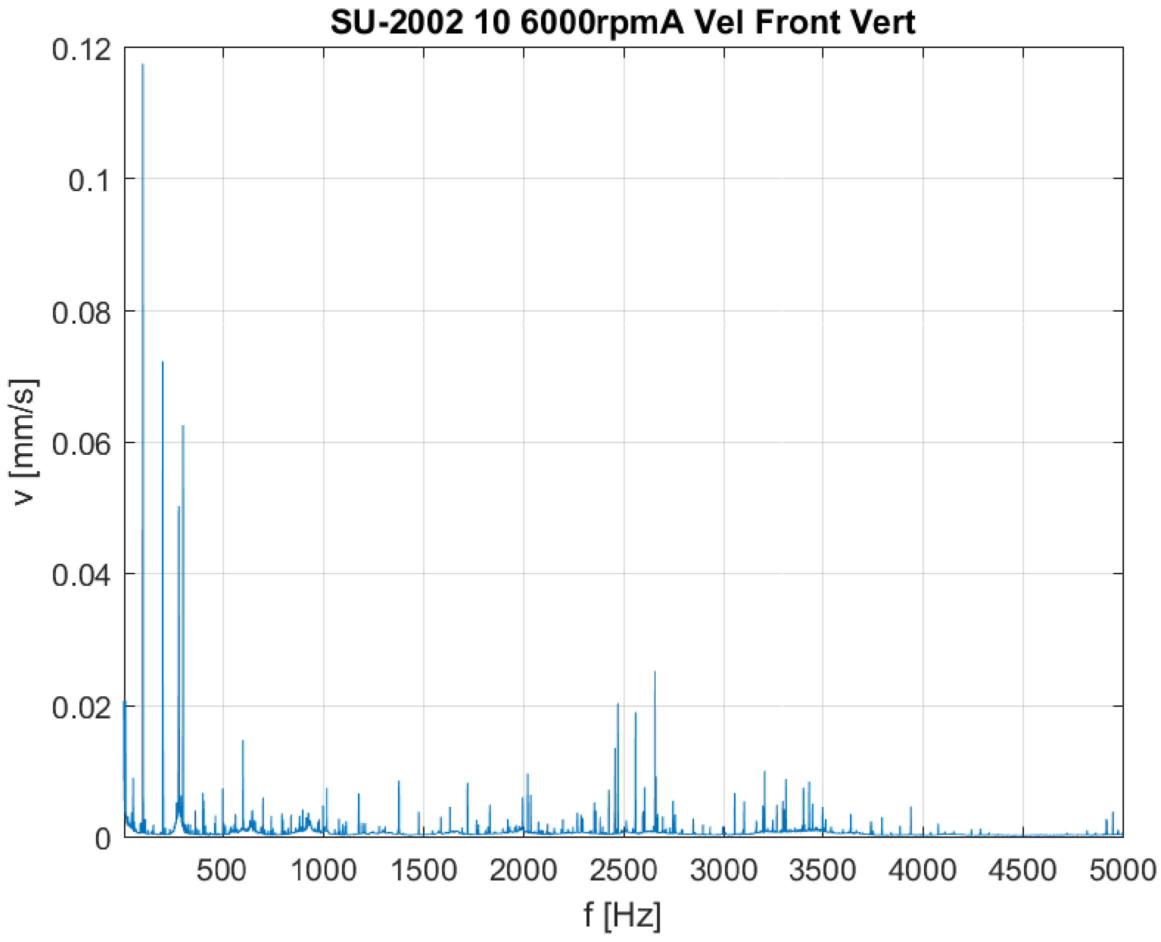


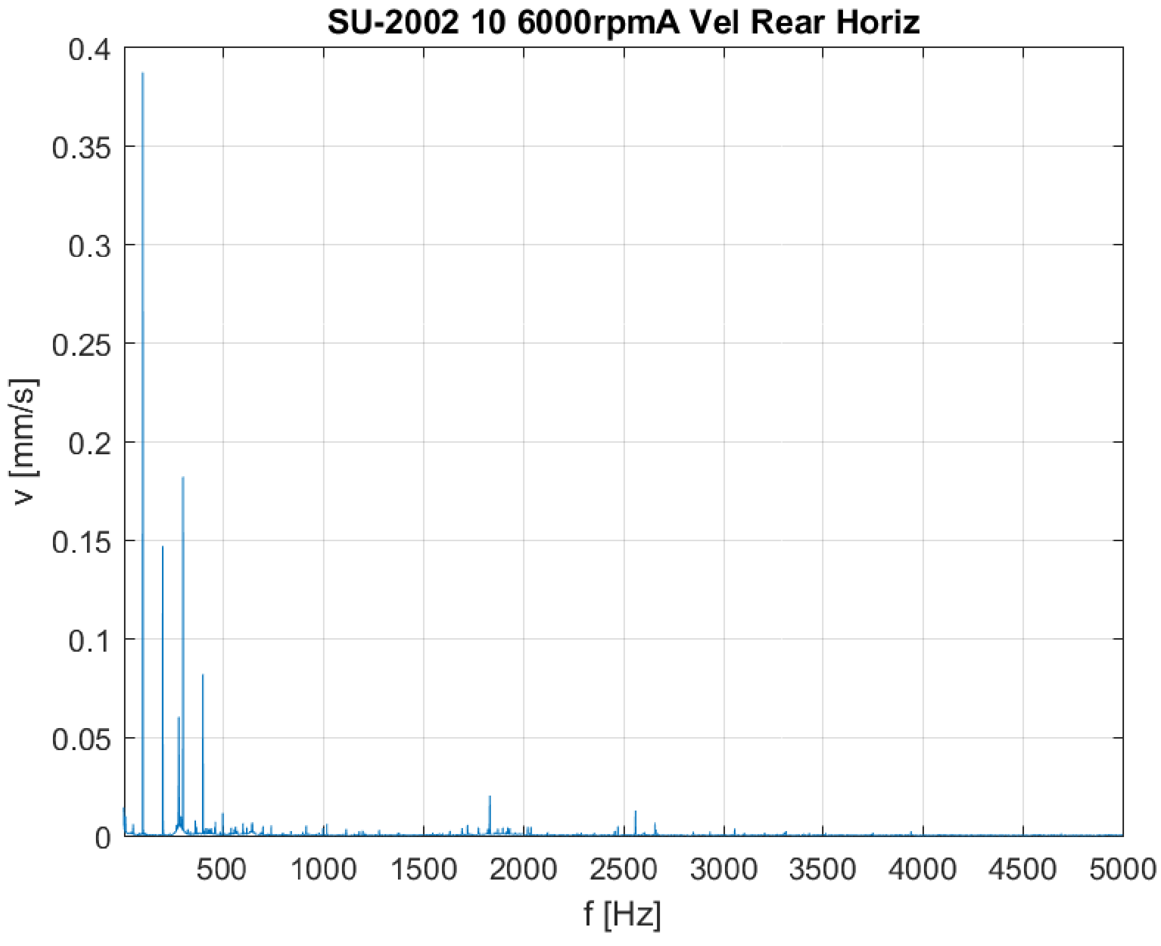

SU-2001 09 6000rpm Vel Front Horiz
v [mm/s]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

