Application of FOG for seismic measurements

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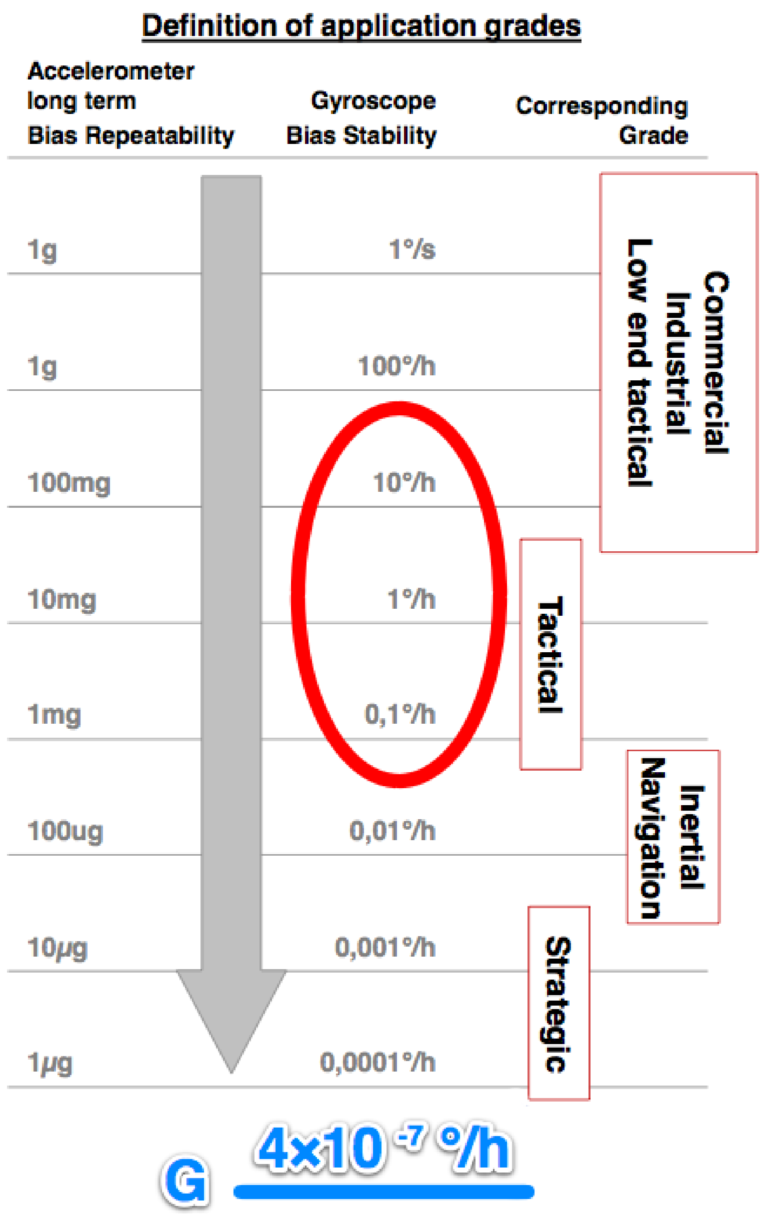
Seismic rotation measurements: goals

- Constraining earthquake source processes when observed close to active faults;
- Estimation of permanent displacements from seismic recordings;
- Correction of seismometer recordings for rotation induced contributions;
- Analysis of tall buildings condition.

