The III International Scientific and Technical Conference
«Aeroengines of the XXI century»

TRANZIT

Dynamics of the rotor system, supported by the active magnetic bearings

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Active magnetic bearings

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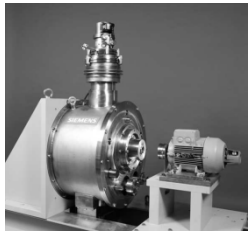
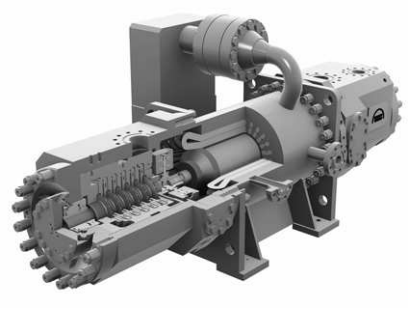
Field of application	Features of application	Problems
• high-vacuum turbo-molecular pumps • precision measuring instruments, gyroscopes, test desks etc. • centrifugal compressors • grinding and milling spindles • balancing machines • flywheels for energy accumulation • gas generators • pump stations	• absence of lubrication and wear • absence of contact and contamination • active control of stiffness and damping • rotation speed(up to 800 000 rpm) • low noise level • precision of rotor axis position (up to 0.5 μ m) • work in extreme conditions (high-vacuum, zero gravity, variable temperatures)	• limited bearing capacity • high objective power • high heat generation • high weight • control system is required

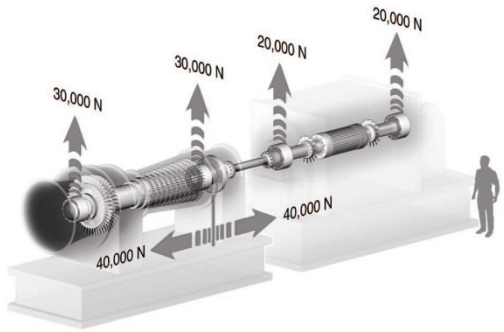
The turbo-blower for cooling a laser (CO_2). Speed is 54000 rpm , the rotor mass is 3.6 kg, the motor power is 12 kW, the radial bearing diameter is 48 mm, the bearing force is 230 N (TRUMPF/MECOS).



The synchronous generator supported by the superconductive magnetic bearings. Temperature is 28K, maximum speed is 4500 rpm (SIEMENS).

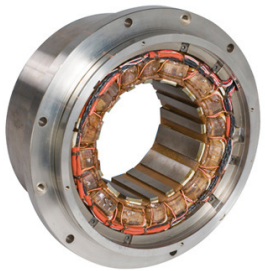


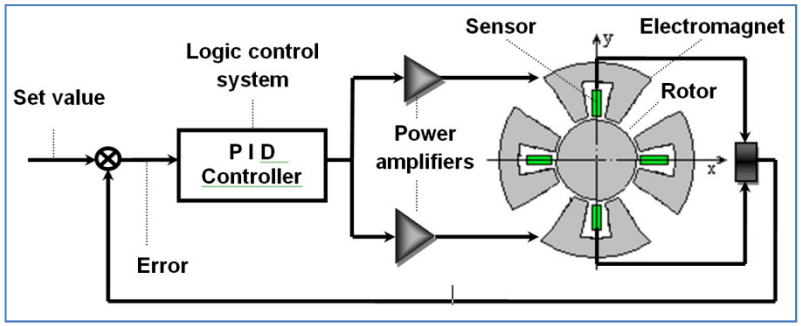
The compressor HOFIM for pumping natural gas: integration of the direct drive and the magnetic bearing in the turbomachine, 6 MW, 9000 rpm (MAN Turbo/S2M).



The gas-turbine generator: 4 radial bearings and 1 thrust bearing, 6010 rpm, 9000 kW, the bearing diameter is 400 mm (S2M).

The modulus – The magnetic bearing– for the rotor dynamics tasks





Magnetic force:

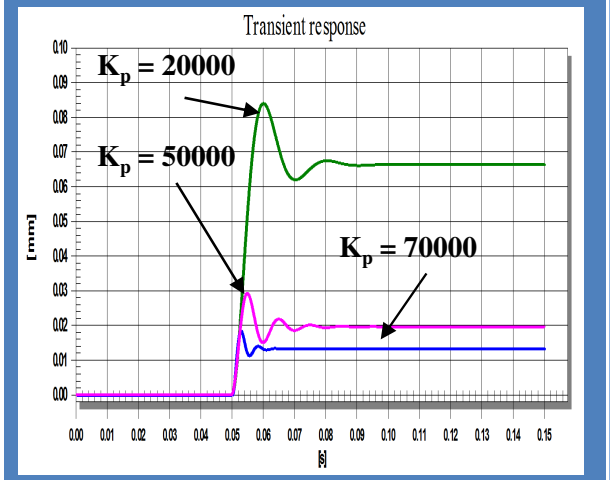
$$F = \frac{\mu_0 N^2 A_\delta}{4}\left(\frac{{I_1}^2}{(\delta - y)^2} - \frac{{I_2}^2}{(\delta + y)^2}\right)$$

PID-controller:

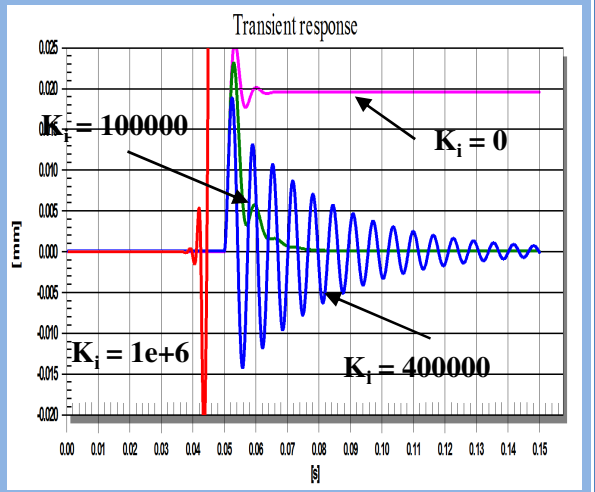
$$I(t) = P + I + D$$

$$I(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de}{dt}$$

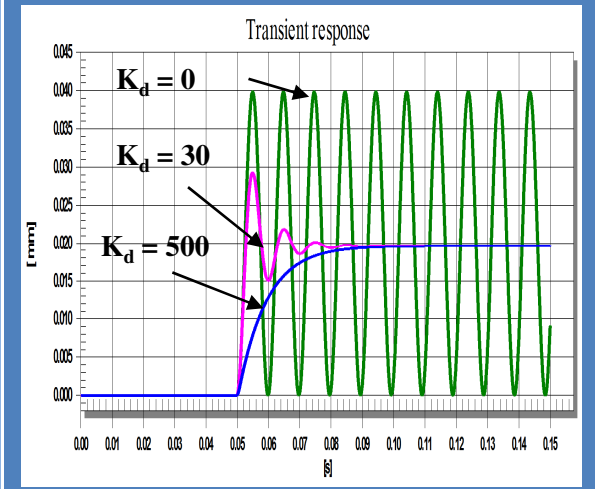
$K_i = 0$ K_d = const
K_p = var



K_p = const K_d = const
K_i = var



$K_i = 0$ K_p = const
K_d= var



The DYNAMICS R4 software for the rotor system analysis and design in the unsteady and non-linear approach

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DYNAMICS R4

САТУРН НПО

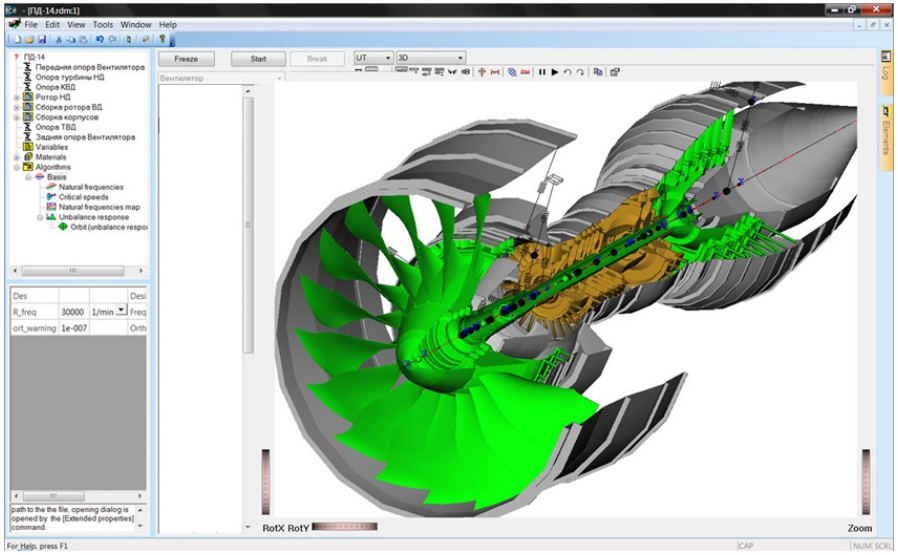
НПО ЭНЕРГОМАШ ИМ. АКАДЕМИКА В.П. ГЛУШКО

СОЮЗ

ОАО „А.Люлька-САТУРН“

SCHAEFFLER GRUPPE INA

MAGELLAN AEROSPACE CORPORATION



ЗОРЯ-МАШПРОЕКТ

KIMM KOREA INSTITUTE OF MACHINERY & MATERIALS

САЛЮТ

CHERNYSHEV

DOOSAN

АВИАДВИГАТЕЛЬ

SAMSUNG TECHWIN

Integration of the "Magnetic bearing" modulus into Dynamics R4

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Any types of dynamic loads – internal and external– F(t)

Dynamic model of the rotor system
Dynamics R4

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\} + \{R\}$$

$\{u\}, \{\dot{u}\}$

$\{R\}$

Model of non-linear link (for example, AMB)

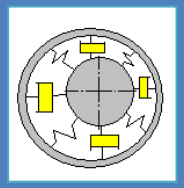
$$\{R\} = K\{u\} + C\{\dot{u}\} + I\int\{u\}$$

$$K = \frac{\mu_0 N^2 A_g I_b}{\delta_0^2}\left(\frac{I_b}{\delta_0} + K_p\right) \quad C = \frac{\mu_0 N^2 A_g I_b}{\delta_0^3} K_d \quad I = \frac{\mu_0 N^2 A_g I_b}{\delta_0^3} K_i$$

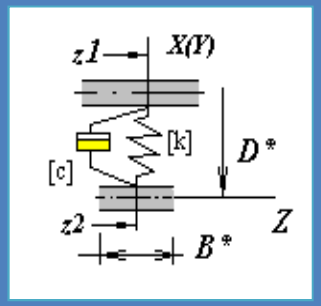
The elements for the rotors simulation in Dynamics R4

Spring link

Representation



Model

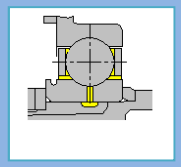


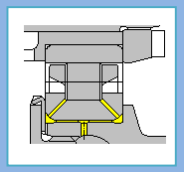
Initial data

Des	Front support		Designation
conn_type	via body		Type of connection
side1_subs	Subsystem 1		Side1 subsystem
side1_l	0	mm	side1 offset
side2_subs			Side2 subsystem
trns_exclude	yes		Exclude from transient analysis
Type	Isotropic		Link type
stiff_matrix	...		Stiffness matrix
damp_matrix	...		Damping matrix
d*	0	mm	Inner diameter
D*	200	mm	Outer diameter
B*	100	mm	width

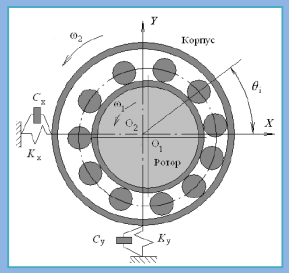
Ball and roller bearings

Representation





Model

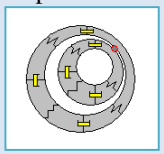


Initial data

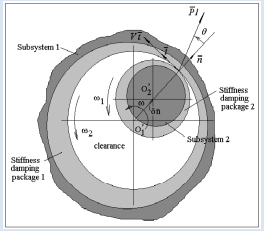
Des	Ball Bearing support 3		Designation
conn_type	via body		Type of connection
side1_subs	Subsystem 1		Side1 subsystem
side1_l	1	mm	side1 offset
side2_subs	Subsystem 2		Side2 subsystem
side2_l	1	mm	side2 offset
Dr	11.9062	mm	Rolling elements diameter
z	11		Rolling elements count
Di	40	mm	Inner race diameter
deltai	0	mm	Inner race clearance
deltao	0	mm	Outer race clearance
Kp_input	input		Type of Hertz stiffness input
KH	1.334e+010	N/m	Hertz stiffness
Cb	2940	N*s/m	Damping coefficient
d*	0	mm	Inner diameter
D*	0	mm	Outer diameter
B*	0	mm	width