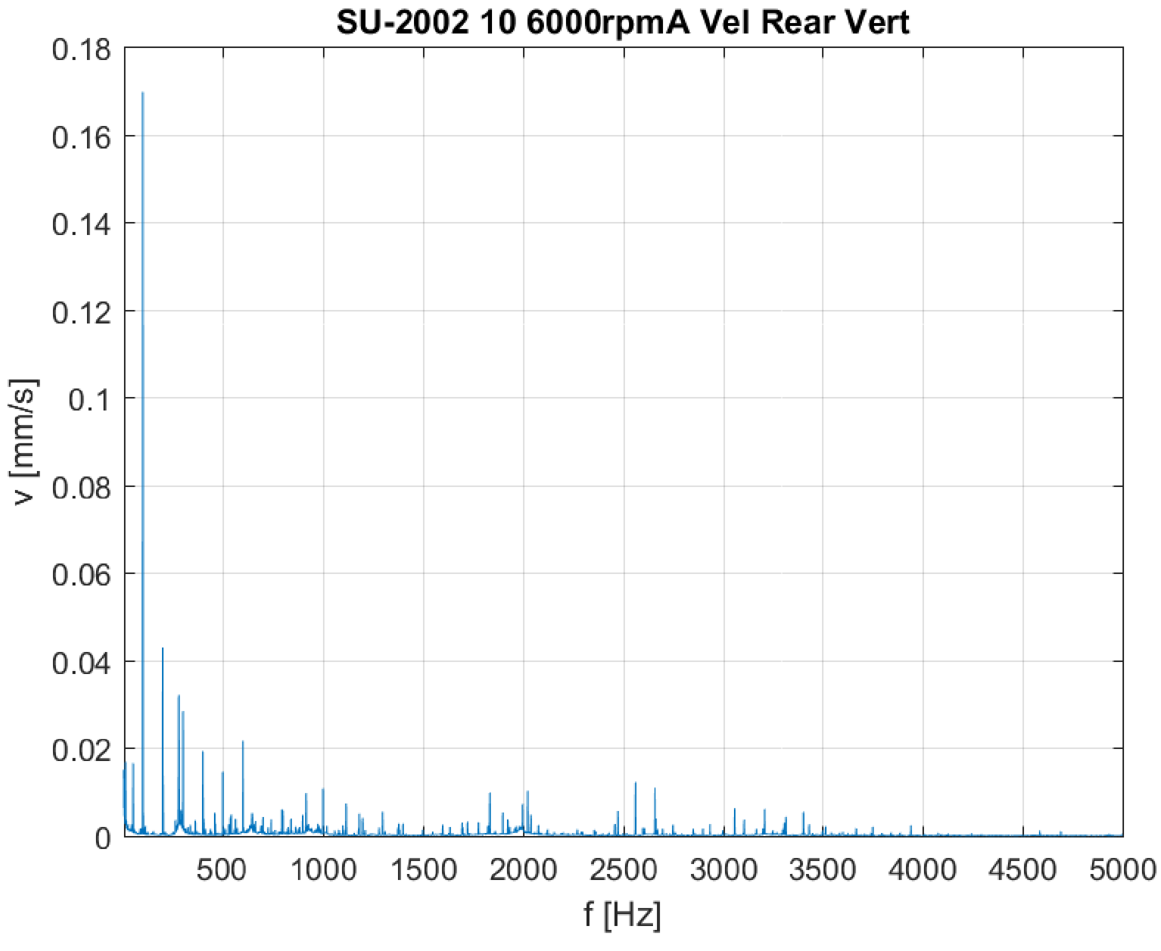

SU-2001 09 6000rpm Vel Front Vert
v [mm/s]
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

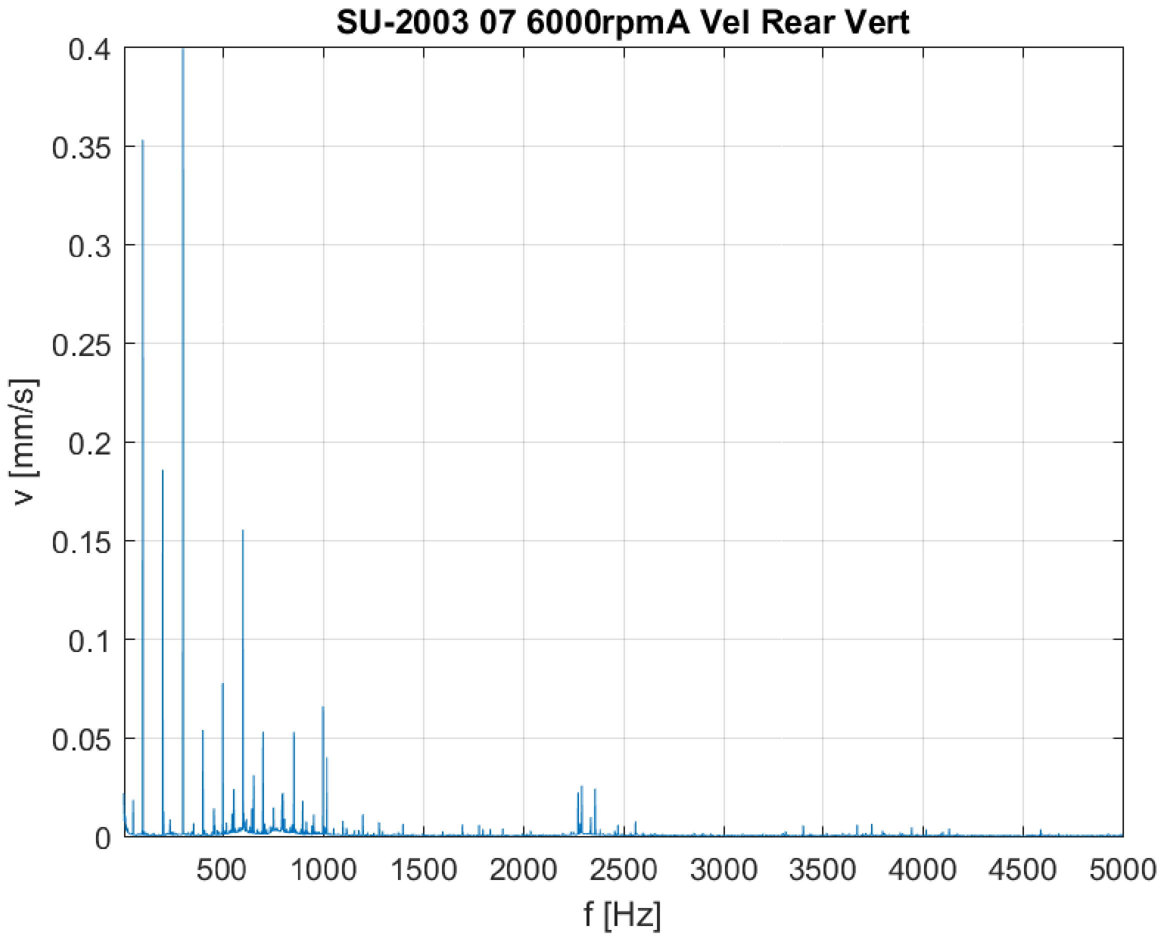

SU-2001 09 6000rpm Vel Rear Horiz
v [mm/s]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