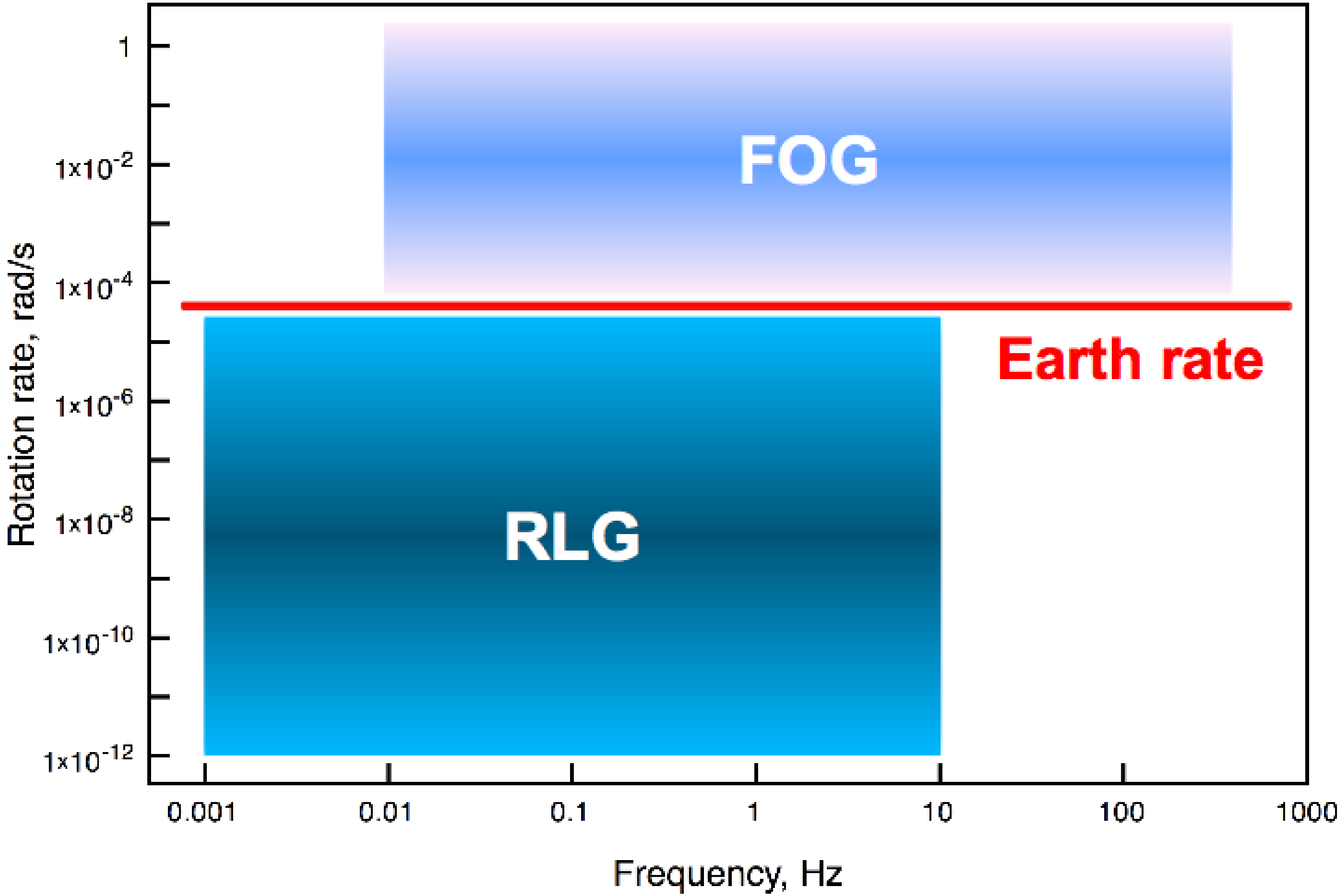
Seismic rotation measurements: tasks

- Creation and unification of rotational sensors test procedures with respect to seismological applications;
- Continuous measurements of angular seismic motion on site (6 DOFs systems);
- Separation of translational and rotational motion components in the recordings of traditional seismometers.

Contemporary inertial sensors qualification



Seismic application of optical rotational sensors



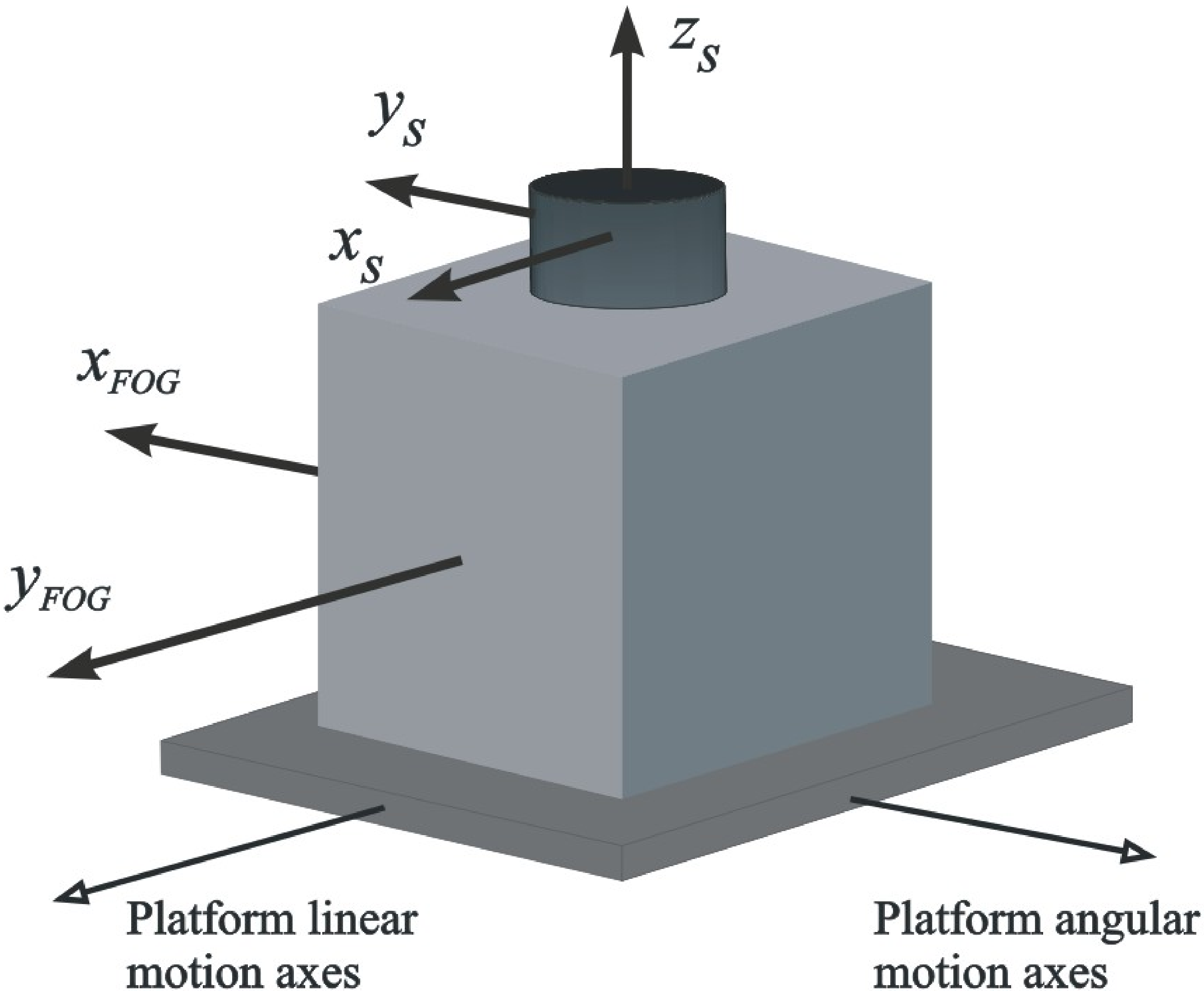
Fiber optic gyros for seismology

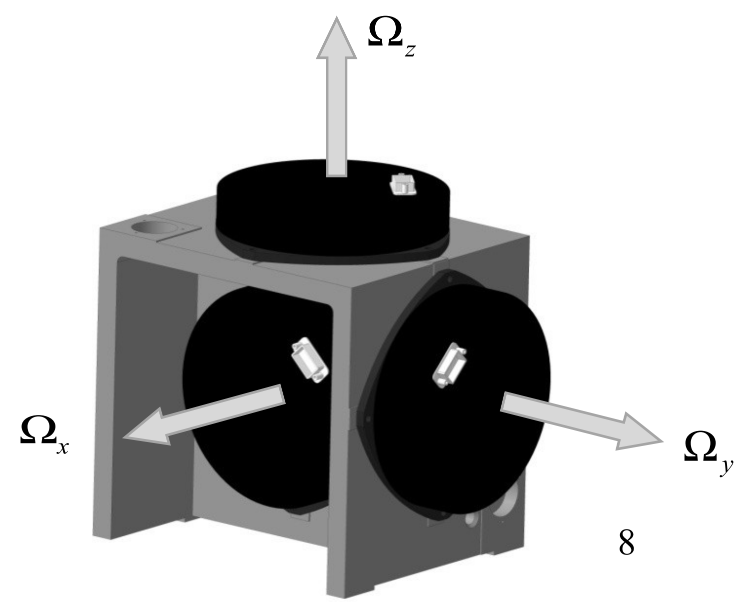
- Wettzell group possess 3DOF unit based on Litef FOGs - work in progress;
- Research group in Poland built a large FOG (AFORS) specifically for seismic applications;
- St.-Petersburg group uses a 6DOF IMU (basically INS without computer);
- Some other groups conduct the experiments with commercially available units.