Deflection limiter (clearance)

Representation



Model

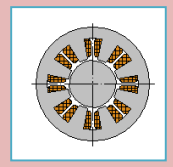


Initial data

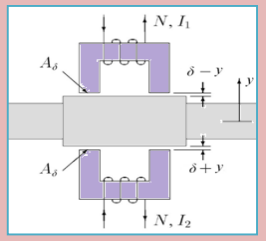
Des	Clearance 2 2		Designation
conn_type	via body		Type of connection
side1_subs			Side1 subsystem
side2_subs	Subsystem 1		Side2 subsystem
side2_l	1	mm	side2 offset
L1	0	mm	Displacement L1
L2	0	mm	Displacement L2
L3	0	mm	Displacement L3
k1	1600	N/m	Damper package 1 stiffness
c1	0	N*s/m	Package 1 damping
k2	1e+010	N/m	Damper package 2 stiffness
c2	0	N*s/m	Package 2 damping
R	50	mm	Packet radius
delta	1	mm	Radial clearance
e1	0	mm	Assembly eccentricity 1
e2	0	mm	Assembly eccentricity 2
Teta1	0	deg	Initial angle position of e1
Teta2	0	deg	Initial angle position of e2
mue	0	Ns/m2	Friction coefficient
Vsmin	0.001		Minimal slipping speed
d*	0	mm	Inner diameter
D*	5	mm	Outer diameter
B*	0	mm	width

Magnetic bearing

Representation



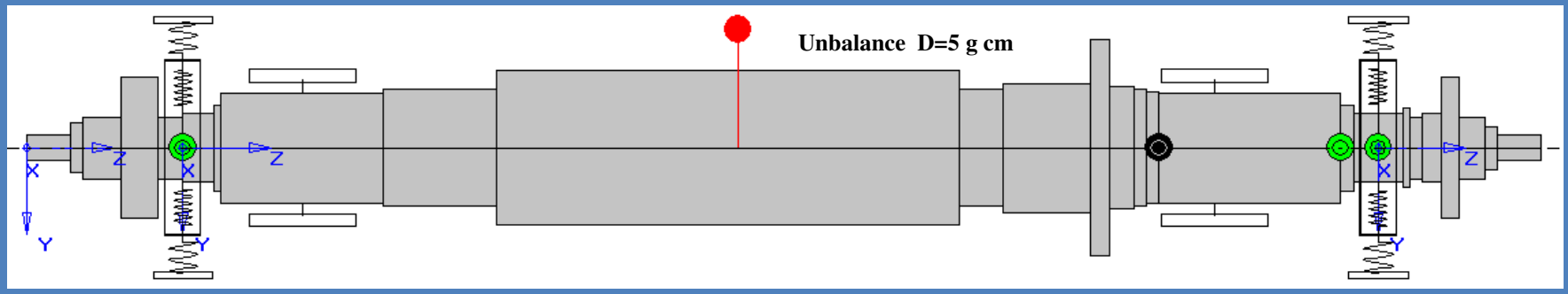
Model



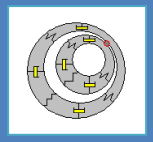
Initial data

Des	АМП1		Название
conn_type	via body		Тип подключения
side1_subs	Подсистема 1		Подсистема для сечения 1 связи
side1_l	155.316	mm	положение граничного сечения 1 связи
side2_subs			Подсистема для сечения 2 связи
Type	Изотропный		Тип связи
Opt.Type	стандарт		Режим ввода параметров
Geometry Type	Цилиндр		Тип подшипника
d1	63	mm	Внутренний диаметр слева
D	220	mm	Внешний диаметр
b	70	mm	Длина пакета стали
gap	0.4	mm	Радиальный зазор между статором и ротором
Imax	5	A	Максимальный ток в обмотке
Np	16		Число полюсов электромагнитов
Ncp	4		Число полюсов управления
Teta_CP1	0	deg	Угол поворота первого полюса управления
Coiling	полное заполнение паза		Тип обмотки
Flux direction	поперечное		Направление магнитного потока
Jmax	6	A/mm2	Максимальная плотность тока в обмотке
Controller	ПД - регулятор		Тип регулятора
Kp	50000		Пропорциональная составляющая ПИД-регул
Kd	5		Дифференциальная составляющая ПИД-регул
d*	0	mm	Внутренний диаметр
D*	0	mm	Наружный диаметр
B*	0	mm	ширина

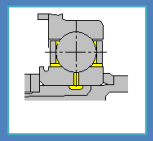
The rotor model on magnetic suspension in Dynamics R4



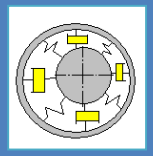
Clearance



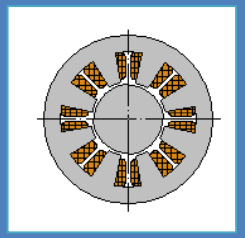
Ball bearing



Spring link with the base



AMB



Rotor parameters

Mass, m	**23.76 kg**
Length, L	**852 mm**
Moment of inertia, J_d	**0.92 kg m^2**
Nominal speed, ω	**500 Hz**

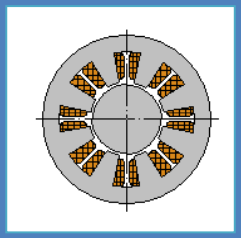
AMB parameters

Nominal stiffness, N/m	**0.5e +8**
Nominal damping, N sec/m	**6000**
Radial clearance, mm	**0.5**

