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New seismic array solution for earthquake observations and hydropower plant health monitoring

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Abstract We present the novel fusion of seismic safety monitoring data of the hydropower plant in Chirkey (Caucasus Mountains, Russia). This includes new hardware solutions and observation methods, along with technical limitations for three types of applications: (a) seismic monitoring of the Chirkey reservoir area, (b) structure monitoring of the dam, and (c) monitoring of turbine vibrations. Previous observations and data processing for health monitoring do not include complex data analysis, while the new system is more rational and less expensive. The key new feature of the new system is remote monitoring of turbine vibration. A comparison of the data obtained at the test facilities and by hydropower plant inspection with remote sensors enables early detection of hazardous hydrodynamic phenomena.

Keywords Seismic network · Remote sensors · Structural health monitoring · Hydropower station · Turbine · Vibration control

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1 Introduction

Hydropower plant along with its dam and reservoir is a large and complex industrial facility, and significant malfunction in its operation may lead to danger for people and environment. Plant structures may be highly affected by natural hazards such as earthquakes, and (or followed by) landslides, rockfalls, liquefaction, floods, water waves in the reservoir, etc. Hazardous situations can be caused by the degraded sate of the dam, by turbine operation disturbances, by aging and other effects to the dam state of health. Processes causing these dangers are of both natural (like earthquakes) and artificial characters—design flaws, omission of geological factors, and construction defects. In order to prevent accidents, many hydropower plants are commonly equipped with several independent monitoring systems utilizing different equipment and related processing techniques. The data of these systems and results of their processing and analysis are usually stored separately, and the complex analysis of all inhomogeneous data is nearly impossible.

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Historically, turbines are designed with static performance in mind basing on characteristics, which are measured for smaller models. This approach gives a satisfactory description of a turbine machine in a stationary and transitionary mode of operation, when regimes are switched smoothly. Nevertheless, such description fails when it comes to fast vibrational processes in the water flow part or an analysis of the dynamic stability is required. In a large amount of cases known today, the dysfunction of turbine machinery is accompanied by an elevated vibration and cavitations. An instability of a turbulent flow in the turbine is a traditional way to explain any unknown effect. However, such events are often related to the dynamic stability of the mechanical construction. The water column decreases the mechanical stability of a model. For example, a theoretical estimation for the case with perturbations that are characteristic for the water flow part (3 Hz pressure pulses of 0.1 atm) returns a 3.5 mm value for the displacement amplitude. Due to the influence of the water column and a drain tube, the characteristic oscillation forms of the working wheel blades change. Firstly, low-frequency forms can move into the range of work frequencies of a turbine given the water column is high enough. In such case, the turbine destabilizes. Resonances will cause a significant elevation of vibrations, which in turn will make the situation hazardous. The influence of the water column alters both frequencies and forms of characteristic oscillations. This phenomenon should occur most intensively at high-pressure turbines with long water lines.

There are a lot of works (i.e., Singhal et al. 1997, Panov et al. 2014) published that do theoretical descriptions or modelling of turbines. However, the data for real turbines and their malfunctions is published only in Russian sources of the twentieth century and for the famous disaster at Sayano-Shushinskaya Hydropower plant. There is practically no information regarding remote methods for hazard early detection, probabiy because of the corporate classification of related data.

We collected the observation results for the hydromechanics dangerous events in Table 1. Basing on these, we propose a method for early hazard detection. Further, an example of an early detection of a cavitation vortex-core flow is given. This technique can be applied in any HPS.

Every monitoring system utilizes its own specific sensors, communication protocols, and timing. Straightforward combining of such systems has the following disadvantages:

- An excessive amount of sensors with some of them duplicating the functionality of others with varying precision
- Difference in time intervals for measurements does not permit simultaneous data acquisition and processing
- Artificial limitation of continuous data acquisition (i.e., recording of seismic events only)

Table 1 List of observed hazardous hydrodynamic phenomena

Suggested cause	Hydropower plant, country	Gauge/measured characteristic	Value	Source
Shaft beating	Novosibirskaya, Russia	Vibrometer, turbine/oscillation displacement	1000 mkm	Beloglazov, Glazyrin 2009
Fluctuation of the water column in a waterway	Burehskaya, Russia	Seismometer, dam point/oscillation velocity	100 mkm/s	Khrapkov et al. 2007
Fluctuation of the water column in a waterway	Chirkey, Russia	Seismometer, dam point/oscillation velocity /	100–400 mkm/s	Our data
Fluctuation of the water column in a waterway	Krasnoharsjaya, Russia	Vibrometer, turbine/oscillation displacement	300 mkm	Bryzgalov 1998
Cavitation vortex-core flow	Chirkey, Russia	Seismometer, machine hall point/ oscillation velocity	50 mkm/s	Our data
Complex origin	Sayano-Shushinskaya, Russia	Seismometer, dam point/oscillation velocity	120–450 mkm/s	Seleznev et al. 2012