Joint test run of FOG triad and seismic 3D accelerometer

- Sensors scale factor verification under the test conditions close to the real application (angular oscillations);
- Correction algorithm and angular rate calculation procedure refinement;
- The assessment of FOG-based system measurement limits with respect to the amplitude-frequency range of interest.

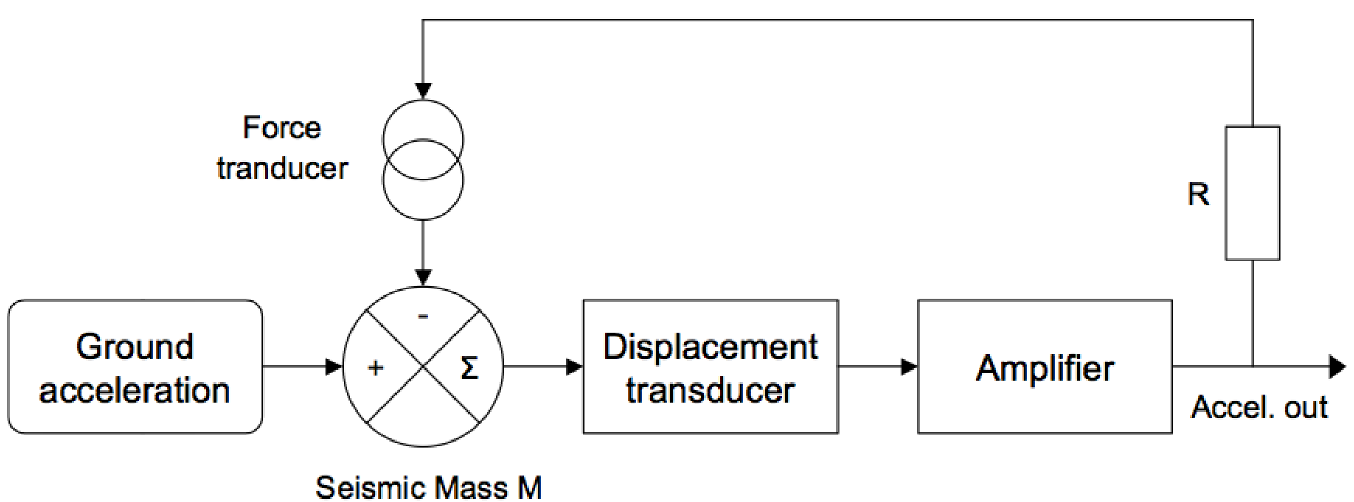
Devices under test



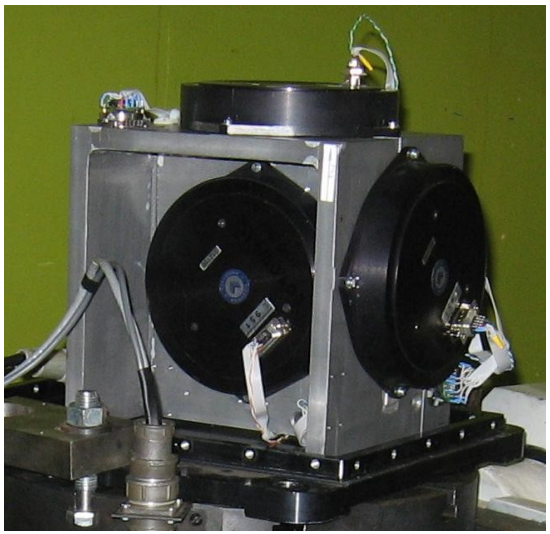


Seismic accelerometer Kinemetrics EpiSensor FBA ES-T

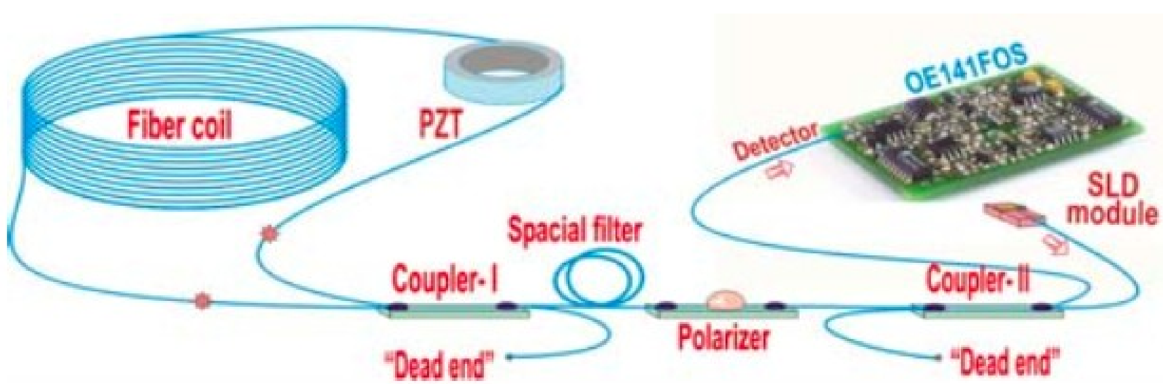
Type	**Triaxial force balance accelerometer**
Dynamic range	155 dB + (EpiSensor noise model available from Kinemetrics)
Bandwidth	DC to 200 Hz
Calibration coil	Standard
Full-scale range	User-selectable at ± 0.25g, ± 0.5g, ± 1g, ± 2g or ± 4g
Full-scale output	User-selectable at: ± 2.5V single-ended; ± 10V single-ended; ± 5V, ± 20V differential
Linearity	< 1000μg /g²
Hysteresis	< 0.1% of full scale
Cross-axis sensitivity	< 1% (including misalignment)



Seismic rotation measurement unit prototype (FOG VG-951)