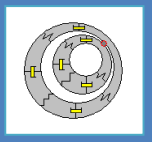
Backup bearings parameters

Stiffness, N/m	**1e+8**
Damping, N s/m	**800**
Radial clearance, mm	**0.25**

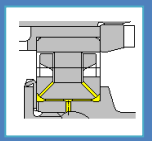
AMB



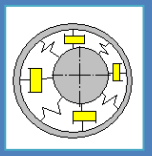
Clearance



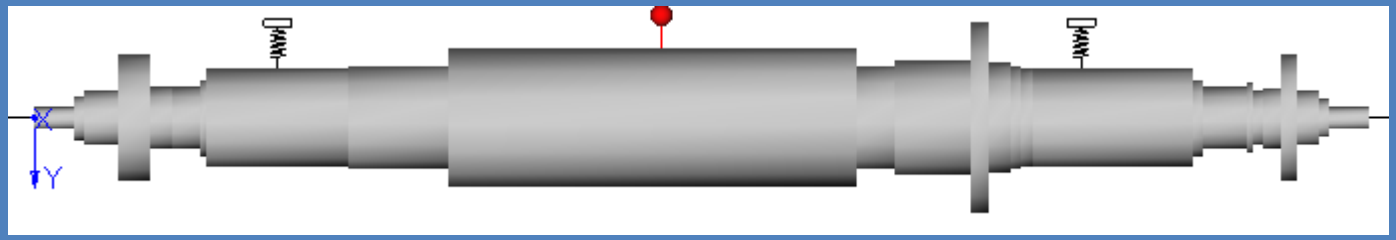
Ball bearing



Spring link with the base



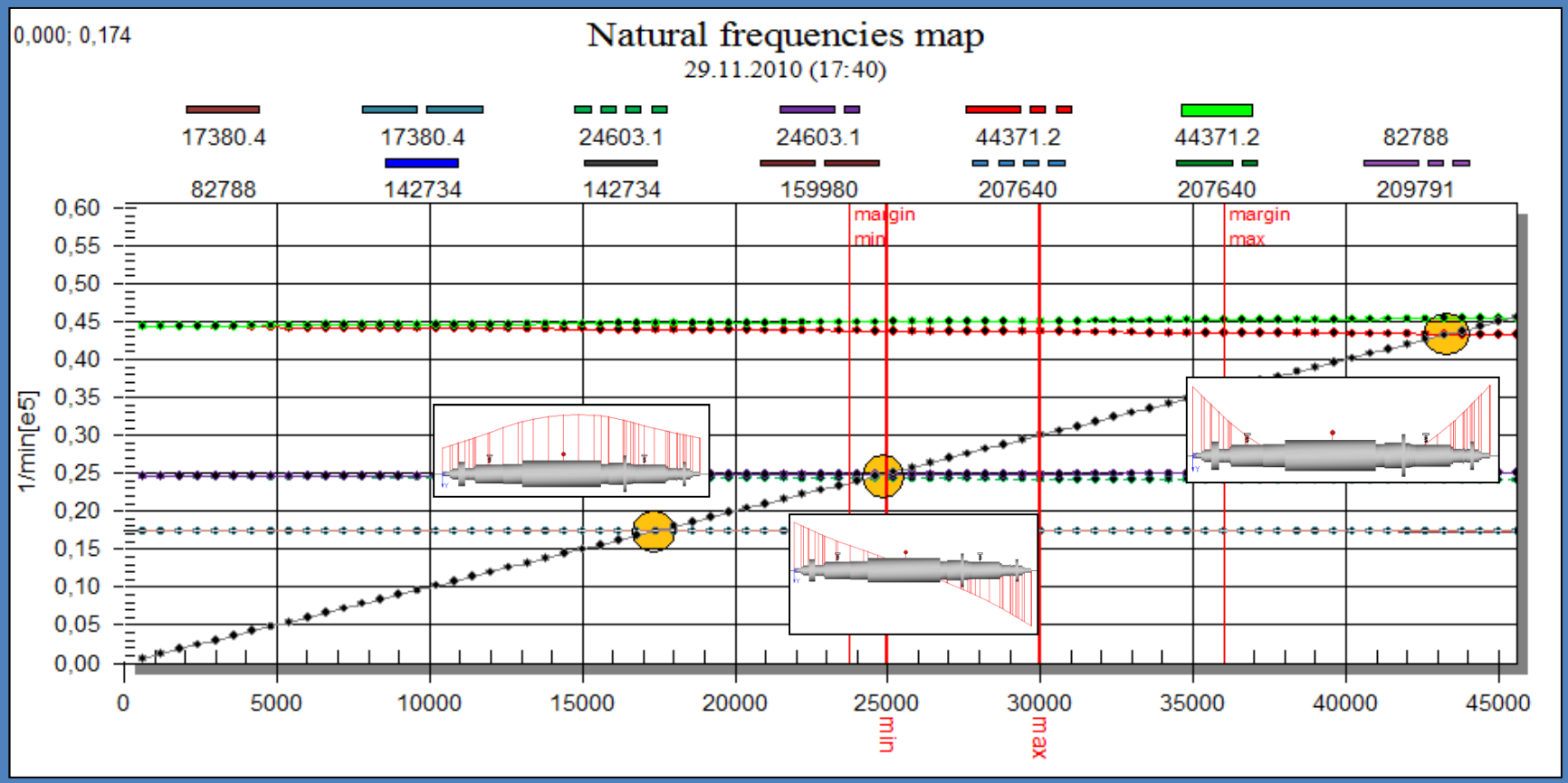
Critical speeds of the rotor supported by AMB



17358.2 (289.3)
17373.0 (289.6)
24106.4 (401.8)
24637.3 (410.6)
43213.1 (720.2)
45303.1 (755.1)

