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SENSOR OF ROTATIONAL MOVEMENT AROUND VERTICAL AXIS FOR SEISMIC MEASUREMENT

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ABSTRACT

Rotational movement belongs among emerging parts of seismology. Classic methods for studying depend on indirect measurement and careful in-situ planning. Described approach is based on the direct measuring of rotations using sophisticated mechanical transmission of ground movement into change of capacitance between plates of capacitor. It enables to construct quite small, portable, sensor for field measurement. Changes are followed by monolithic capacity-to-digital (C/D) converter with 24-bit resolution and 4 aF calibrated precision. In this paper are presented ideas, movement equations, dynamic characteristics – theoretical and measured. There is also discussed shape of all the sensor and possible improvements in sense of sensitivity and parasitic features rejection. This application is also one of great opportunities for integrated circuits (C/D) and microcomputers for measurement and data processing. There are also mentioned other applications and future development.

KEYWORDS: seismology, rotation, vertical axis, horizontal plate, capacitance, angle

1. INTRODUCTION: HISTORY, MOTIVATION AND ADVANTAGES

Studying of rotational components of ground movements belongs among emerging approaches in recent geophysics. Rotations can be nowadays observed indirectly – using a dense seismic array (small aperture array) formed from classic three-dimensional seismic sensors. The aim of this project that results we would like to present here was to develop a sensor for a direct measurement of this kind of movement.

1.1. *HISTORY AND MOTIVATION*

During more than one hundred years of systematic seismic monitoring was discovered several issues of rotational movements during earthquakes Hobbs, 1907; Igel et al., 2005; Huang, 2003. There are some theoretical papers about existence of rotational movements Bouchon and Aki, 1982; Takeo and Ito, 1997, but we still grope way about propagation of such rays through the ground. That why we decided to construct a portable instrument that can be easily installed. Such a device should be moved among several places in the region of interest (e.g. western and eastern Bohemia) to find the best site for precise seismic monitoring. Classic method using arrays is not as flexible because of hard fieldworks.

Another opportunity for rotation measuring is in civil engineering for evaluation of dynamic parameters such building as piles, bridges, generally constructions with prevailing linear shape and objects with high seismic risk (e.g. nuclear power plant).

1.2. *ORIGIN OF ROTATION*

The rotation components of seismic ground motion can be spread from the source or can be generated when seismic waves pass through anisotropic rock massif or rise as a response of building structures on dilatational excitation. The rotation component of strong ground motion can represent a non-negligible contribution to the whole earthquake hazard to building structures in near zones. An excitation of rotation vibration depends heavily on the subsoil Buben and Rudajev, 2004.

1.3. *AIMS OF PRESENTED SOLUTION*

By a sophisticated combination of exceptional mechanic and electronic parts of sensor we can achieve high sensitive device with a compact size. Sensor measures movement around vertical axis – in the horizontal plane. There is also possibility to modify it to measure in horizontal axis but this area is not as focused in seismology – nevertheless not being the second-rate.