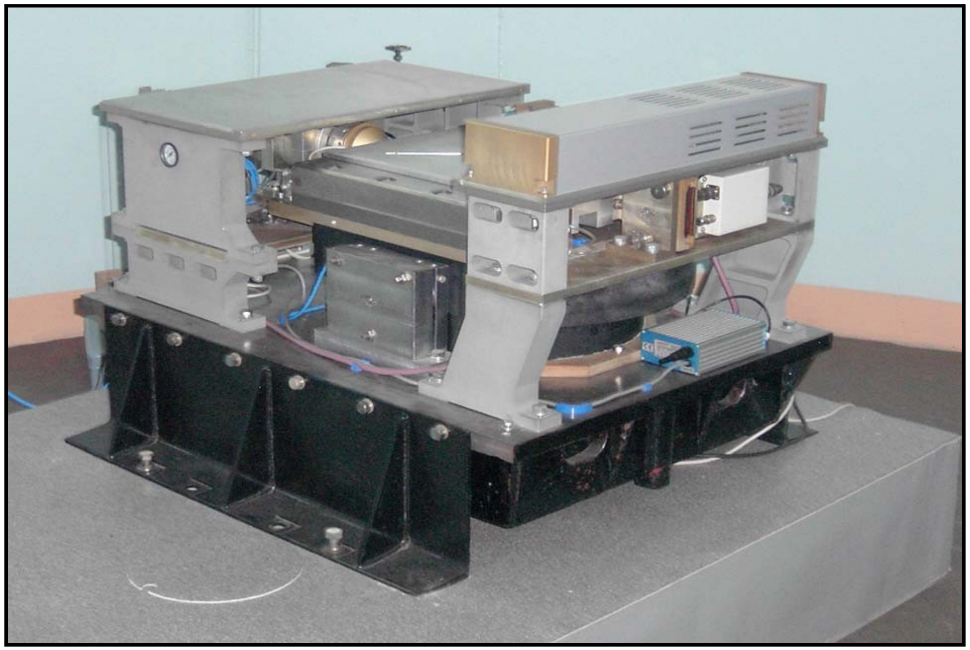


Measurement range	± 60 deg/s
Sensitivity	24 mV/deg/s
Random walk	15×10^{-3} deg/ $\sqrt{h}$
Bandwidth	0 … 450 Hz
Bias stability	1 deg/h
Scale factor stability	0.1%
Power	5 V
Temperature range	-30 … 70 C°
Dimensions (diameter, height)	16 and 3.8 cm



Test equipment

USG-3M Test bench



USG-3M parameters

Parameter	Value
Translational motion range	10^{-3} … 10 мм
Angular motion range	10^{-7} … 10^{-3} rad
Frequency range	0.001 … 0.5 Hz
Platform dimensions	30×30 см
Max load	40 kg

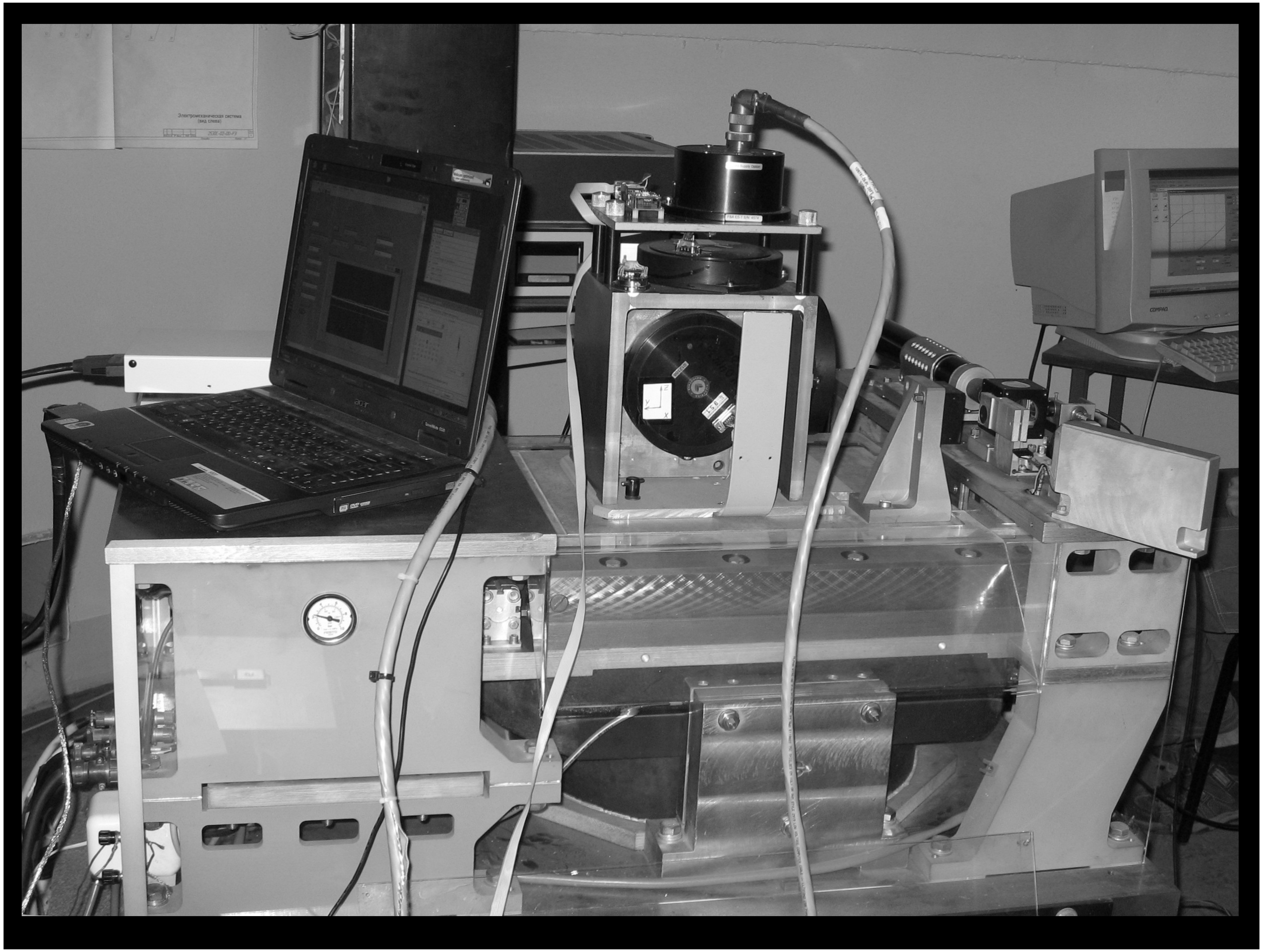
Platform motion:

$$L = L_0 \sin(2\pi f t)$$

Angular motion:

$$\alpha = L / R, \quad R = 10 м$$

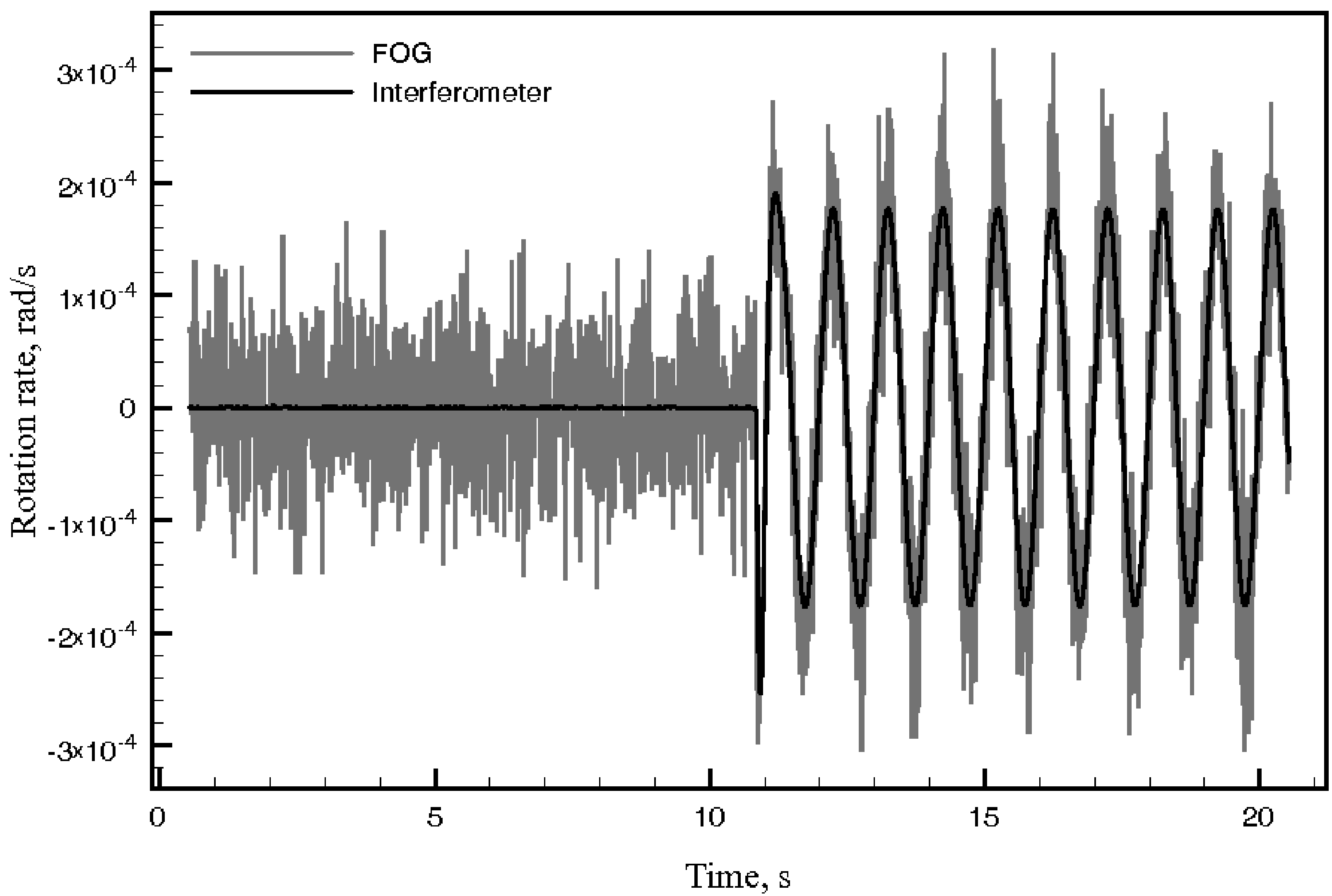
Experimental setup



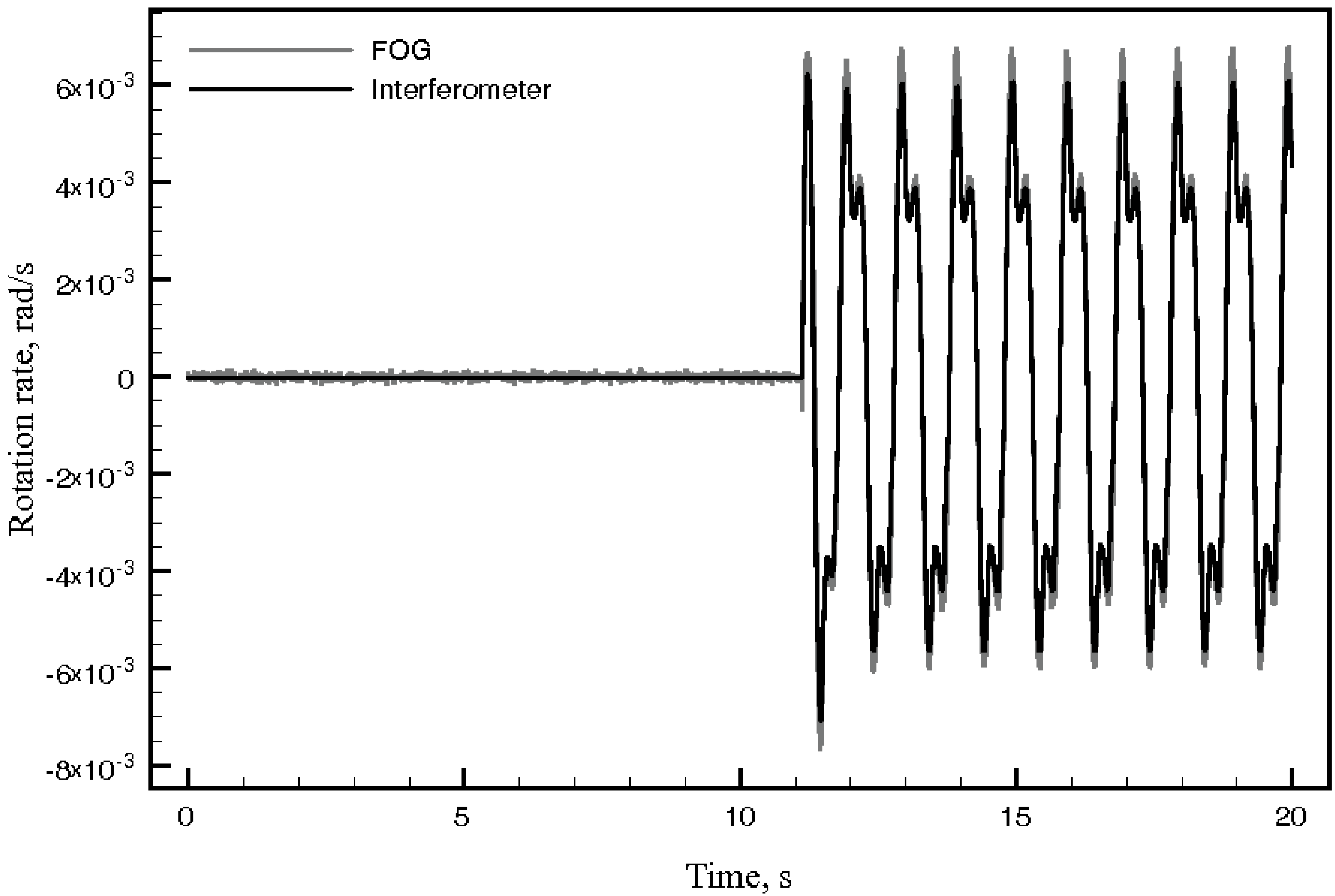
Test program

- Linear oscillations of the platform with constant acceleration of 2.5×10^{-3} m/s^2 with frequencies within the range of 0.3 … 5 Hz;