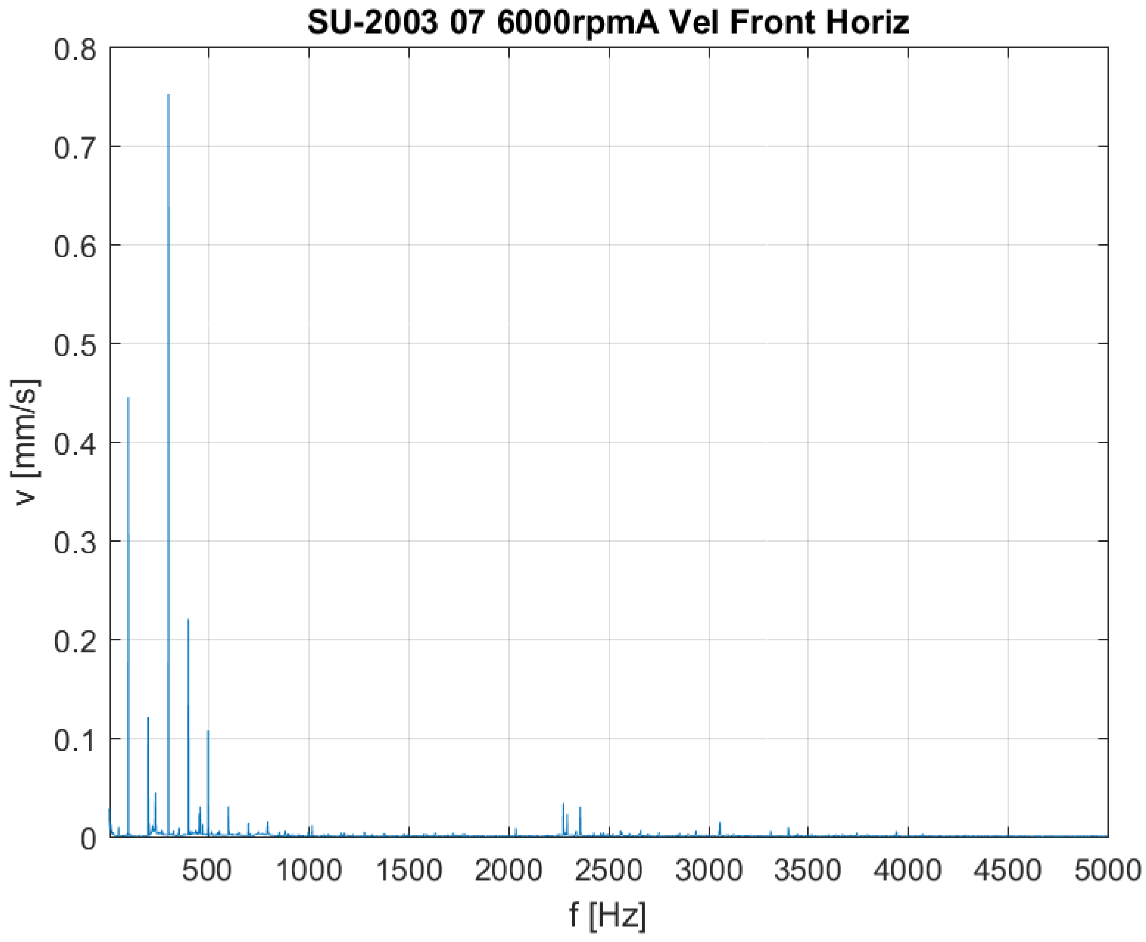

SU-2002 10 6000rpmA Vel Front Horiz
0.25
0.2
0.15
0.1
0.05
0
v [mm/s]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