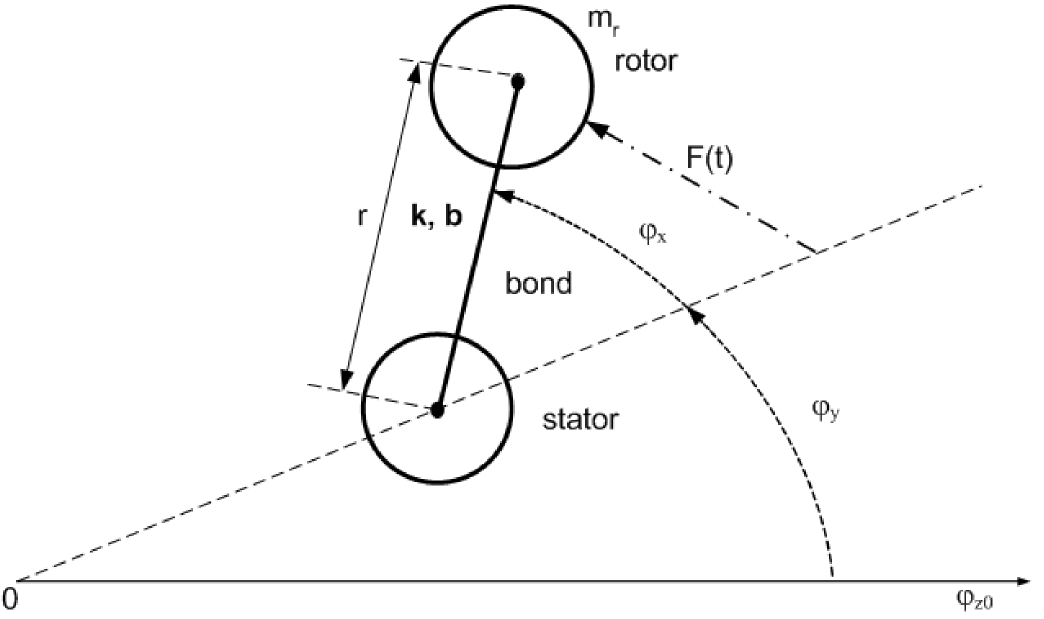

Fig. 1 Schematic model of rotational seismometer.

Portability of this sensor enables to measure in many different places and many different kinds of signal – natural earthquakes, blasts at quarries, impacts etc. This is its main benefit for seismology.

2. MODEL

In this paragraph we describe mathematical model, its characteristics and main parameters. On a simplified model we discuss steady and excited stage.

2.1. EQUATION OF MOTION

In a model ion Figure1 suppose stator and rotor part as their equivalent masses. They are coupled by a bond with two parameters – rigidity *k* and damping *b*. The viscous damping is proportional to the velocity. Angular deflection φ_y effects on stator and rotor of mass m_r. Flexible element – bond, e.g. represented by a spring – transfers this move to an angular deflection of rotor φ_x. Steady state where inertial force, direct force and viscous damping are in balance represents equation (1).

$$m_r \cdot r \cdot \frac{d^2\varphi_z}{dt^2} + b \cdot r \cdot \frac{d\varphi_x}{dt} + k \cdot r \cdot \varphi_x = 0 \tag{1}$$

There is angular movement of mass m_r specified as φ_z that is combination of uniform φ_{z0} and time variant φ_x and φ_y (2).

$$\varphi_z = \varphi_x + \varphi_y + \varphi_{z0} \tag{2}$$

Now rewrite (1) as equation of motion in sense of starting conditions and influence of external force (3).

$$m_r \cdot r \cdot \frac{d^2\varphi_x}{dt^2} + b \cdot r \cdot \frac{d\varphi_x}{dt} + k \cdot r \cdot \varphi_x = m_r \cdot r \cdot \frac{d^2\varphi_y}{dt^2} \tag{3}$$

3. SENSOR FOR MEASURING ANGULAR DEFLECTION OF SEISMIC MASS

Rotational seismometry has to detect and evaluate extremely small angular move. There are many possibilities how to realise such detection (e.g. optical, inductive, and capacitive). With respect to main goal of this project – portability – was chosen the capacitive method.

Capacitive sensors are several kinds – change of air gap between electrodes (gap sensors), change of overlapping area of electrode (area sensors) or change of capacity by inserting dielectric material between electrodes.

Sensitivity of capacitance sensor can be generally improved by combination of multi-electrode design and suitable measuring of final capacity. From this point of view the gap sensors seems to be the best choice, but its drawback is nonlinear relation between capacity and angular deflection. Inherent linear transfer characteristics has area sensor, but there is necessary to provide stability of air gap and reduce influence of boundary fields.