In most cases, plant health monitoring is served by three systems, which perform observations of different objects and areas (Fig. 1):

1. Seismic monitoring of the reservoir area
2. Structure monitoring of the dam itself
3. Monitoring of turbine vibrations

All three types are obligatory according to code norms in Russia (Technical guidance document 1995) and in a number of other countries (Standard: ANSI/ASA S2.47 1990; Mivehchi et al. 2003). This is a legacy of an old analog data acquisition and processing inability to exploit sensors to their full potential. Thus, low precision sensors were intentionally selected, due to artificial division of seismic oscillation field into frequency bands, each responsible for several types of oscillations: earthquakes, dam oscillations, separate vibrations of turbine and its parts, etc. We review each set of requirements in detail to determine which restrictions are substantial and which ones are due to the hardware limitations.

1.1 Seismologic observations

The main goal of seismologic observation is collecting information on local earthquakes. Obtained focal locations and magnitudes are utilized for (a) estimation of possible impacts on a dam, (b) calculation of seismic activity for earthquake hazard estimation, and (c) detection of induced seismicity. Initially, only relatively strong events were observed (magnitude $M > 3$). In the last decade, the data on microseisms (Yudakhin et al. 2005) and micropulses ($M < 0$) (Spungin et al. 1997) have been appended successfully. The following requirements can be deduced from published experience (Simson et al. 1988; Savich et al. 1990; Kirkegaard and Brincker 1994; Technical guidance document 1995; Manual… 2001; P 92–01 Manual 2001; Gupta 2002; Mivehchi et al. 2003; Kapustian and Yudakhin 2007; Gupta and Rastogi 2013):

i) *Sensors* have to be triaxial (*X*, *Y*, *Z*) broadband (frequency range from 0.2 Hz) seismometers with a noise floor better than −130 dB and preferably velocity-meters. Horizontal axis shall be oriented along cardinal directions (N-S, E-W). Dynamic range of sensors have to be higher than 130 dB, with the full scale of 1 g. Stability of sensor characteristics and its linearity is very important because we analyze not only wave arrival times but also amplitudes and spectra of the monitored signals.
ii) *Data acquisition* and transmission shall not degrade performance of the sensor; meaning that the dynamic range is not less than 130 dB and the sampling rate should exceed 50 Hz. Some sensors provide analog output only with signal level of dozens of microvolts; thus, the data sampling/amplification in such case is to be performed in a close proximity to sensor. The recording must be continuous (not triggered events only); therefore, data stream rate from one triaxial sensor shall be at least 4800 bps. Data can be either stored locally or transmitted to a

Fig. 1 Chirkey plant health monitoring system, main parts: *1*—seismic monitoring of the reservoir area; *2*—structure monitoring of the dam itself; *3*—monitoring of turbine vibrations

central processing unit. There are usually at least three observation points in the reservoir area at a distance of 30 km from the dam. The crucial parameter is the precision of synchronization of signal to Coordinated Universal Time (UTC). According to review (Danilov et al. 2014), sensors in seismology provide synchronization between 1 and 20 μs.

1.2 Seismic monitoring of a dam

The goal of seismic observation is estimating the dam's stress-strain state, to identify weakened areas within the dam's body and its junctions with sides. Depending on the exact task and codex requirements in a country, two methods are applied. First method is a calculation of a response spectrum of the structure to strong impacts and the second one is based on probing a dam by ambient noise with the subsequent derivation of characteristic oscillation forms (Ibrahim and Mikulcik 1977; Fenves et al. 1992; Loh and Tsu-Shiu 1996; Daniell and Taylor 1999; Darbre and Proulx 2002; Chuhan et al. 2009; Antonovskaya et al. 2014). The former method requires permanent observations, while "moving point" observations have to be performed for the latter. If the ambient noise has to be monitored, either the sensors have to be connected in one network with permanent data acquisition or local data storages have to be installed. The latter approach is efficient only if the amount of sensors is small. For moving point observations, one sensor has to be stationary while others are moved across a dam.

Based on Ibrahim and Mikulcik (1977), Fenves et al. (1992), Loh and Tsu-Shiu (1996), Daniell and Taylor (1999), Darbre and Proulx (2002), Chuhan et al. (2009), and Antonovskaya et al. (2014), the following requirements have to be met:

i) *Sensors*: in case of the permanent observation, one can use sensors with low sensitivity; however, the strong motion detection and recording is required. Frequency band is 0.5–25 Hz and the dynamic range is over 124 dB. High sensitivity sensors (130 dB, 0.5–50 Hz) are required for noise probing and moving point scheme, capable of identifying the characteristic oscillations of a dam. Both velocimeters and accelerometers are suitable for either method. Sensors shall be triaxial ones (*X*, *Y*, *Z*) with lateral axis aligned with radial and tangential directions of an arc dam or lengthwise and crosswise for a linear dam.

ii) *Data acquisition*: in permanent measurements, the bandwidth can be up to 50 Hz, 124 dB, and registration is a continuous recording only of those events, which STA/LTA ratio exceeds certain threshold (Allen 1978; Technical guidance document 1995). The accuracy of data synchronization with UTC is of the same level as in seismological observations. For the moving sensor method, sampling rate should be more than 100 Hz, 130 dB, to ensure recording of high-frequency characteristic oscillations. The duration of recording at each point can be from minutes to hours. Data is saved either on internal storage of a digital sensor or to the server by LAN. Time synchronization should be better than 1 μs, which is required for further data processing by correlation algorithms (Antonovskaya et al. 2014). Technical solution for precise time synchronization can be tricky because either GPS sensors need to be placed outside the dam body to function or sensors have to rely on their internal clock.