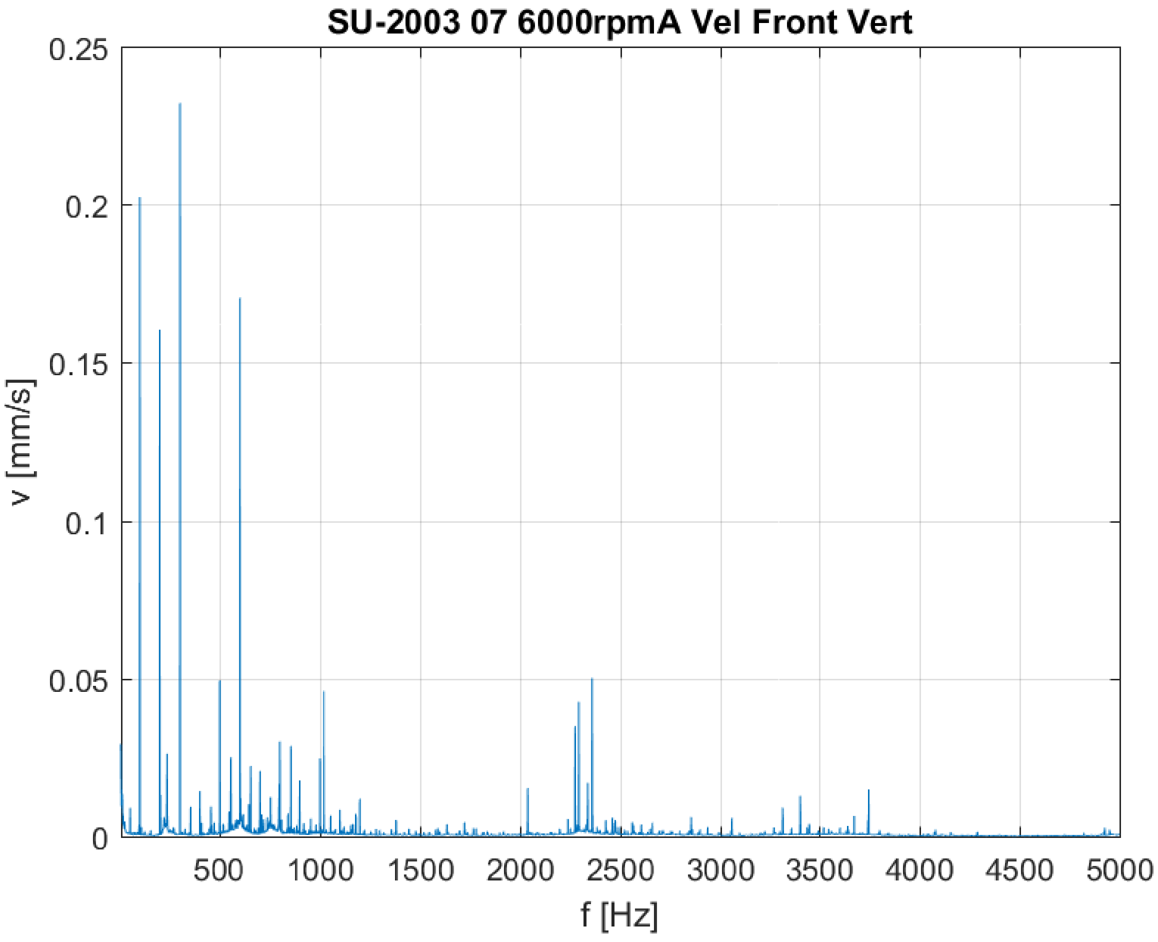

SU-2002 10 6000rpmA Vel Front Vert
0.12
0.1
0.08
0.06
0.04
0.02
0
v [mm/s]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

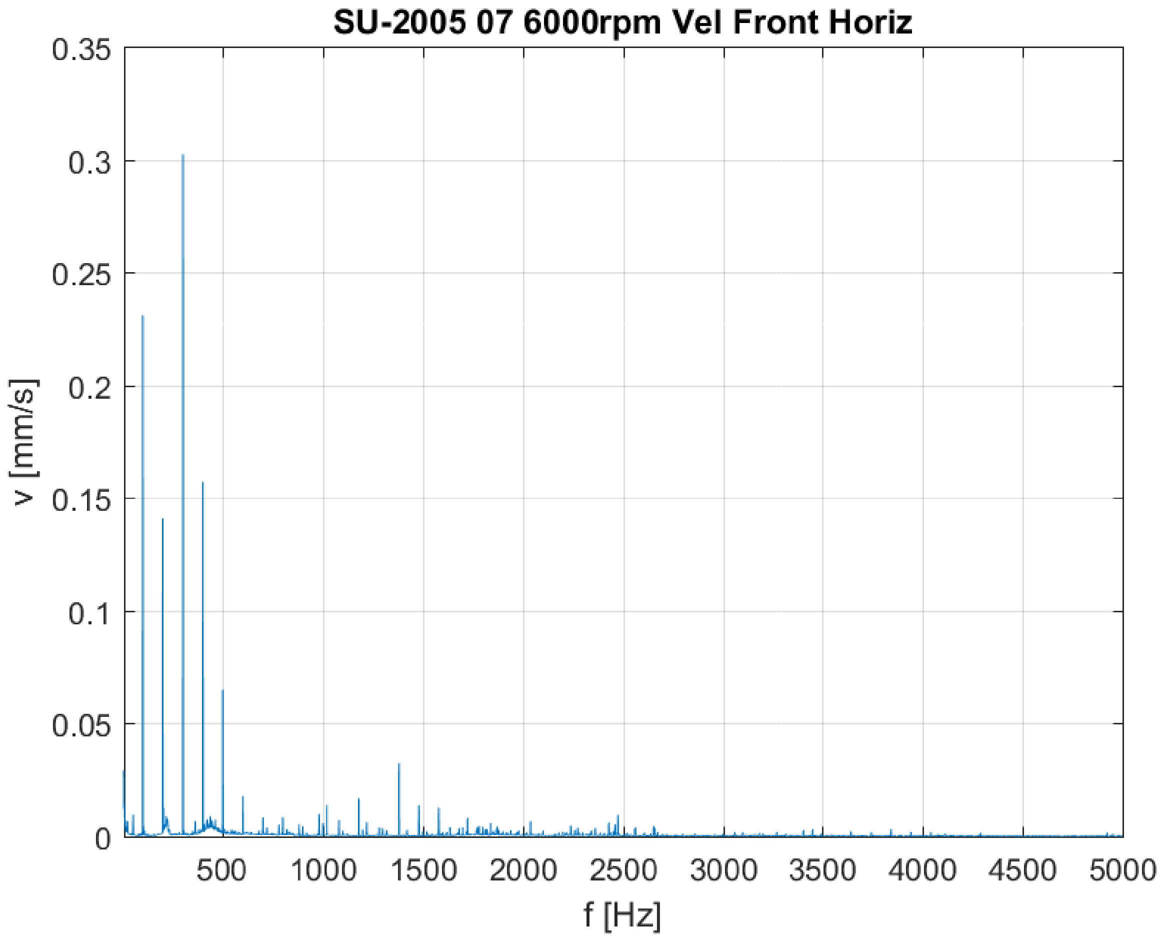

SU-2002 10 6000rpmA Vel Rear Horiz
v [mm/s]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