The realized capacitor is differential one– three plates each above the other (Figure 2) – and its shape is one twelfth of roundel (Figure 3). Maximum size is limited by technology of printed circuit boards (PCB). Differential capacity does not depend on the distance between the inner (rotor) and outer (stator) boards – vertical move of the rotor electrode cannot influence whole capacity of the sensor Dado and Kreidl, 1999.

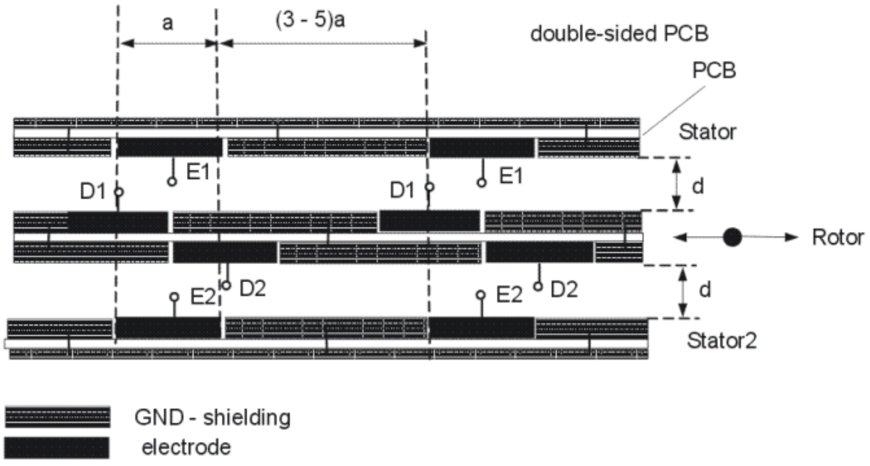

Fig. 2 Design of sensor realised on Printed Circuit Boards (PCB).

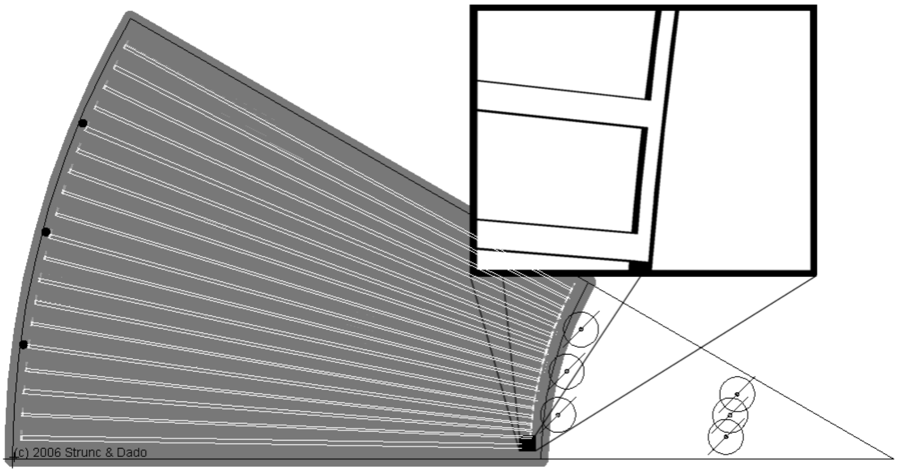

Fig. 3 Sensor segment with 19 differential flat capacitors.

In this chapter the words *stator* and *rotor* used as names of capacitor parts.

Two plates are fixed to the stator of sensor and the middle one is mounted on the rotor mass with crossed flat springs in the centre (Figure 4). The springs have to be formed to minimize transfer of vertical vibrations onto horizontal plane. The only damping is caused by internal friction due to bending of springs– in Figure 4 is the move of springs drawn exaggerated. Relevant scale is given further.

The differential capacitor (Figure 5) is mounted on a long arm fixed by balancer in stabilized position. The balance wheel hangs on a flat spring realizing the sensor of rotation around the vertical axis. Its natural oscillations are damped electro-magnetically using strong permanent magnets and copper lamellas at the opposite side of the arm.