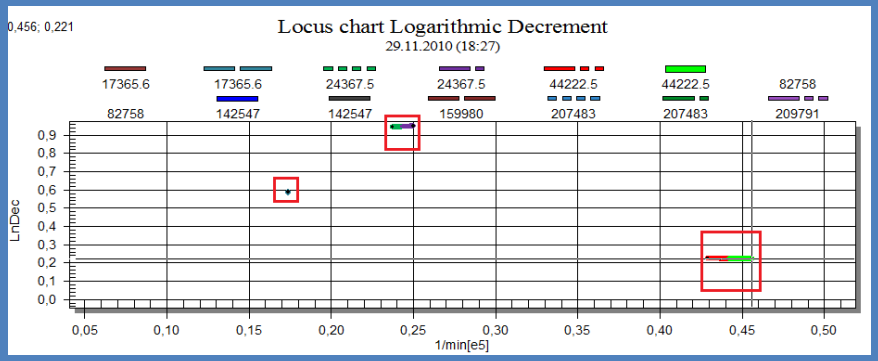
k_1=0.5e +8 Н/м

k_2=0.5e +8 Н/м



Forced oscillations of the rotor supported by AMB

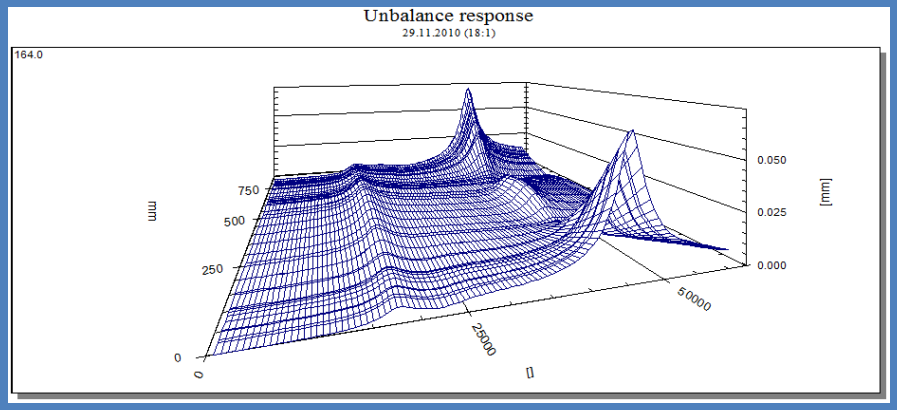
Locus chart of logarithmic decrements



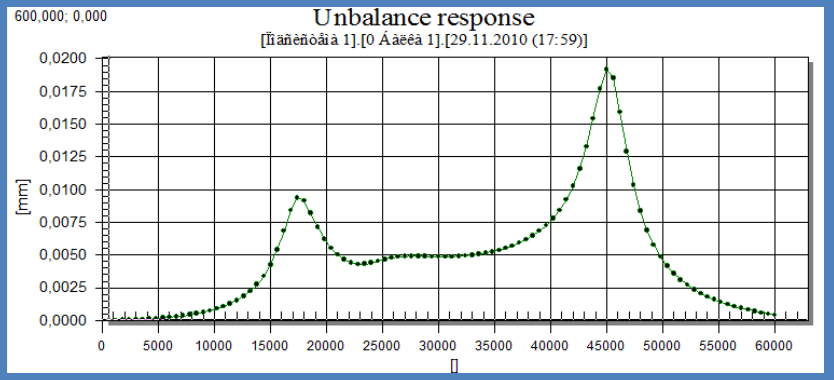
Distribution of deformations potential energy

Узел	Критические частоты вращения, об/мин		
	17373	24637	45303
Вал ротора	15.506	3.843	87.558
$АМП_1$	48.745	43.710	3.602
$АМП_2$	35.749	52.447	8.839
Сумма	100	100	100

3D - amplitude-frequency rotor response

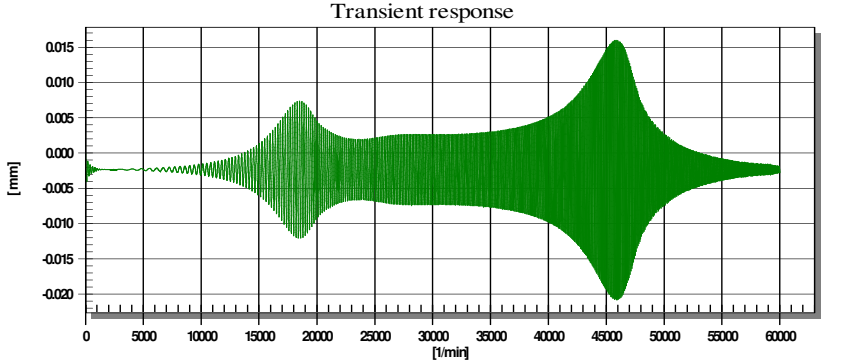


2D - amplitude-frequency rotor response. The AMB_1 section

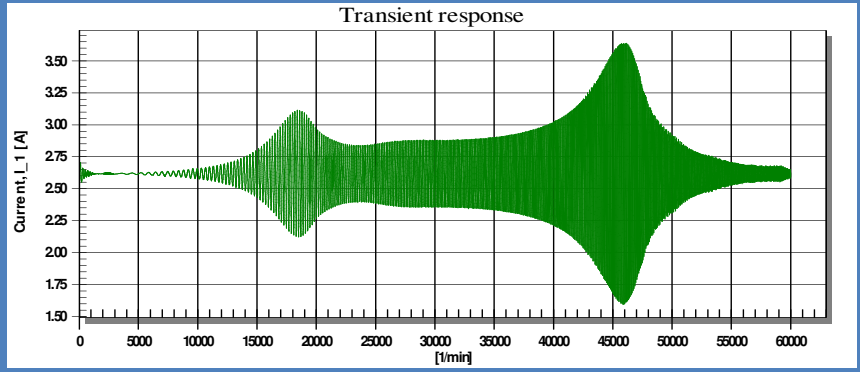


Unsteady analysis of the rotor supported by AMB

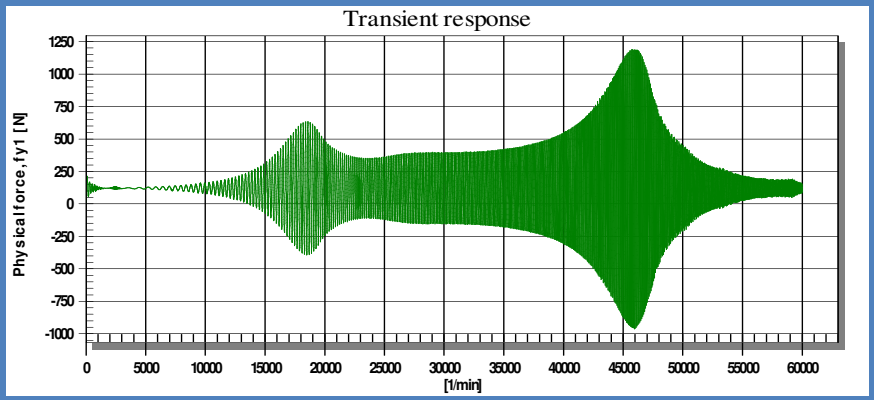
Unsteady analysis in consideration of weight, K=0.5 e+8 =const