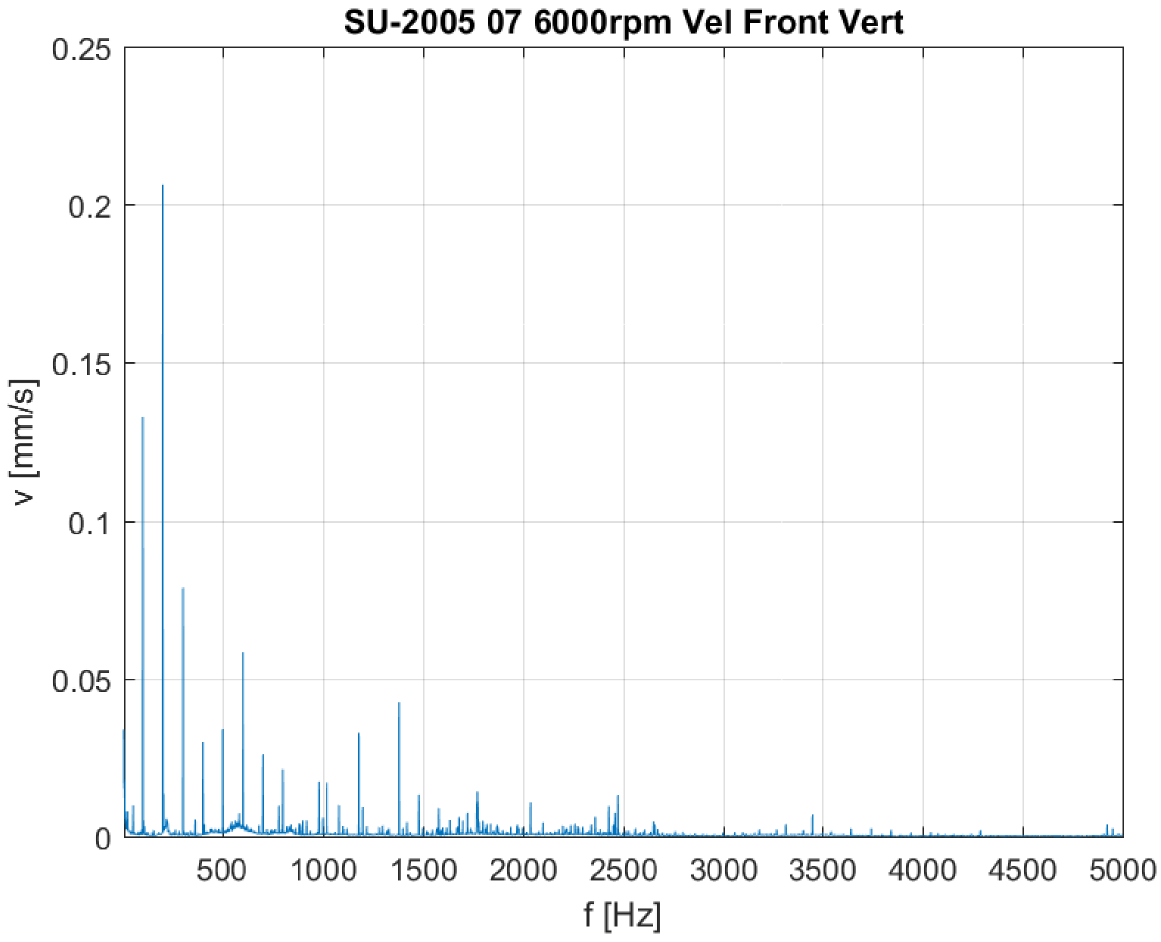

SU-2002 10 6000rpmA Vel Rear Vert
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
v [mm/s]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

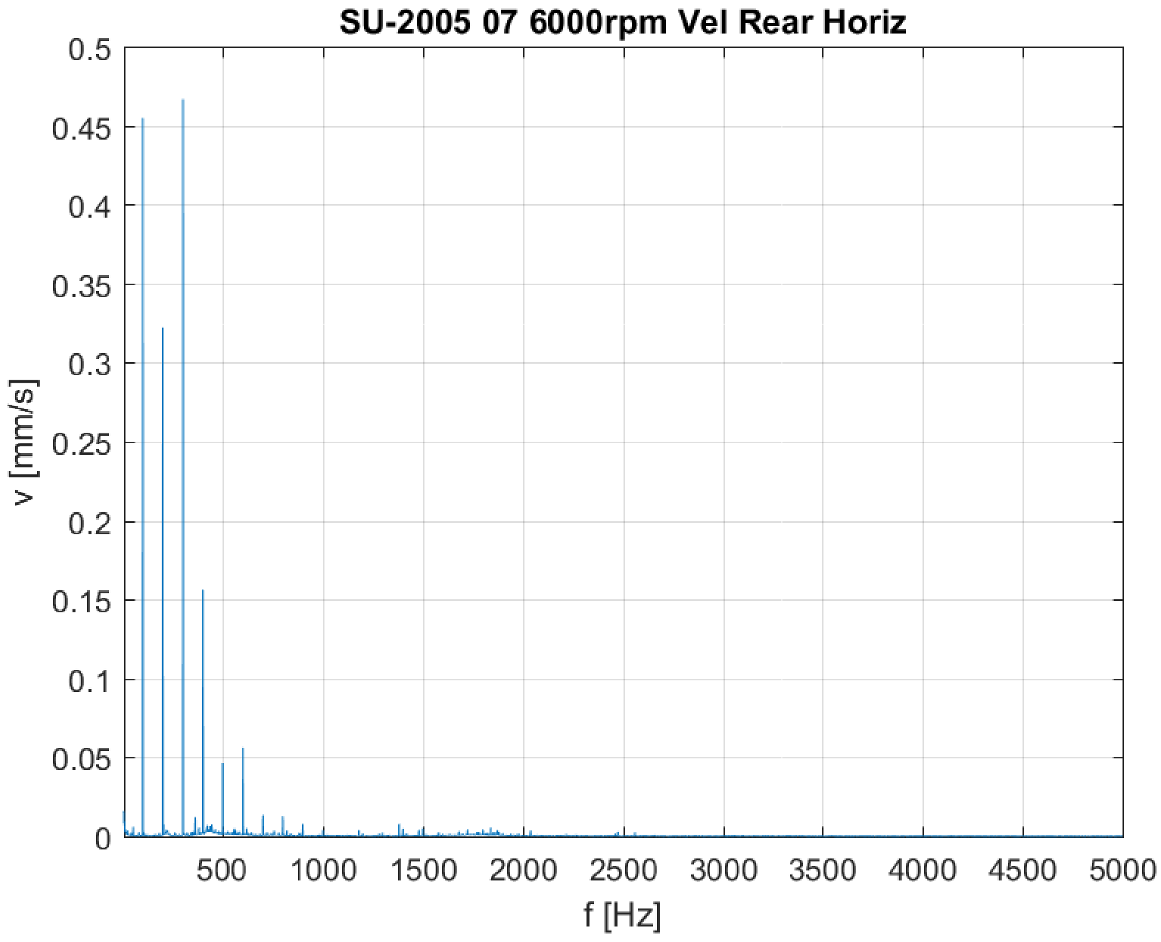

SU-2003 07 6000rpmA Vel Rear Vert
v [mm/s]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
f [Hz]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