Flat capacitive sensor for portable seismometer (Figure 2) is designed to have these features:

- linear dependence between overlap change ΔS and angular move – this is reached by capacitor construction based on the principle of calculable capacity (Thomson-Lampard theorem). – This type of design reduces influence of boundary fields by shielding electrodes width $3 - 5\ a$, where a is width of active electrode;
- enables differential operation that increases sensitivity and reduces influence of common mode noise;
- depending on configuration is possible to increase sensitivity even more using a set of n parallel electrode groups $E1_i - D1_i$, $E2_i - D2_i$. ()

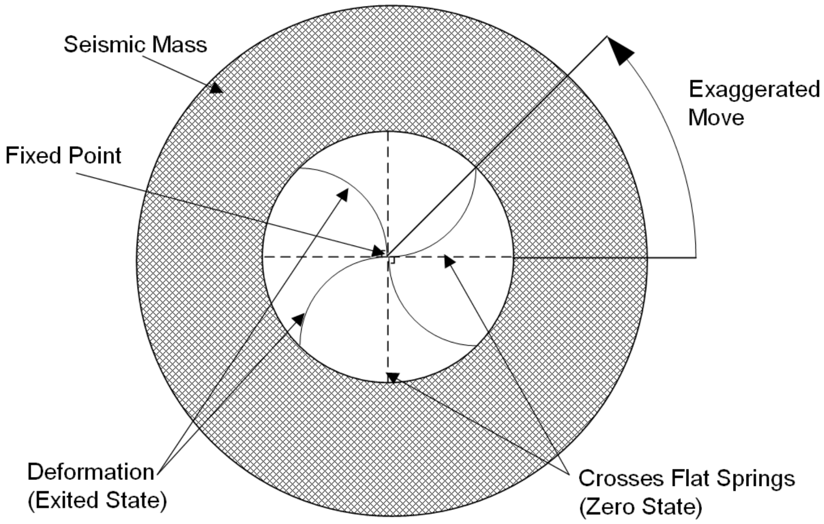

Fig. 4 Top view of the rotor mass with cross flat springs.

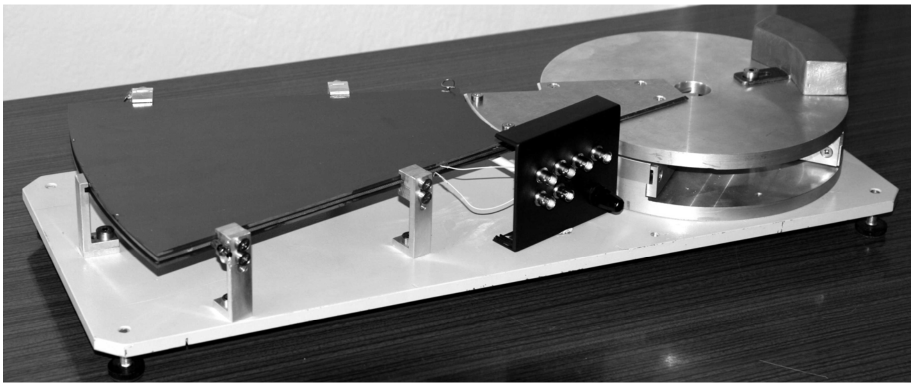

Fig. 5 Final design of rotational seismometer.

3.1. BASIC LAY-OUT OF ELECTRODE GROUPS

There are seven basic configurations of electrode interconnection (Table 1). For purpose to function as seismic instrument was selected the option A_0, where electrodes E1 and E2 and joined, shielding parts of stator are grounded and shielding parts of rotor are disconnected.

Capacitance between *D1* and combined *E1* and *E2* is sum of particular capacitances between *D1 – E1* and *D1 – E2* (i.e. C_{D1E1} and C_{D1E2}). At a free position is overlapped area equal to S_0 and an air gap is equal to d_0.