Change in current, $I_{пред}$ = 5 A

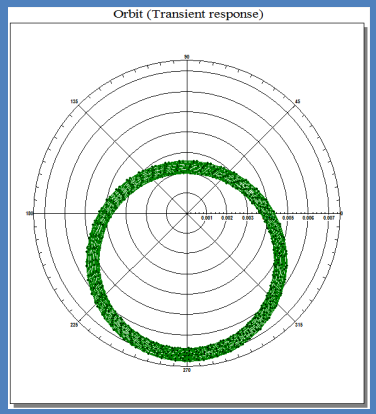


Reactions in support

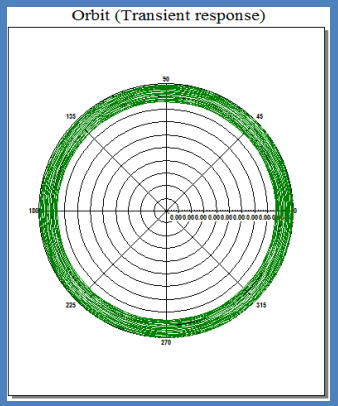


Motion orbits, AMB_1 section

PD controller

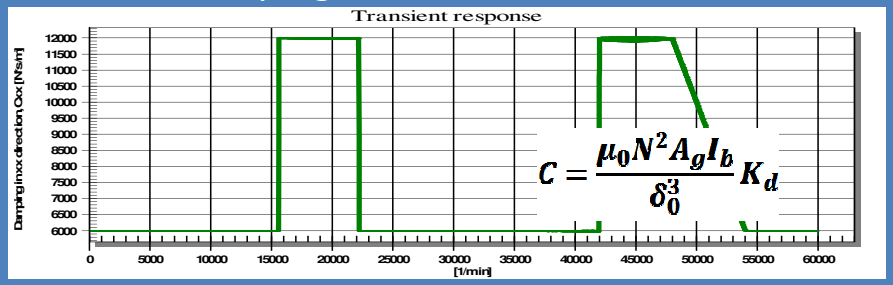


PID controller

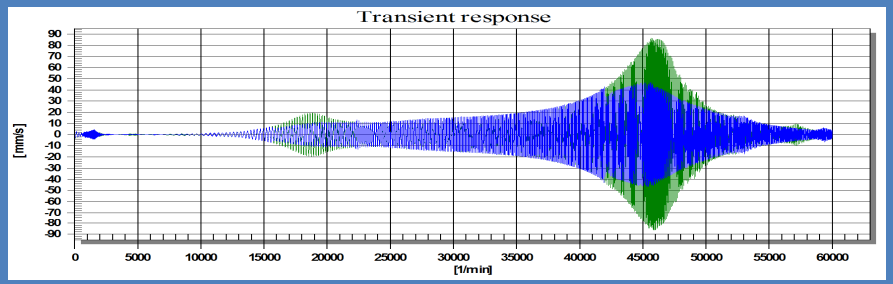


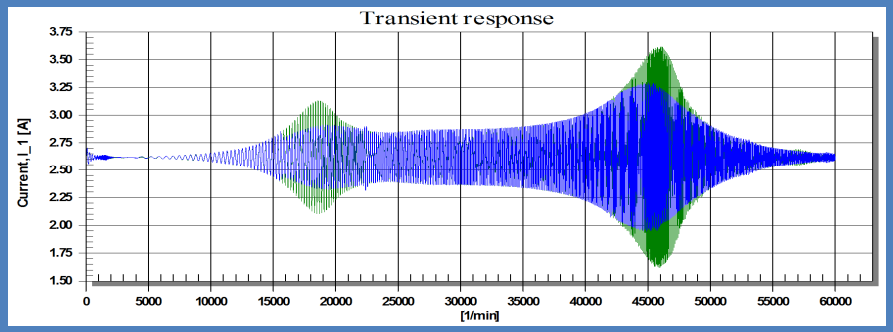
AMB stiffness and damping control

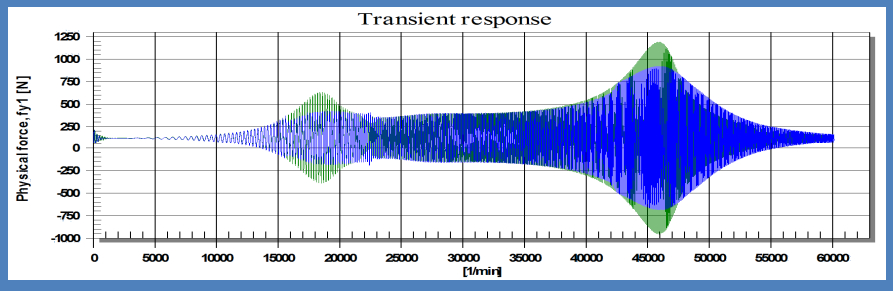
AMB damping control



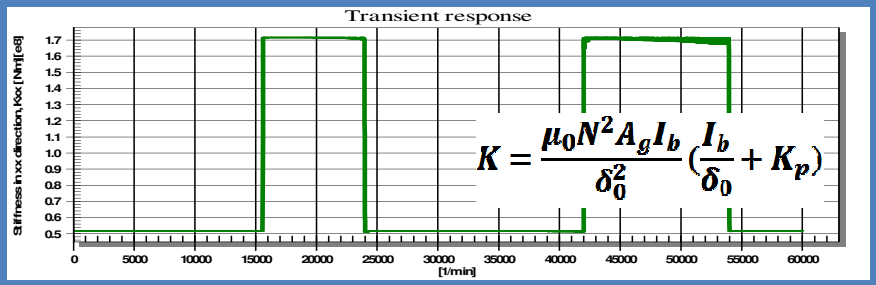
$$C = \frac{\mu_0 N^2 A_g I_b}{\delta_0^3} K_d$$