- Angular oscillations of the platform with constant angular rate of 1.7×10^{-3} rad/s (frequency varies for each run);
- Angular oscillations of the platform with fixed frequency of 1 Hz and variable amplitude of angular rate (1.75×10^{-4} … 5.15×10^{-3} rad/s).

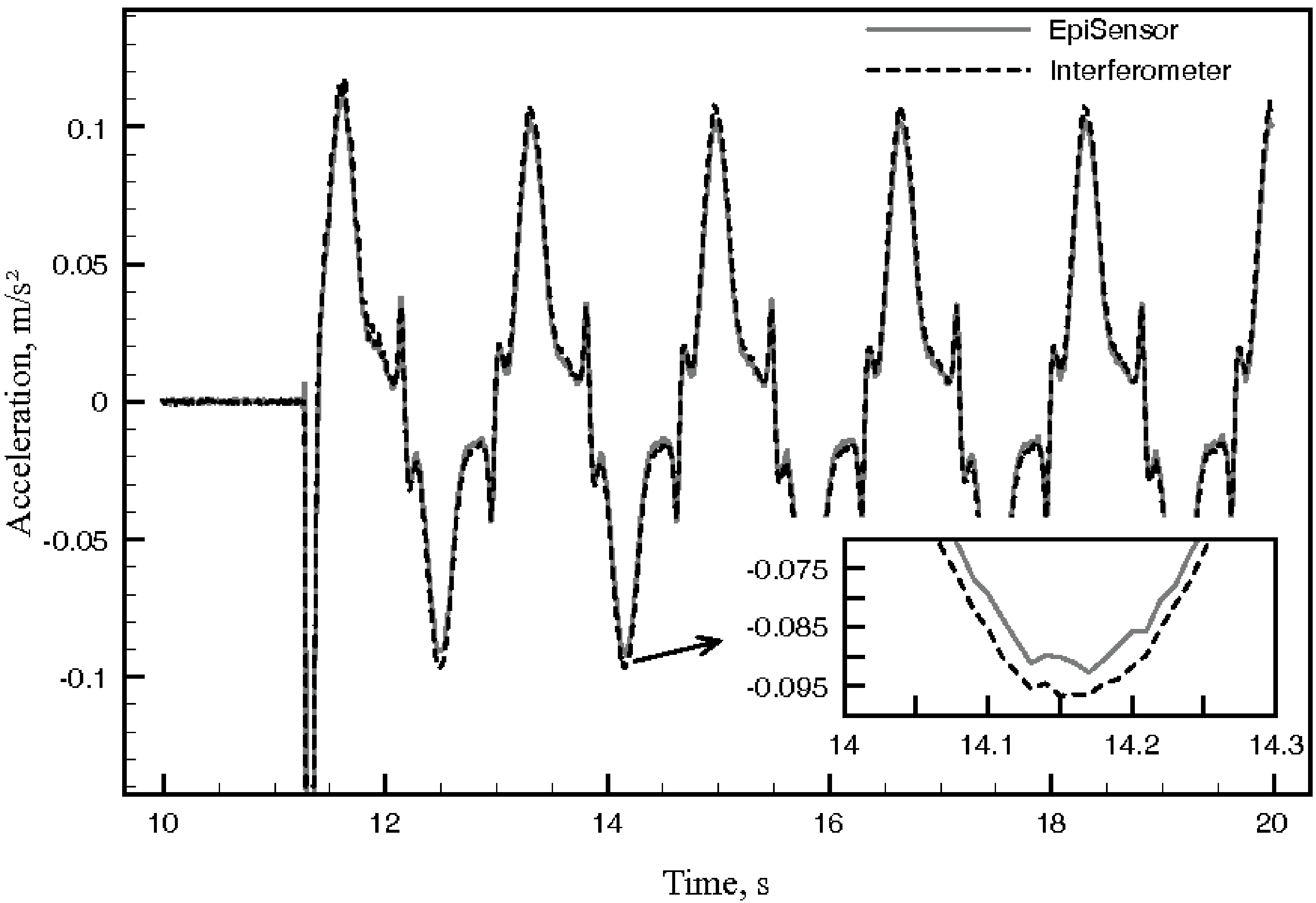
Lowest angular rate ω= 1.75× 10^{-4} rad/s