Capacitance between electrodes *E1*, *E2* and grounded shielding part of stator has limited effect due to the configuration of measuring circuit; it is connected parallel to the voltage source with a small output resistance. This is also a method how to eliminate capacitances between conductive parts of stator and rotor situated near the electrodes *E* and *D* – these spurious capacitances are parallel to active electrodes *E*, *D* and thus they have indisposed influence to sensitivity.

4. MEASURING CIRCUIT AND C/D CONVERTER

C/D converter should be preferably used as measuring circuit. This is why AD7746 – two channel 24-bit C/D converter by Analog Devices was chosen as a measuring system Analog Devices, 2005.

This IC contains Σ–Δ converter with two inputs for single or differential floating sensors and up to 21-bit effective resolution. Full scale changing capacitance of ±4 pF can be measured and common mode capacitance up to the 17 pF can be compensated by programmable D/C converter (called CAPDAC). High accuracy is reached by factory calibration with uncertainty equal to ±4 fF. The linearity is high

Table 1 Possible configuration of electrode groups.

name	E1	E2	D1	D2	shielding stator	shielding rotor	measuring	application
A_0	connected to E2	connected to E1			GND	n.c.*	C_{E1D1}, C_{E2D1}, C_{E1D2}, C_{E2D2}	2πS
A1	connected to E2	connected to E1			n.c.	n.c.	C_{E1D1}, C_{E2D1}, C_{E1D2}, C_{E2D2}	2πS
A2			connected to D2	connected to D1	n.c.	n.c.	C_{E1D1D2}, C_{E2D1D2}	dif. X
B1			GND or n.c.	n.c. or GND	n.c.	n.c.	C_{E1E2} (throughput capacitance)	πS
B2			periodic cross-switching between GND and n.c.		n.c.	n.c.	$C_{E1E2(D1\text{-}GND)}$, $C_{E1E2(D2\text{-}GND)}$ (throughput capacitance)	2πS
C			GND	GND	n.c.	GND	$C_{E1\text{-}GND}$, $C_{E2\text{-}GND}$	dif. X
D					GND	n.c.	C_{E1D1}, C_{E2D1}, C_{E1D2}, C_{E2D2}	πS, dif. x

* n.c. means "not connected"

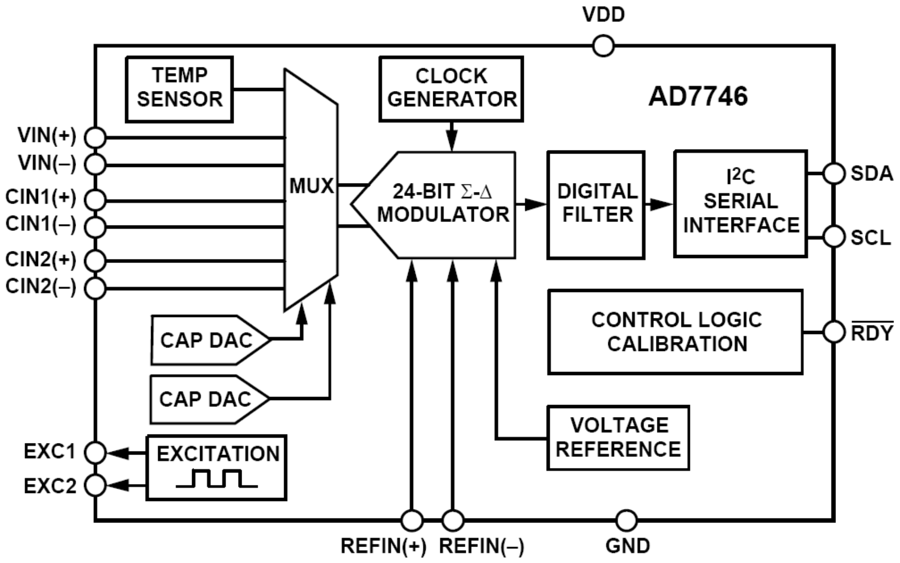

Fig. 6 Functional block diagram of AD7746 (from Analog Devices, 2005).