1.3 Vibration monitoring of turbines

Quick identification of their abnormal oscillations can prevent a possible incident of a turbine malfunction. Sensors measure mechanical vibration and if its level exceeds a threshold, the turbine is shut down. According to Russian codex (Technical guidance document 1995), all vibration sensors are to be united in a single network, which is connected to an automated control system.

Despite tens of sensors used for monitoring, some phenomena may remain undetected or misinterpreted. For example, the vibrational control system cannot distinguish on its own whether the turbine, local earthquake, or a malfunction of some machinery in close proximity causes an abnormal signal. Another crucial safety issue is a cavitation effect. Pressure sensor in a deferent chamber (Xu Zhenyu et al. 2015) is mostly used to detect it. The signal processing is limited to the detection of abnormal pressure spikes, and the noise from other processes deteriorates it. To improve the quality of detection, the monitoring system has to be extended with remote sensors, complex data processing, and sensors that measure seismological events, as demonstrated by the example below.

Table 2 is a collection of sensor and data processing requirements for any seismic network built for

Table 2 Main requirements for hydropower plant monitoring seismic networks

Monitoring type	Study subject	Dynamic range of sensor, dB	Dynamic range of digitizer, dB	Frequency band of signal, Hz	UTC accuracy, μs
Seismology	Earthquakes	>130	>130 at 50 sps	0.2–25	1–20
Seismic inspection of structural integrity	Strong motion	>124	>124 at 50 sps	0.5–25	1–20
	Ambient noise	>130	>130 at 100 sps	0.5–50	1 or seconds
Vibration control of turbines	Fluid pressure pulsations	>130	>100 at 200 sps	1–100	20
	Turbine vibration	>130	>130 at 200 sps	1–100	1

hydropower plant monitoring. The first two types of monitoring systems can be combined into a single network, which also allows monitoring of turbine vibrations. Importantly, the fusion is not a simple data stream collation but involves new principles for sensor placement and data acquisition. One such network is on Chirkey plant (Caucasus Mountains, Russia).

The goals of this article are to present technical solutions and to demonstrate new capabilities of the multipurpose seismic monitoring system, which we have built for Chirkey plant.

2 Experimental section: combining monitoring networks

2.1 Network construction principles and monitoring requirements

A monitoring system in design shall meet the following criteria:

- Recording of both local and regional types of seismic events (earthquakes, explosions, hydroturbine launches) with microseisms included. Data processing measures seismic intensity of an event in real time. Seismological data processing and main interpretation includes the estimation of the event type (earthquakes or local vibrations), its magnitude, and epicenter location. Processing can be performed with the addition of data from regional seismic networks. Microseism registration system should provide means to identify characteristic (or natural, eigen-) frequencies of the dam, oscillations caused by hydrodynamic pulses during the turbine operation, and micropulses (i.e., using methods from the article (Yudakhin et al. 2013)). Monitoring of dam oscillation magnitude for turbine rotation impact is performed in real time. Continuous observations are required by the technique of probing dam body and geologic media, using seismic signal generated by turbine rotations (Antonovskaya et al. 2016).
- All low-sensitivity seismic sensors on the dam operating in the triggering mode are to be replaced with high-sensitivity ones for recording not only the rare strong events but also regional earthquakes of smaller magnitudes. Additionally, this enables the dam monitoring based on ambient noise and natural mode shape analysis.
- All data have to be collected by the data center in real time, so that all estimations and processing (calculating spectra, STA/LTA event filtering (Trnkoczy 2009)) can be done promptly. The system must include real-time processing software and must allow control of the system operation and calibration of sensors from the central access point. Timing of all data channels shall be synchronized with UTC with the precision of at least 0.1 μs.
- Processing software should include option to export data into formats supported by standard packages for seismological analysis, finite elements calculations, etc.
- System should be expandable and support sensors of various types (velocity-meters and accelerometers) in case of a need for urgent replacement.
- No constrains to the range nor location of sensor placement. Sensors can be placed at a long distance from the center or inside the dam body, as well as in the turbine hall. Data transmission lines should be noiseproof including shielding from atmospheric electricity.