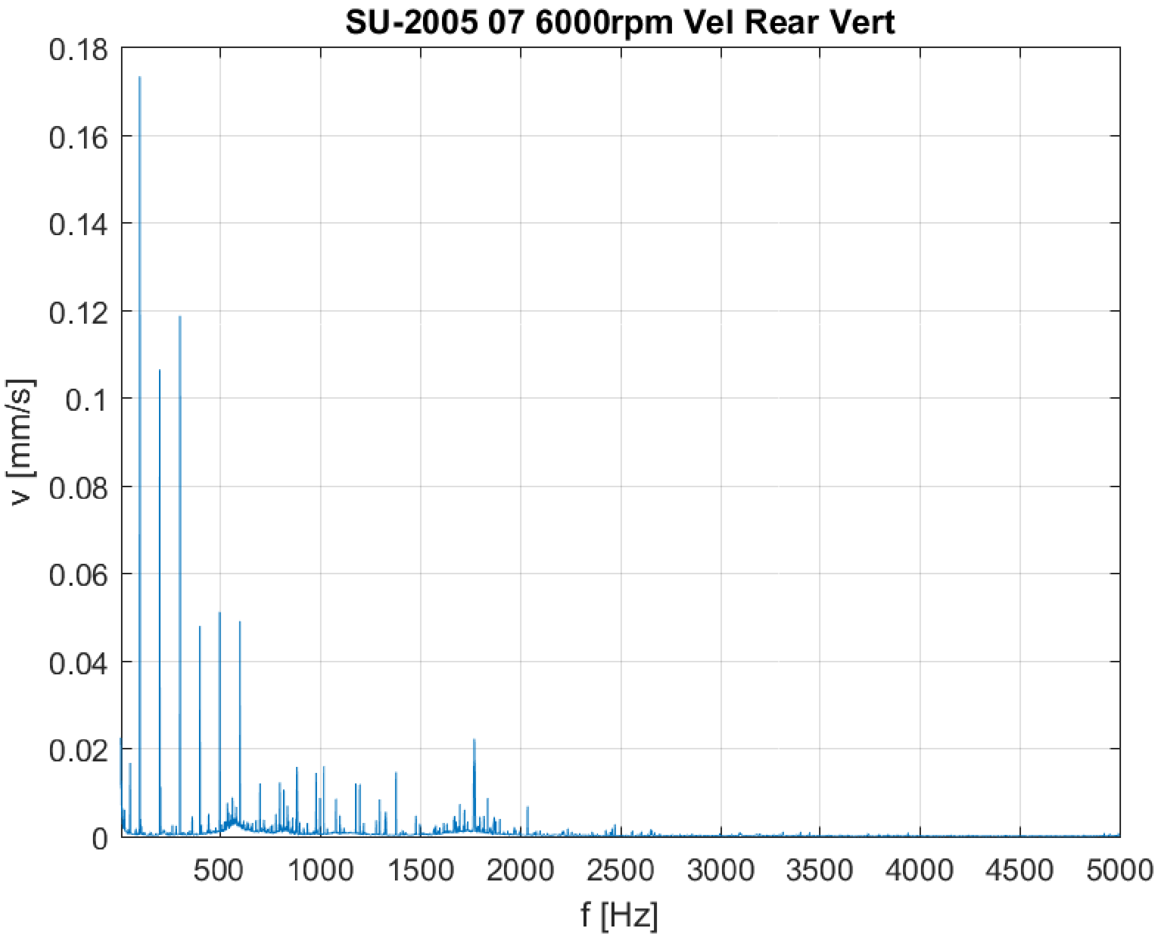

SU-2003 07 6000rpmA Vel Front Horiz
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
v [mm/s]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

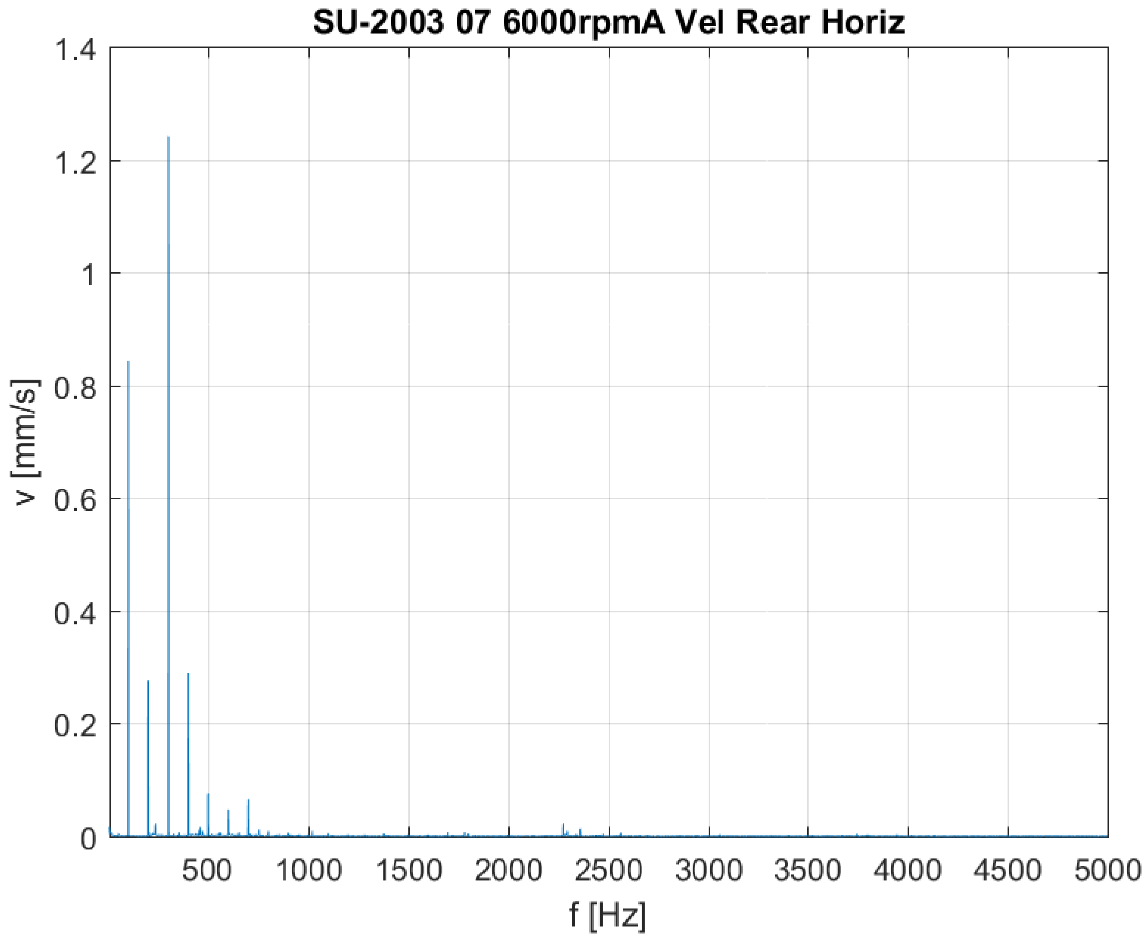

SU-2003 07 6000rpmA Vel Front Vert
0.25
0.2
0.15
0.1
0.05
0
v [mm/s]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