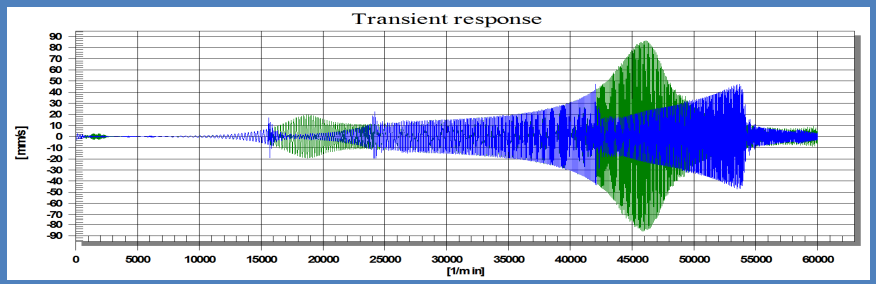


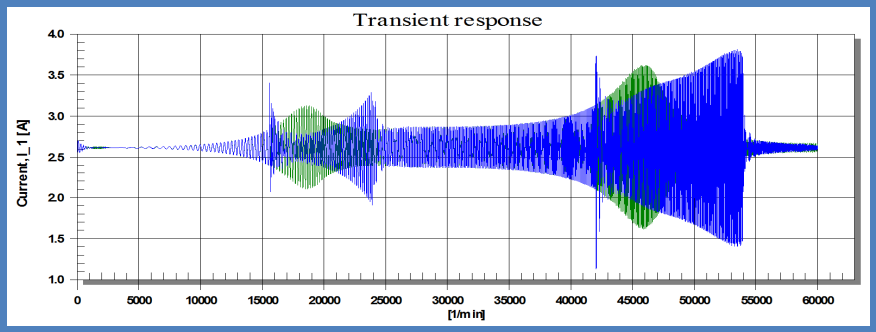


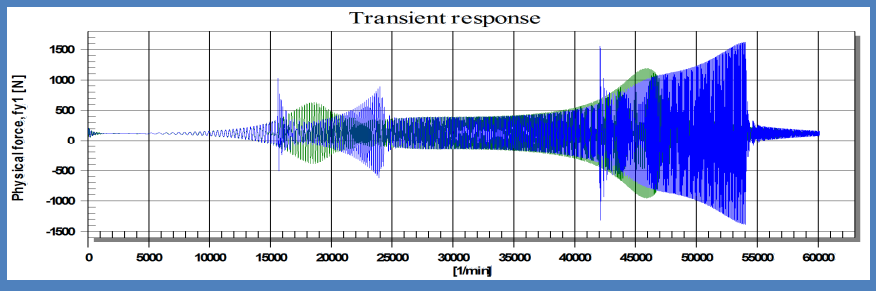
AMB stiffness control



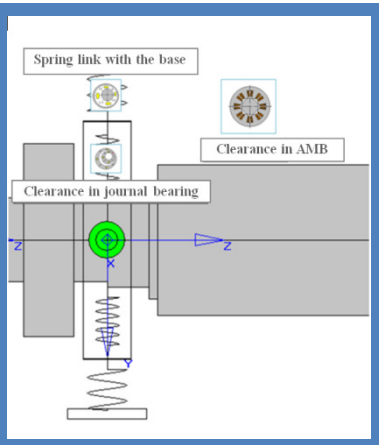
$$K = \frac{\mu_0 N^2 A_g I_b}{\delta_0^2} \left(\frac{I_b}{\delta_0} + K_p\right)$$





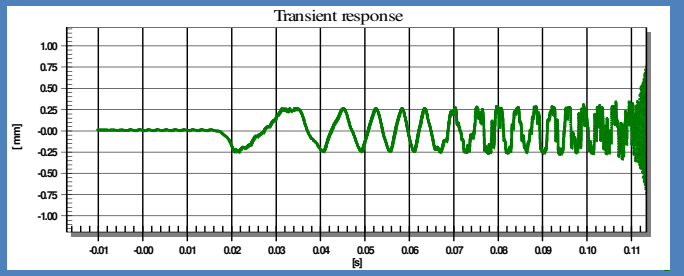


The rotor dropdown on the journal bearings

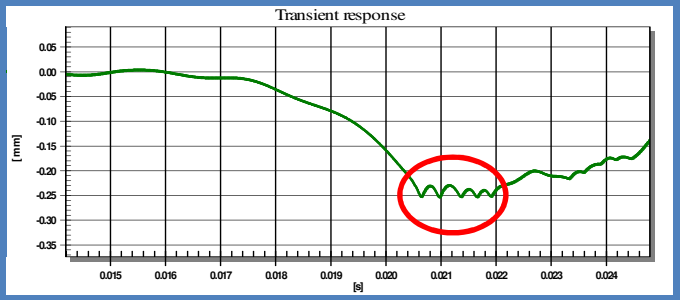


Radial clearance in AMB , mm	0.5
Radial clearance in journal bearing, mm	0.25
AMB stiffness, N/m	0.5e+8
AMB damping, N s/m	6000
Contact stiffness, N/m	1e+10