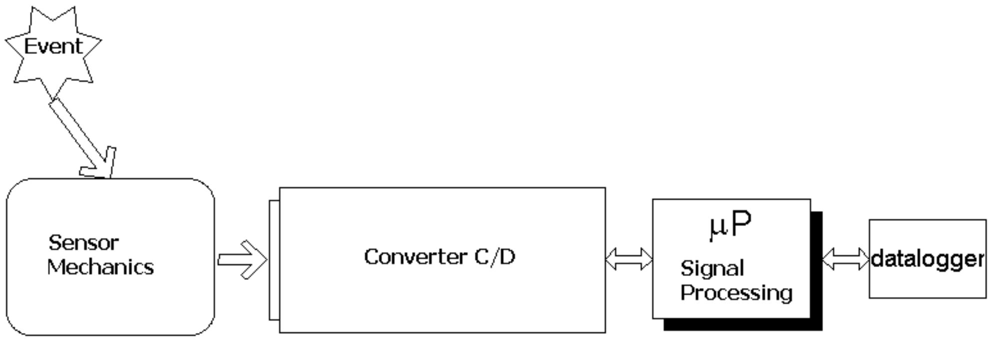

Fig. 7 General block diagram of all the measuring system.

Table 2 Parameters of sensor system.

factor	value
f_0 (Hz)	2
δ	0.236
Q	26
B	0.019

(±0.01%), and sampling rate can be varied between 10 to 90 Hz.As an excitation source is used 32 kHz square wave signal with optional amplitude (several steps up to voltage of power supply).Although there are several parts in whole measuring chain the AD7746 is the most important one. During the test mentioned further were used simplified configurations and all measured data were stored on a computer. Final sensor should be autonomous and should provide the digital output (Figure 7).

5. EXPERIMENTAL IDENTIFICATION OF SENSOR PARAMETERS

From the responses to the step impulse of the angular deflection were identified these parameters Table 2 (damping factor δ, quality factor *Q*, normalized critical damping coefficient *B* and eigenfrequency *f*). Note: During the experiments we found several non-documented features of *Evaluation Software* – e.g. *Real Time* part does not plot data according to sampling rate and is too sensitive to computer performance. For all evaluations were used data obtained in off-line working regime called *Analysis* – so all the tests were blind – there were no visual checkout.

5.1. LEAST MEAN SQUARE PARAMETERS IDENTIFICATION

Parameters in Table 2 were reached off-line – from impulse characteristics and from known material parameters and constants. For testing and calibrating purposes is suitable to prepare an on-line system parameters identification. This is very important for the first in-situ test to analyze changes that can be effected e.g. by an environment.

Transfer function *F(p)* of continuous system inferred from equation (3) with the input variable φ_y and the output φ_x is (4). There is used Laplace's transformation with this notation: $\varphi_y \to Y(p)$ and $\varphi_x \to X(p)$.

$$F(p) = \frac{X(p)}{Y(p)} = \frac{-p^2}{p^2 + \frac{b}{m}p + \frac{k}{m}} \tag{4}$$

All data measurements are digital with specified sampling – thus it is necessary to convert continuous formula (4) to discrete Z-transformation. The best way is bilinear transformation (5) with substitutions (6) and (7) where *T* means sampling period.

$$p = \frac{2}{T} \cdot \frac{z-1}{z-1} \tag{5}$$

$$a_1 = \frac{b}{m} = 2B\omega_0 \tag{6}$$

$$a_0 = \frac{k}{m} = \omega_0^2 \tag{7}$$

$$F(z) = \frac{-4z^2 + 8z - 4}{(a_0T^2 + 2a_1T + 4)z^2 + (2a_0T^2 - 8)z + (a_0T^2 + 2a_1T + 4)} \tag{8}$$