If all listed requirements are met, the amount of sensors, their data storages, or processing units can be reduced to minimize the cost of the installation. For example, a few sensors from seismologic network can be replaced with sensors installed on the dam and its joints, therefore eliminating at least one seismologic registration point and if the dam is large—two points (right and left sides of the dam). This is particularly essential because the sites in rocky areas are often hard to reach and each of them requires costly infrastructure (a pavilion, power solution, maintenance works, etc.).

Additionally, sensors on the dam can improve the quality of picking weak earthquakes if the recordings are summarized. Figure 2 contains an illustration of this by recording a local earthquake (31 March 2013, $M = 4$) by the system on Chirkey plant.

In Fig. 2, recordings are shown for points along the gallery (st. 2, 3, 4) with the adjusted result of their summarization with delays between channels. The summarization shows arrivals of S-waves clearly, which allow locating the event more precisely.

Seismic monitoring of the reservoir area is similar to the typical regional seismic network, calculating earthquake epicenter location from P- and S-wave arrivals. Usually, it is not recommended to place sensors on a structure for seismologic observations because the recorded signal would include a response of the structure. Dynamic characteristics are altered in such case but wave arrivals are not. This is proved by observation of waveforms at the dam and outside (dam-board joint)—Fig. 2.

2.2 System at Chirkey hydropower plant

Chirkey plant is built on the river of Sulak in a Caucasus high seismicity region. Concrete arch dam is 232.5 m high and 338 m long (Fig. 3). Turbine halls next to the dam accommodate four Francis turbines. System installation was performed in two steps for possible corrections. During the first step, we have placed sensors at the points, which are critical for the dam state. Data cables are laid in a way that additional nodes can be easily appended to the system. The first part of the system was commissioned in 2012. It had been operating for 4 years without any malfunction, and a decision was made to expand the network.

Seismometers were placed along two inner galleries of the dam (315 and 265 m marks), in side-dam joints, turbine halls, and 7 km away in seismic station Dubki (DBC, Russian Geophysical Survey). All sensors are listed in Table 3, and Fig. 3 shows their location on the dam.

We used Russian seismometers SM-3 and accelerometers CMG-5T (Guralp, http://www.guralp.com). Seismometers have higher sensitivity in low-frequency range and are preferred for recording of earthquakes and dam oscillations. Recordings by accelerometers are better suited for the needs of the structure computer simulations, at least in Russia. We installed one velocitymeter and one accelerometer in the center of the dam at the level of 315 m, so that these data types become comparable in a single point. Data collection center is located near the dam ridge. It also contains a GPS to perform time synchronization. Fiber optic cables are used for interconnection of all sensors in the network and for communication with the seismic station Dibki.

2.3 Physical layer of Chirkey hydropower plant network

Physical layer of seismic network includes seismic sensors, data loggers, and optical fiber lines, which connect

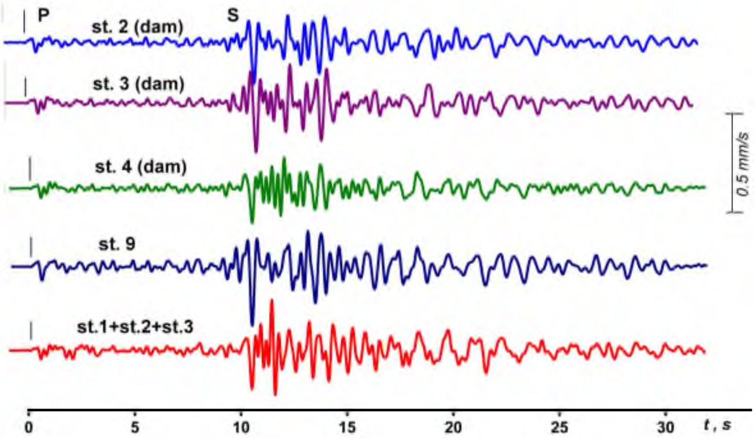
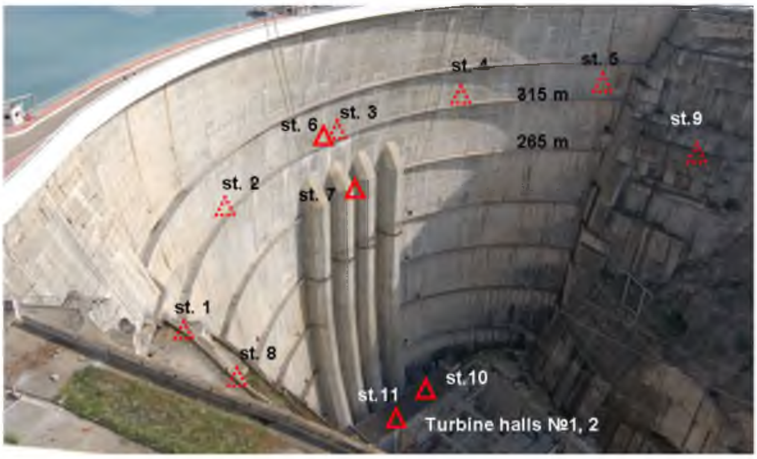


Fig. 2 An example of the local earthquake (31 March 2013, $M = 4$) recorded by Chirkey monitoring system, and shown are P- and S-waves' arrivals. Seismic sensor location: *st. 2*, *3*, and *4*—dam body, *st. 9*—dam-board joint

Fig. 3 Chirkey dam view with seismic sensors position (*solid triangles*—accelerometers, *dotted ones*—seismometers)



data loggers to the data processing center. Data loggers are placed near sensors to avoid problems with analog signal transmission.