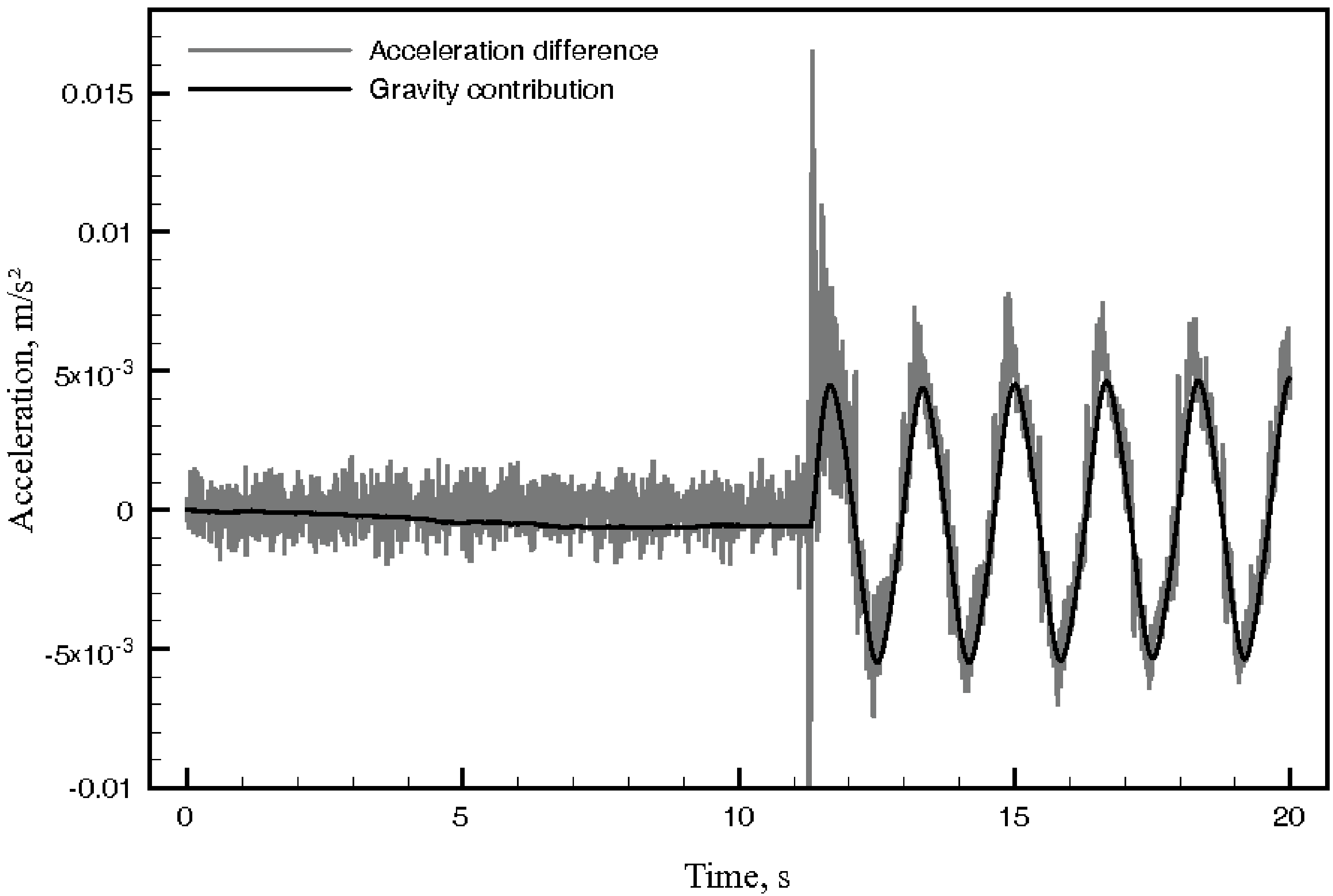
Maximal angular rate
$\omega = 5.15\times 10^{-3}$ rad/s



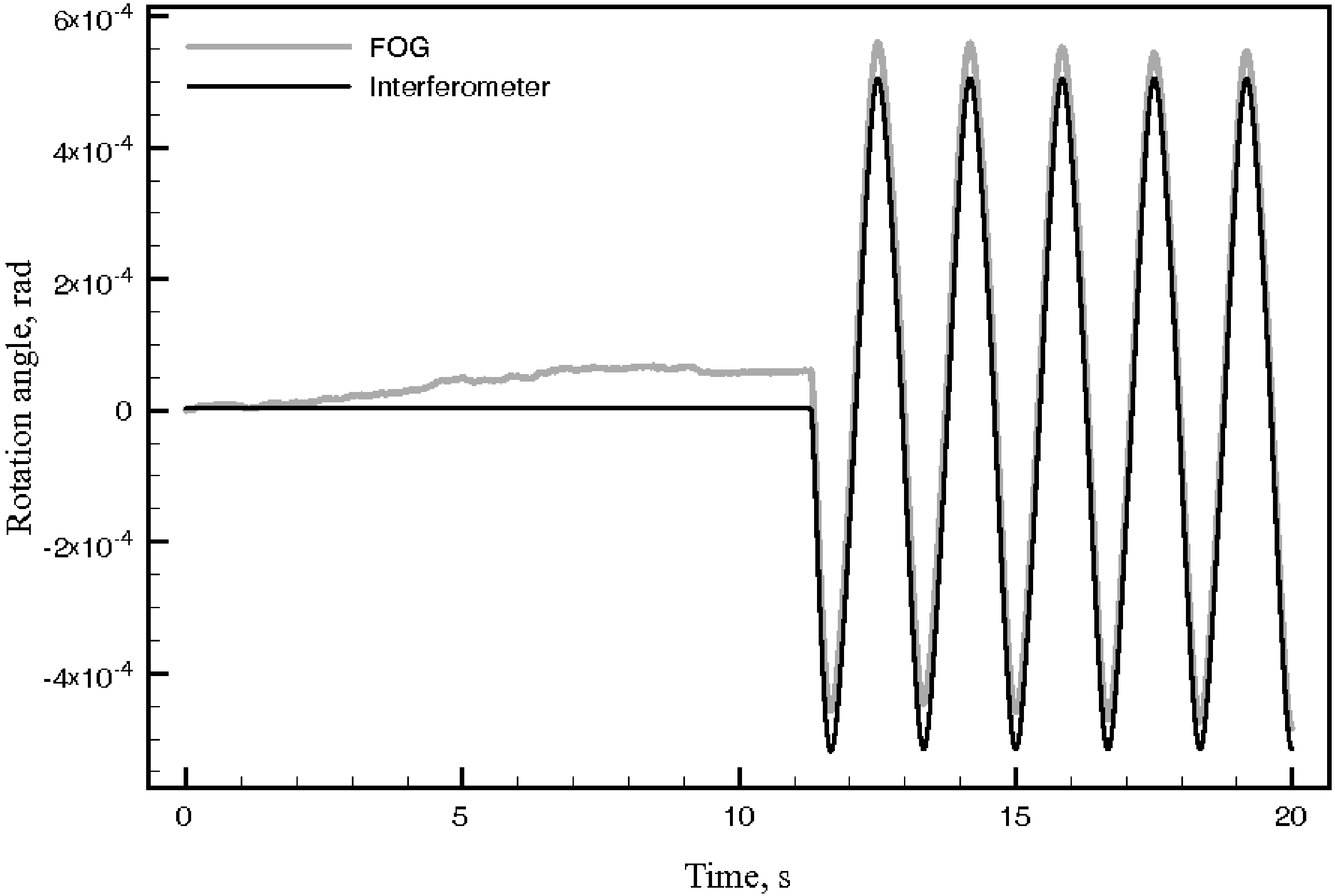
Comparison of reference acceleration and recorded by accelerometer