Basic form *F(z)* from equation (8) is transferred into normalized form (12) using substitution (9) – (11). Note the final three parameters a_{22}, a_{21} and a_{20} are inferred from two (a_1 and a_0) and sampling period *T*.

$$a_{22} = a_0T^2 + 2a_1T + 4 \tag{9}$$

$$a_{21} = 2a_0T^2 - 8 \tag{10}$$

$$a_{20} = a_0T^2 - 2a_1T + 4 \tag{11}$$

$$F(z) = \frac{-\frac{4}{a_{22}} + \frac{8}{a_{22}}z^{-1} - \frac{4}{a_{22}}z^{-2}}{1 + \frac{a_{21}}{a_{22}}z^{-1} + \frac{a_{20}}{a_{22}}z^{-2}} \tag{12}$$

Formula (12) is used in least mean square (LMS) identification algorithm Simandl, 2000. The response to the impulse signal is used for the LMS (Figure 8). Measured signal is filtered by band-pass filter (FIR) with the corner frequencies 0.45 and 4.5 Hz. Input and measured signals are normalized.

Supposed transfer function of discrete system calculated from (8) using parameters from Table 2 and sampling period *T* is $F_d(z)$:

$$F_d(z) = \frac{-0.9925z^2 + 1.985z - 0.9925}{z^2 - 1.976z + 0.9945}, \tag{13}$$

where zeros and poles are: $z_1 = z_2 = 1$; $p_{1,2} = 0.9878 \pm 0.1372i$.
The result of the identification process is the formula (14).

$$F(z) = \frac{-0.9952z^2 + 1.99z - 0.9952}{z^2 - 1.982z + 0.9987}, \tag{14}$$

where zeros and poles are: $z_1 = z_2 = 1$; $p_{1,2} = 0.9910 \pm 0.1288i$.

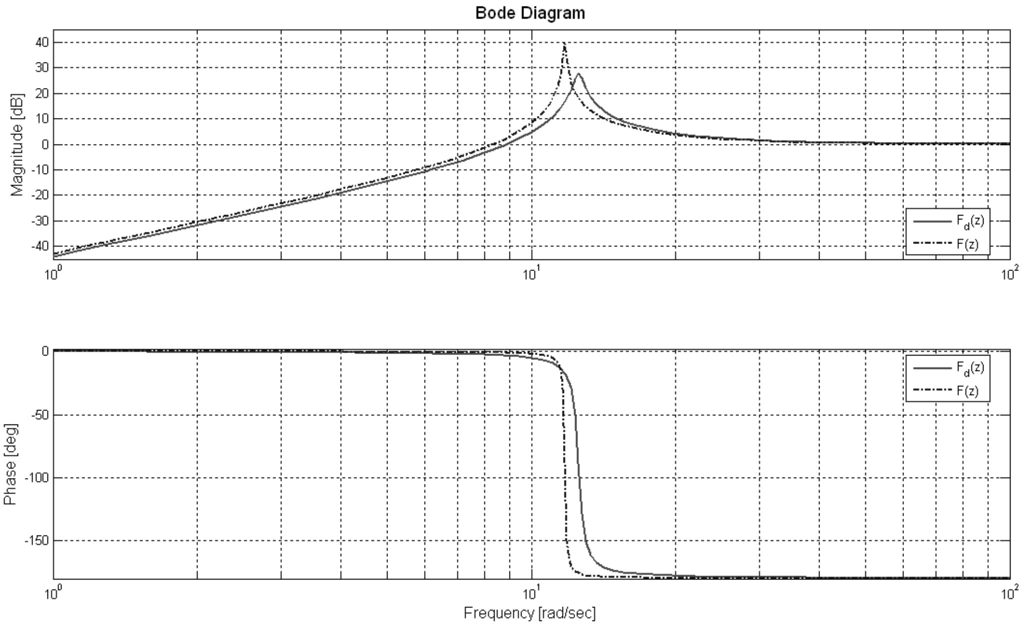

Fig. 9 Bode characteristics of sampled continuous model *F(p)* → $F_d(z)$ and identified *F(z.)*

Finally at the Figure 9 are Bode characteristics for sampled $F_d(z)$ and computed *F(z)*. Shapes of both diagrams fit the ideal characteristics in sense of the sensor parameters Štrunc and Dado, 2009. The difference between them is quite small. It might be caused by several mechanical improvements that were done during the described experiments. But generally LMS identification is the easiest and reliable way how to collect parameters during in-situ test period.