The seismic network uses Precision Time Protocol based on IEEE 1588 standards. Single Precision Time Protocol master unit is located in the data processing center and contains GPS timing module, which generates GPS synchronized 10 MHz clock pulses and 1 s pulses. The synchronizer unit keeps Precision Time Protocol clocks of all data loggers locked to GPS clocks. Our tests on site with the network including one Ethernet switch and few media converters demonstrated that the time error is below 150 ns with a typical error of 50 ns.

Table 3 Sensors and installation points of Chirkey monitoring system

Point no.	Seismometer type	Location
1	CM-3 (SM-3)	Mark 315 m section 16
2	CM-3 (SM-3)	Mark 315 m section 10
3	CM-3 (SM-3)	Mark 315 m section 1
4	CM-3 (SM-3)	Mark 315 m section 7
5	CM-3 (SM-3)	Mark 315 m section 15
6	CMG-5T (±0.1 g)	Mark 315 m section 1
7	CMG-5 T (±0.1 g)	Mark 265 m section 1
8	CM-3 (SM-3)	Mark 265 m right board
9	CM-3 (SM-3)	Mark 265 m left board
10	CMG-5T (±1 g)	Turbine hall no.
11	CMG-5T (±1 g)	Turbine hall no 2
12	CM-3 (SM-3)	Seismic station “Dubki”

The data logger consists of analog-to-digital converters (ADCs), microprocessor controller, and optical transceiver. It communicates with the data processing center through single-mode optical fiber line 100BASE-FX WDM standard. Length of fiber cables can exceed 20 km.

Analog front-end contains three delta-sigma ADC with low-noise (5 nV/Hz$^{1/2}$) programmable gain amplifier. ADCs have extremely high resolution of 130 dB SNR (signal-noise ratio) at 250 SPS and linearity of −122 dB THD (third harmonic distortion). These parameters allow recording of signals in a wide dynamic range without switching the input amplifier gain. Two selectable conversion rates are 250 and 1000 samples per second. Rate of 250 samples per second is minimal for the given ADC type. Lower rates of 125 and 72.5 samples per second are possible by applying additional filtering in the microprocessor using low-pass finite impulse response filter with decimation. ADC clocking scheme has a phase-locked loop generator disciplined by Precision Time Protocol clocks. Clocking scheme uses pulses from Precision Time Protocol module to synchronize ADCs. Data sample format is 32-bit integer.

The data logger sends measured data in packets of 100 samples using an internal protocol encapsulated in the TCP/IP packet. Each packet has a timestamp from Precision Time Protocol clock. The data are stored in ring buffers with the length of 10,000 packets (more than an hour at 250 samples per second) in the on-board memory. The data processing center controls data loggers and monitors their state by using UTP protocol. On-board arbitrary form generator based on 12-bit DAC (digital-to-analog converter) acts as a source of the test signal for sensor testing and calibration.

Data processing software acquires processes and stores seismic data from sensors. It uses the following procedures:

Data acquisition. Software collects packets from data loggers together to form a continuous data flow for each data logger.

Preprocessing: scaling. Converting raw ADC counts to floating point physical values of acceleration or velocity.

Preprocessing: filtering. Software uses number of filters for different purposes:

- Low-pass filter for STA/LTA detector
- Set of narrow-band filters for single frequency component monitoring
- High- and low-pass filters to display signals from sensors on data center monitor in real time. Filtering is necessary for better visual signal representation

Processing: STA/LTA. Detector of STA/LTA events uses standard procedure with individual parameters for each sensor.

Processing:sSingle frequency components. Set of frequencies (up to 16) are recorded continuously. Software compares power of selected spectral components against thresholds to generate events.

Monitoring. Software monitors the status of loggers, quality of time synchronization, and continuity of data flow. It generates errors (alerts) on any detected malfunctions.

Data storage. Software stores preprocessed data to a disk storage unit and keeps an archived copy in NAS storage.

Database. Software registers all received data, spectral power of single frequency components, and all events in a database.

3 Experimental section: observations of pressure pulsation

Observation network of Chirkey plant monitors natural frequencies of the dam, earthquakes, their impact on the dam, and a response of the dam (Antonovskaya et al. 2016). All operations are performed in accordance with the traditional methods (Savich et al. 1990; Kapustian and Yudakhin 2007). One new function of our monitoring system is a detection of abnormal turbine pulsations by seismic observations in a remote point.