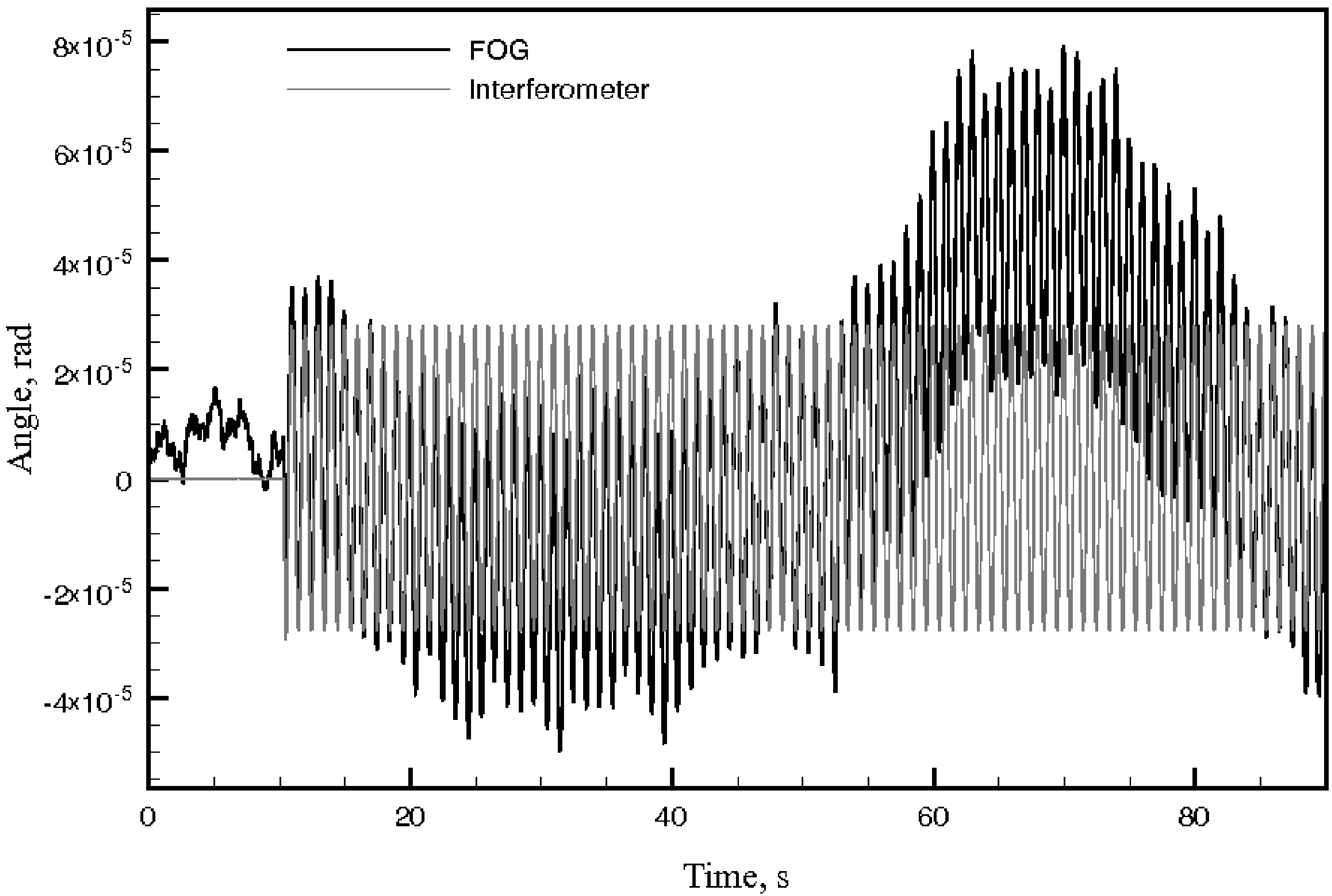
Contribution of tilt to the seismic accelerometer signal



Angular variations according to FOG and reference interferometer ($\omega = 1.83\times 10^{-3}$ rad/s)



Same for lowest angular rate (ω= 1.75$\times$ 10^{-4} rad/s)



Errors in determination of tilt induced gravity contribution

$\omega, rad/s$	$\sigma\phi, rad$	$g\sigma\phi, m/s^2$	relative error, %
$1.75 \cdot 10^{-4}$	$1.64 \cdot 10^{-5}$	$1.61 \cdot 10^{-4}$	59
$3.14 \cdot 10^{-4}$	$2.29 \cdot 10^{-5}$	$2.25 \cdot 10^{-4}$	46
$6.26 \cdot 10^{-4}$	$3.70 \cdot 10^{-5}$	$3.70 \cdot 10^{-4}$	38
$1.55 \cdot 10^{-3}$	$1.94 \cdot 10^{-5}$	$1.90 \cdot 10^{-4}$	7.8
$2.75 \cdot 10^{-3}$	$2.85 \cdot 10^{-5}$	$2.80 \cdot 10^{-4}$	6.5
$5.15 \cdot 10^{-3}$	$5.12 \cdot 10^{-5}$	$5.00 \cdot 10^{-4}$	6.2

Some conclusions

- The carried out test procedures may be included in the future test draft for seismic rotation devices;
- Open-loop FOGs are able to successfully detect the rotational signals within the range specified. However this class of devices is not suitable for seismometer data correction, at least in the lower rotation rate region;
- In order to establish reliable seismometer data correction one needs the sensors with lower noise level - presumably closed-loop FOGs;
- The application of other types of rotational sensors is still questionable as their only obvious advantage so far is the price;
- There may be the need in further separation of application field - namely very strong motion (open-loop FOGs) and regional observations (closed-loop FOGs).

Possibilities

- Higher precision FOGs (however costly);
- Units optimization (lower range but also noise, higher resolution);
- New FOG technologies (utilizing hollow-core fiber)