6. CONCLUSION

The rotational seismometry is quite young part of seismology. In this article was described our contribution to the measuring equipment for rotational seismometry. The first laboratory tests confirmed rightness of the proposed measuring system. Hopefully it can help to prove and interpret seismic rotation components.

The next steps should be some mechanical improvements and finishing of the electronic part of the sensor for the real in-situ tests. Tests will start near the quarries because blasts are perfect sources of vibrations (earthquakes) that are very strong. Despite the fact that the seismic noise near testing laboratory is quite high it was possible to reach quite high SNR.

After quarry-tests will come the most important experiment phase – measuring at a distant seismic station together with a group of classical seismographs – at the Ostas array (OSTA), Kvetna array (KVCA) or Novy Kostel array (NKCA).

The presented sensor features are high directional horizontal sensitivity, low penetration of the vertical move into measured quantity, high range of measurement (±2.5 mrad) and ability to measure from the low frequencies – in principle for 0 Hz because capacitive sensor measures position and not velocity as in case of classical seismometers. This is why the sensor allows to measure also vertical tilts not only rotations in horizontal plane. This feature can be used also for calibration Precision of angle measurement was during preliminary basic tests better than 10^{-4} rad thus reaching accuracy better than 10^{-6} rad seems to be feasible.

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SNÍMAČ ROTAČNÍHO POHYBU KOLEM SVISLÉ OSY PRO SEISMICKÁ MĚŘENÍ

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ABSTRAKT:

V rámci tohoto projektu se podařilo jednak zkonstruovat a otestovat rotační senzory na dvou principech a dále připravit generátor rotačních kmitů pro testování a seismickou prospekci.

Během teoretických analýz a praktických testů jsme objevili možnost použití rotačních vln jako prospekční metody. S ohledem na to jsme připravili v týmovém složení Jiří Málek, Johana Brokešová a Jaroslav Štrunc prototyp a následně patent na rotační generátor a na rotační senzor na indukčním principu. Patentovou přihlášku jsme podali v listopadu 2008 na Úřadu průmyslového vlastnictví ČR. Texty popisující vynálezy jsou součástí literatury Takeo and Ito, 1997; Buben and Rudajev, 2004.

Na rotačním senzoru na kapacitním principu jsme pracovali v týmovém složení Jaroslav Štrunc a Stanislav Ďaďo. Podrobný popis senzoru je uveden v článku Hobbs, 1907 . I tento typ snímače je právě v patentovém procesu v USA - prostřednictvím amerického Texas Institute of Science. Konstrukce vychází z popisu uvedeného v návrhu grantu a dále z výsledků získaných během prvního roku řešení. Kapacitní řešení se ukázalo také jako vhodné pro měření náklonů - a to buď pro účely přímého měření tzn. senzoru ve funkci náklonoměru, nebo využití náklonu o známé velikosti k přesné kalibraci senzoru.

Všechny realizované přístroje - dva typy senzoru a generátor - najdou uplatnění v rámci základního výzkumu ÚSMH AV ČR. V případě kladných výsledků patentových řízení předpokládáme také licencování jak pro vědeckou tak pro geo-inženýrskou praxi.

Z hlediska konstrukce senzoru a jeho testováni jsme dosáhli stanovených cílů. Další důležité výsledky očekáváme od rutinního provozu, který poskytne delší časový snímek pro porovnání naměřených dat se záznamy pořízenými seismickými sítěmi."