μ (Steel on graphit) 0.1

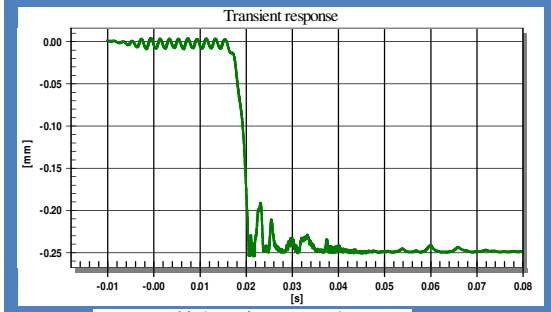


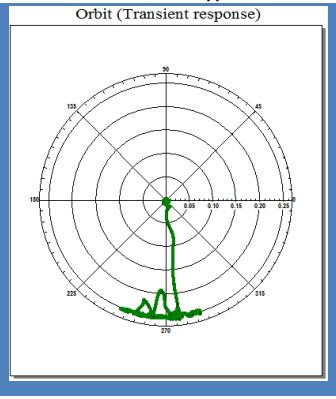
Transition period



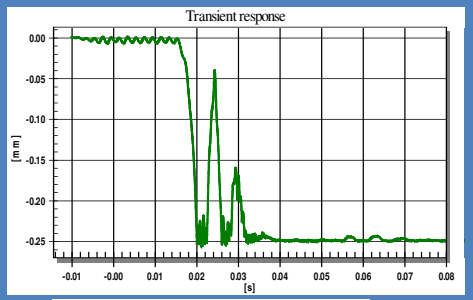
μ (Steel on babbit) 0.005

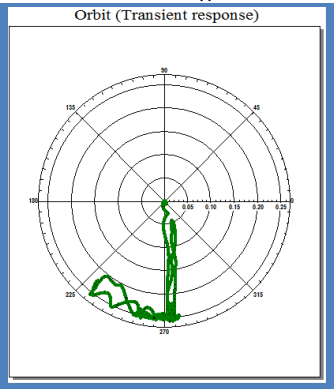
Journal bearing 1



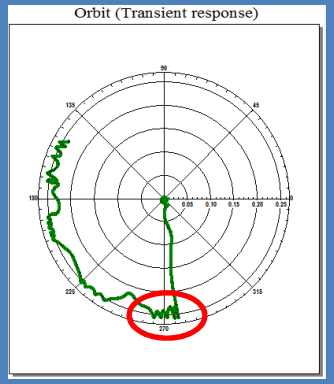


Journal bearing 2

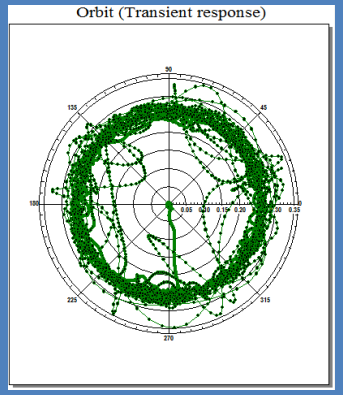




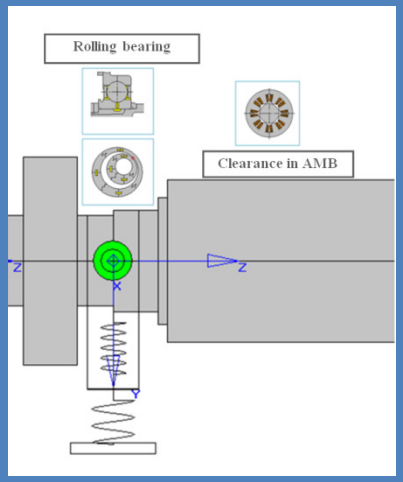
Going into backward precession



Backward precession

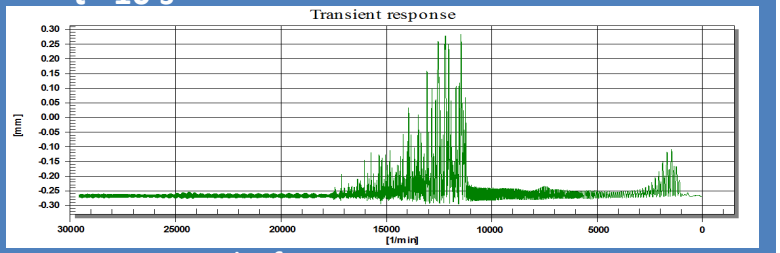


The rotor dropdown on the rolling bearings

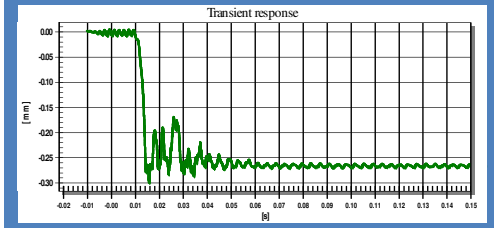


Radial clearance in AMB , mm	0.5
Radial clearance in rolling bearing, mm	0
Radial clearance between the shaft and the rolling bearing, mm	0.25
AMB stiffness, N/m	0.5e+8
AMB damping, N s/m	6000
Contact stiffness in rolling bearing, N/m	1e+10

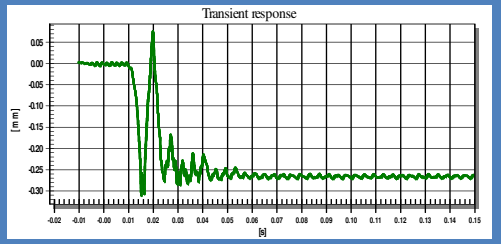
The rotor stop.
Rotating speed changes from n = 30000 rpm up to n = 0 rpm
Δt= 10 s



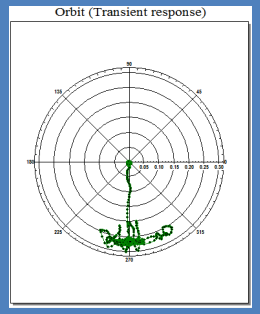
Bearing 1



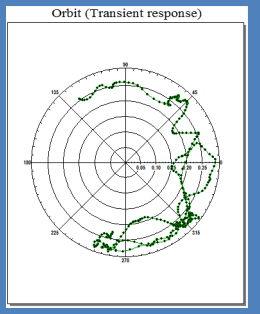
Bearing 2

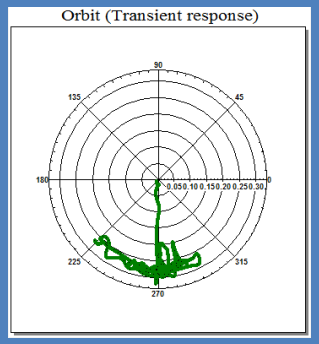


Movement before whirling motion

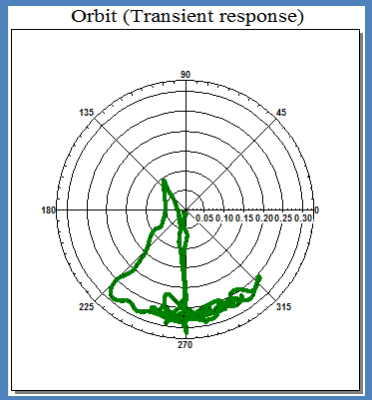


Going into whirling motion

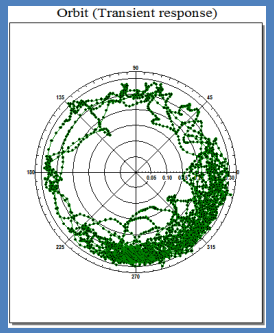




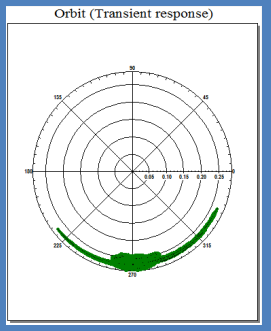
Rotating speed of inner ring of rolling bearing
n = 30000 rpm



Full-clearance motion



Following stop



The general methodology of designing the rotor supported by AMB

Determination of necessary values of AMB stiffness and damping

Estimation of AMB control coefficients and adjustment of the control system

Determination of the rotor's damped critical speeds and mode shapes – places of prospective resonances

Calculation of forced oscillations and amplitude values of vibroparameters : displacements, vibrovelocity, reactions in supporting units. etc.

Development of the program of current – AMB stiffness and damping – control for passing systems resonances and going into the operating range

Unsteady analysis of the rotor supported by AMB with the aim of more precise definition of the rotor's characteristics at transient regimes

Simulation of the rotor supported by backup bearings. The non-linear unsteady rotor analysis. The aim is to determine the possibility of the rotor's going into whirling motion or backward precession

The unsteady rotor analysis after switching off AMB supported by non-linear rolling bearings while the rotor's deceleration and determination of resonance regimes

THANK YOU FOR

YOUR ATTENTION!