There is a great number of publications devoted to the study of abnormal pulsation and cavitation phenomena. Mostly, these are computer simulations with various levels of detail that describe different stages of a process evolution (Singhal et al. 1997; Casoli et al. 2005; Bykov et al. 2014; Panov et al. 2014; Dekterev et al. 2015). Values of operation parameters, at which events take place, such as water pressure or electric load receive the highest attention (Bondarenko et al. 1984; Dekterev et al. 2015). Conclusions are drawn by comparing simulated values and real observations but latter ones are present only as a validation of the model. In Abelev and Solovyova (1983), authors derive the specific ratio of water pressure to turbine power that leads to dangerous events. On its basis, pressure-power space is split into zones, where turbine can or cannot operate (an example is in Fig. 13).

Our interest is to define the criteria for oscillations, which can indicate the increasing risk of a hazardous cavitation. This is of high practical value for turbine monitoring, which is performed from a remote point with values of pressure and power not yet known and a cavitation already being born. In papers (Ahuja et al. 2001; Panov et al. 2014; Dekterev et al. 2015), authors have come closest to the solution of this probiem; however, the data presented is obtained by a sensor placed directly on the turbine and no information regarding the remote point is given.

3.1 Natural modelling of turbine operation on a test bench

Prior to oscillation field analysis of Chirkey plant, we performed a study of the Francis turbine with a test bench at JSC Silovye Mashiny. The aims of the experiment were to identify signatures of cavitation pulsations, to confirm that these events can be detected at a distant point, and to determine optimal parameters of sensors.

We used the following equipment: triaxial accelerometers Guralp (http://www.guralp.com/products/instruments/guralp-5-series) – CMG-5T (analog) and 5TD, analog rotation velocity-meter METR-03 (Agafonov et al. 2015; Zaitsev et al. 2015), data loggers ADAS3 (Antonovskaya et al. 2016) (the same as in

Chirkey plant), and GSR-24 (GeoSIG Ltd., www.geosig.com). Seismic records were compared with the reference signal of vibration displacement sensor IVP-05-0.8/200 (in Russian ИВП-05-0.8/200 (http://www.tnlab.ru/ivp05.php)). Prior to the experiment, all sensors were placed on a single slab in order to receive simultaneous recordings of the ambient noise signal (Fig. 4) and to ensure required correlation of all sensors.

Sensors IVP-05-0.8/200 were attached to the sides and to the back of the exit pipe. Accelerometers were placed at different points on the turbine lid, on the stand base, on the floor nearby, and 15 m away from it. Accelerometer axes are 1—across the water stream, 2—along it, and 3—vertical. The information provided by recordings at these points was similar; therefore, indicating the vibration diagnostics at the remote location is a viable option.

Francis turbine operated in nine different modes, both the optimal (recommended) and non-recommended ones. Figure 5 contains the so-called propeller characteristic showing the efficiency of turbine operation dependency on reduced revs and reduced water flow values with points marking these regimes. Regimes 5, 6, and 7 are discussed below with sixth one being optimal. Other two imply a possibility for hazardous cavitation vortex-core flow with opposite directions of rotation.

Data processing We describe here the procedure for processing of the signals from seismic sensors. Firstly, the visual inspection reveals low-quality data, which is excluded, and the rest is registered into a logbook. Then, we adjust the parameters of power spectra calculation: number of points (frequency resolution) and number of windows for spectra summarization (to decrease arbitrary component dispersion and to identify stable peaks more precise). The common values are 1024 points and 20 windows. Power spectra are the most powerful tool to study processes discussed. It can be 2D graph of power spectrum versus frequency or 3D graph of spectra-temporal analysis (STAN), which is a procedure of power spectrum calculation in sliding window along time axis. If required, we convert acceleration into displacement. In order to separate peaks, generated by the bench, from the peaks that originate at the pipe, we compare spectra at the time of launching different machines and spectra for test runs. Figure 6 shows acceleration power spectra for vertical component (Z) of the background signal for different modes of the bench and at launches of the pump and turbine. Peak at 36 Hz is associated with the pump operation. Pre-launch signal recordings enable the correct identification of this and other peaks. Turbine-operating regimes were cycled in series with the duration of 20 min each.

Figure 7 shows signal processing results for sensors on the bench housing and at the floor, and the presented STAN diagrams are for regimes 1–4. Characteristic frequency maxima (10 Hz and above) are prominent in both points. At the floor, however, a parasitic signal is present at 5 Hz. Further analyses are mostly with the signal from the bench housing. Turbine vibration propagates well beyond the bench like it does at Chirkey plant, where turbine vibration is detected even at the dam-side joints.