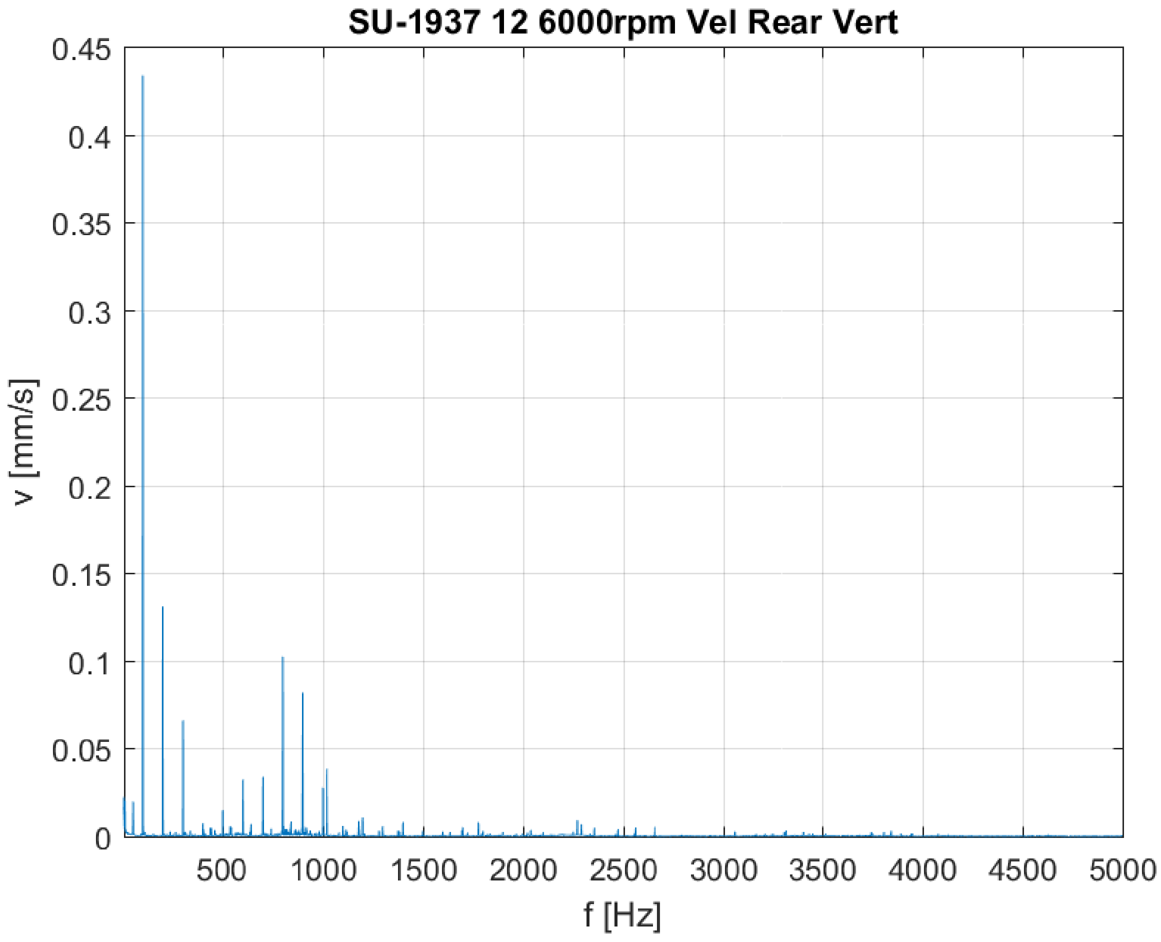

SU-2005 07 6000rpm Vel Front Horiz
v [mm/s]
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

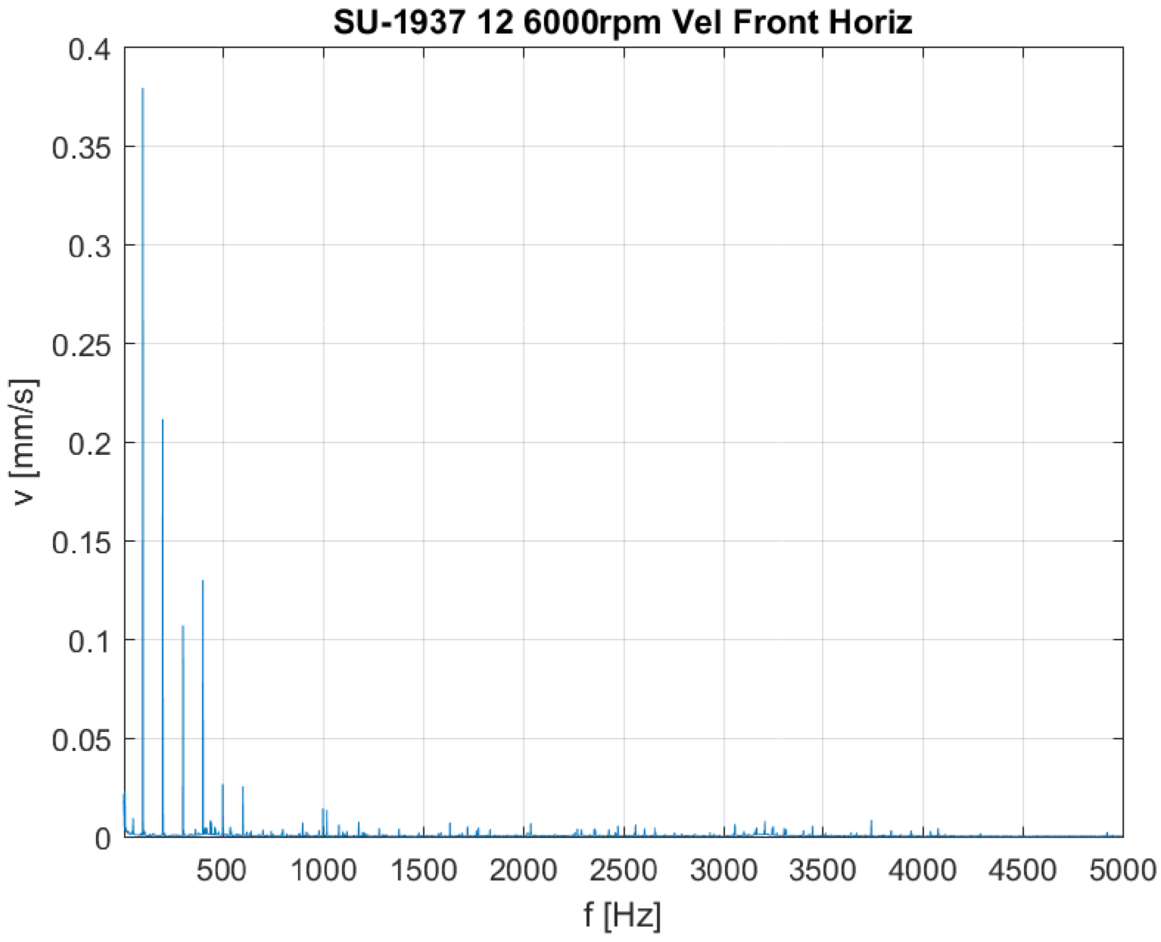

SU-2005 07 6000rpm Vel Front Vert
0.25
0.2
0.15
0.1
0.05
0
v [mm/s]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

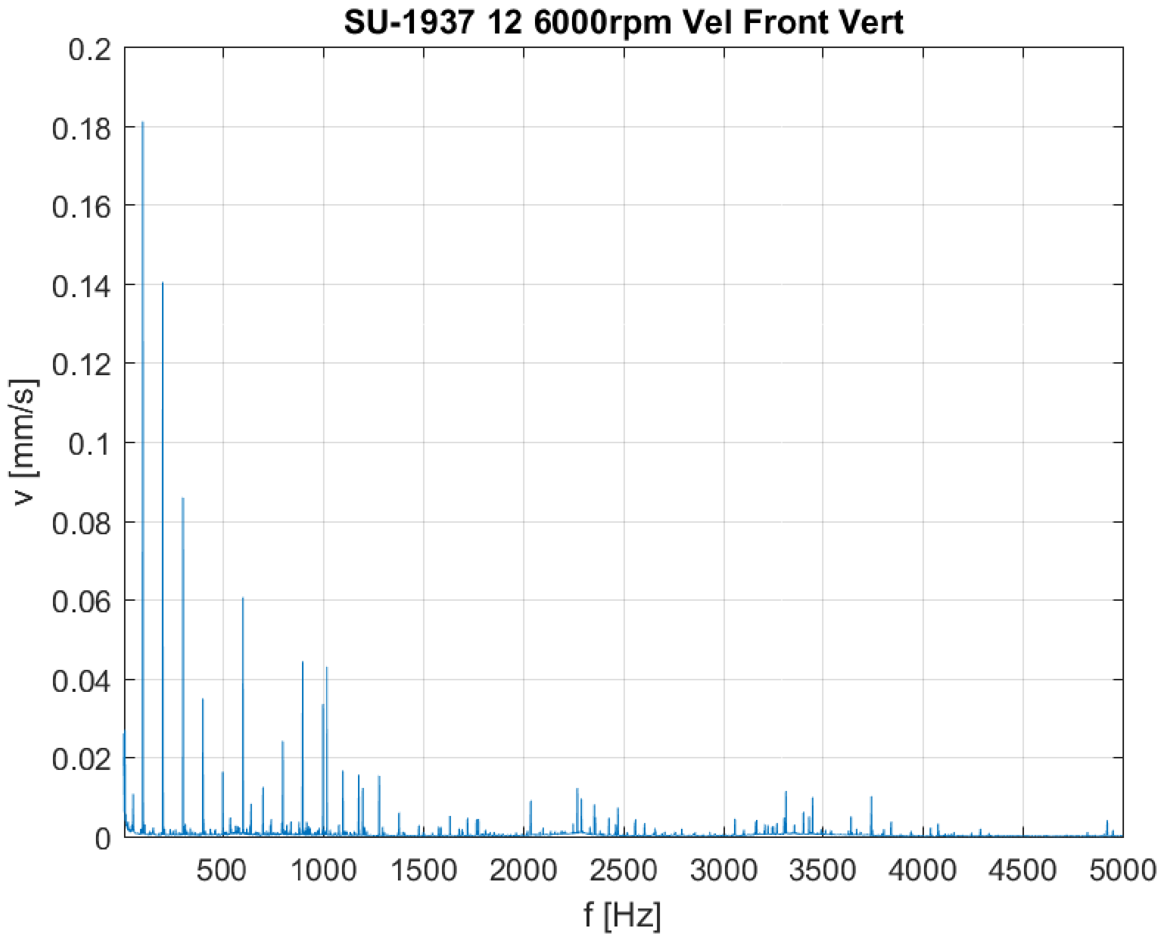

SU-2005 07 6000rpm Vel Rear Horiz
v [mm/s]
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]

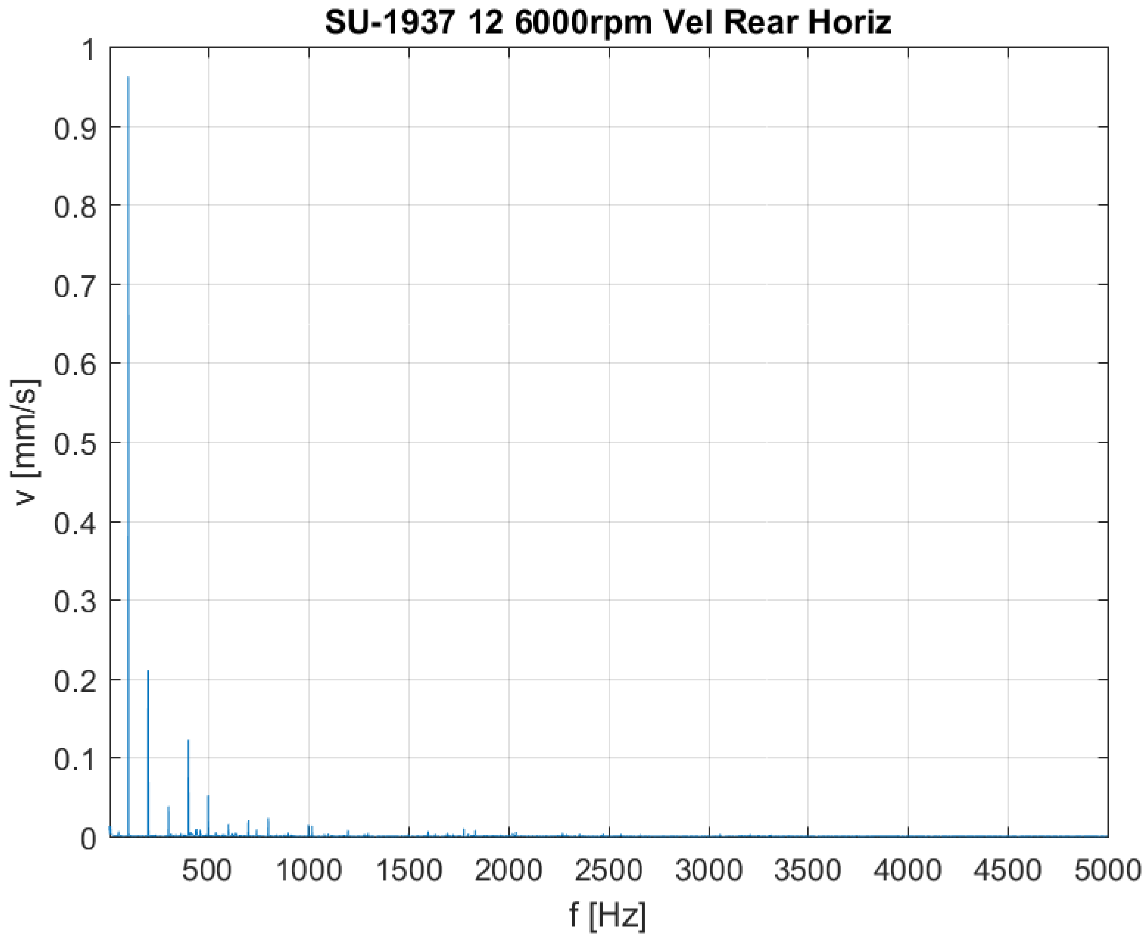

SU-2005 07 6000rpm Vel Rear Vert
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
v [mm/s]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]


SU-2003 07 6000rpmA Vel Rear Horiz
v [mm/s]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]


SU-1937 12 6000rpm Vel Rear Vert
v [mm/s]
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]


SU-1937 12 6000rpm Vel Front Horiz
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
v [mm/s]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]


SU-1937 12 6000rpm Vel Front Vert
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
v [mm/s]
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
f [Hz]


SU-1937 12 6000rpm Vel Rear Horiz
v [mm/s]
f [Hz]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
1000
1500
2000
2500
3000
3500
4000
4500
5000