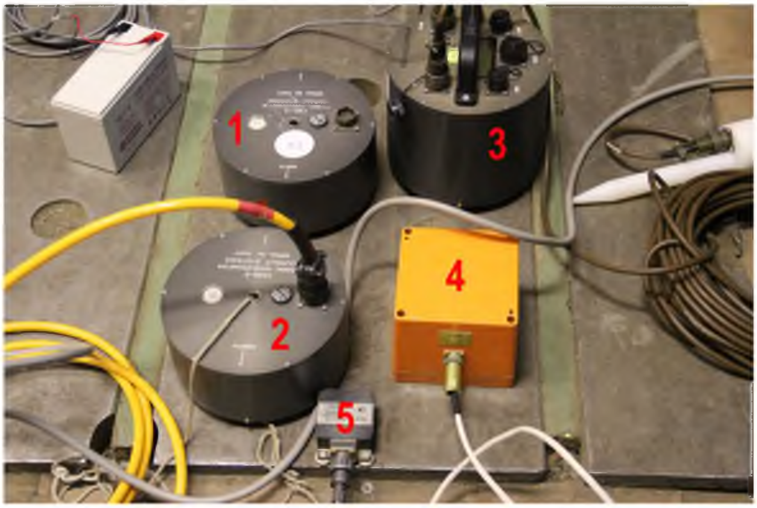


Fig. 4 Sensors on the slab: CMG-5T with sensitivity 1 g (*1*) and 0.1 g (*2*), CMG-5TDE (*3*), METR-3 (*4*), and IVP-05-0.8/200 (*5*)

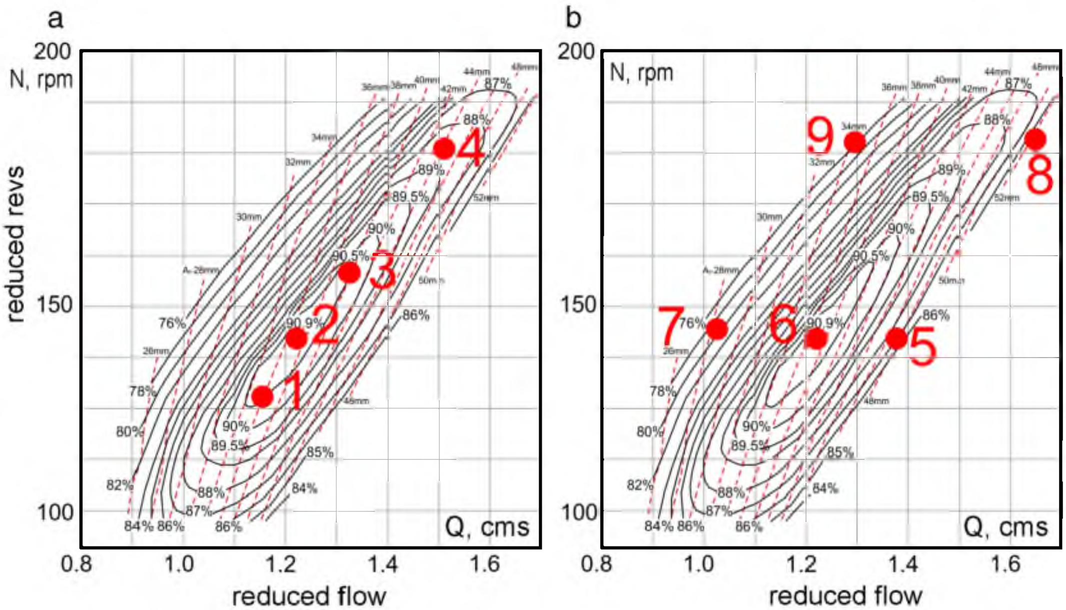


Fig. 5 Propeller characteristics for the two parts of experiment (**a**, **b**). *Spots with numbers* mark Francis turbine operation regimes. Percents show turbine operation efficiency

Figure 8 contains power spectra for the vertical component of accelerometer on the bench and allows comparing 2D (power vs frequency graph) and 3D (STAN diagram) presentation. Peaks marked with a black arrow correspond to the turbine rotation and are well distinguished. When a regime shifts across the propeller characteristic, these peaks move to higher frequencies. Pink arrows mark peaks with the frequency equal to 0.7 of the rotational one. These peak frequencies do not shift while the regime is changing. STAN diagram in Fig. 8 demonstrates a visible "jump" from a constant frequency line to another when the regime changes. Peak marked in the 2D graph with a pink arrow is frequency stable but disappears sporadically in regime 4. Therefore, we used both types of processing presentation and in discussion picked those, which illustrate the effect better.

3.2 Monitoring of Chirkey hydropower plant

The possibility of the vibration control by seismic system of Chirkey plant is illustrated by Fig. 9. A local earthquake and the turbine launch take place within a short time interval. High dynamic range of the system allows seeing both events on seismograms recorded on the dam, at its joints with boards and in the turbine hall, especially if a filtering is applied. This proves that if seismic monitoring is combined with vibrational control, the system gains the ability to separate impacts of

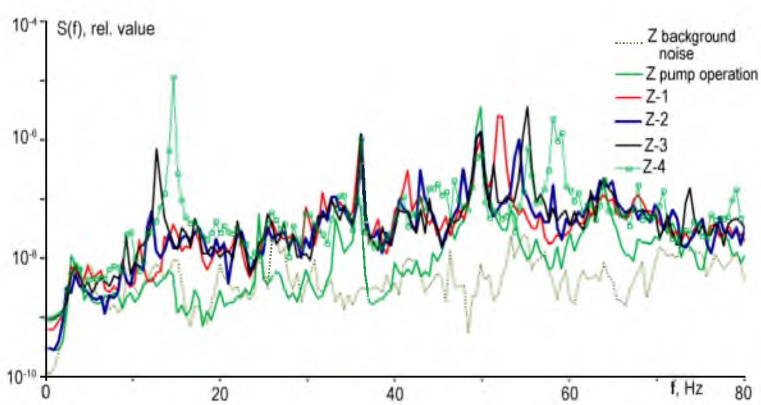


Fig. 6 Acceleration power spectra (*Z* component) for seismic noise, pump operation, and different regimes (see in Fig. 5 the numbers and parameters of operation)

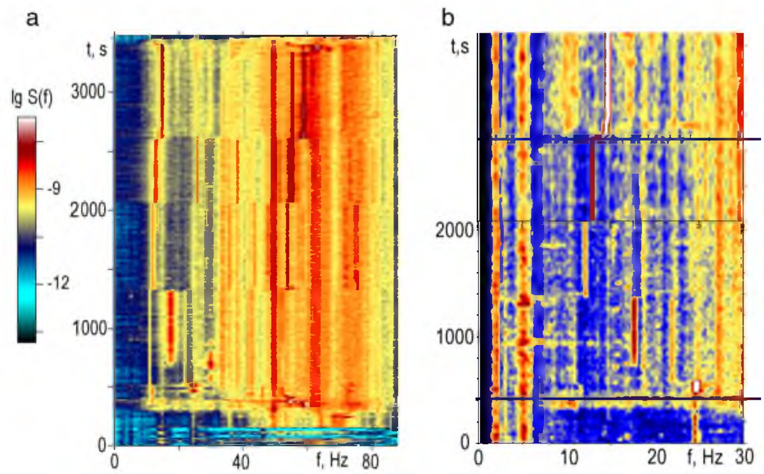


Fig. 7 STAN diagrams for two sensors—at the bench (**a**) and on the floor (**b**)

turbine movement from displacement due to earthquake automatically.

4 Results and discussion

4.1 Experiment at the test bench

4.1.1 Comparison of sensors

Signals of both standard seismic and vibration sensors (CMG-5T and IVP-05-0.8/200) had been recorded simultaneously. Figure 10 shows the power spectra (recalculated into displacement) for sensors IVP-05-0.8/200 and for *Z* component of an accelerometer at the top of the turbine lid.

Accelerometer power spectra for all three components are similar and therefore we show only *Z* component. The spectra from different devices are comparable and particularly above 7 Hz. In a lower frequency range, displacements measured on the pipe are significantly more intense than displacements on the lid. We explain this by partial damping of vibrations by machine parts. Noticeably,

- peaks at the rotation frequency f_0 = 12 Hz are the most prominent on accelerometers recordings
- spectra of IVP-05-0.8/200 records are different for points on the side and in the back of the pipe and up to the disappearance of peaks at the rotation frequency f_0 (regime 6: pipe side)
- spectra of accelerometer records of all regimes contain a wide maximum at f_1 = 8 Hz

According to Panov et al. (2014), $f_1 \approx 0.7\ f_0$ is an indication of a situation, when a cavitation vortex-core flow can appear. Oscillation magnitude ratio for f_1 and f_0 is approximately 1:2 for regime 7 and 1:4–1:5 for regimes 5 and 6. It is worth noticing that spectra by IVP-05-0.8/200 contain less prominent maxima. Comparison of data by linear (accelerometers and IVP-05-0.8/200) and rotational sensors is complicated because it is difficult to convert

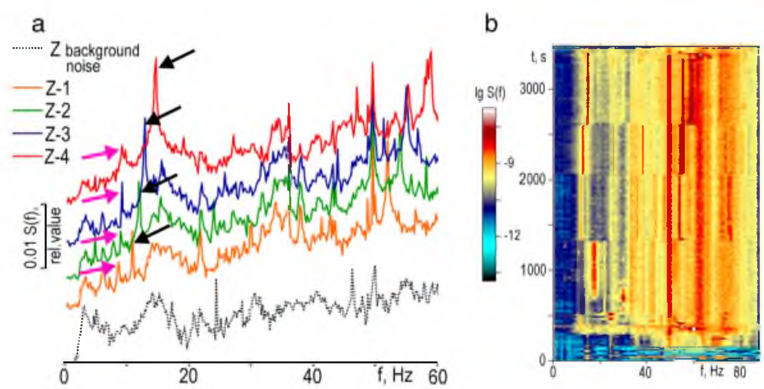


Fig. 8 Acceleration power spectra for *Z* component (**a**, graphs shifted vertically) and STAN diagram for regimes 1–4 (**b**)

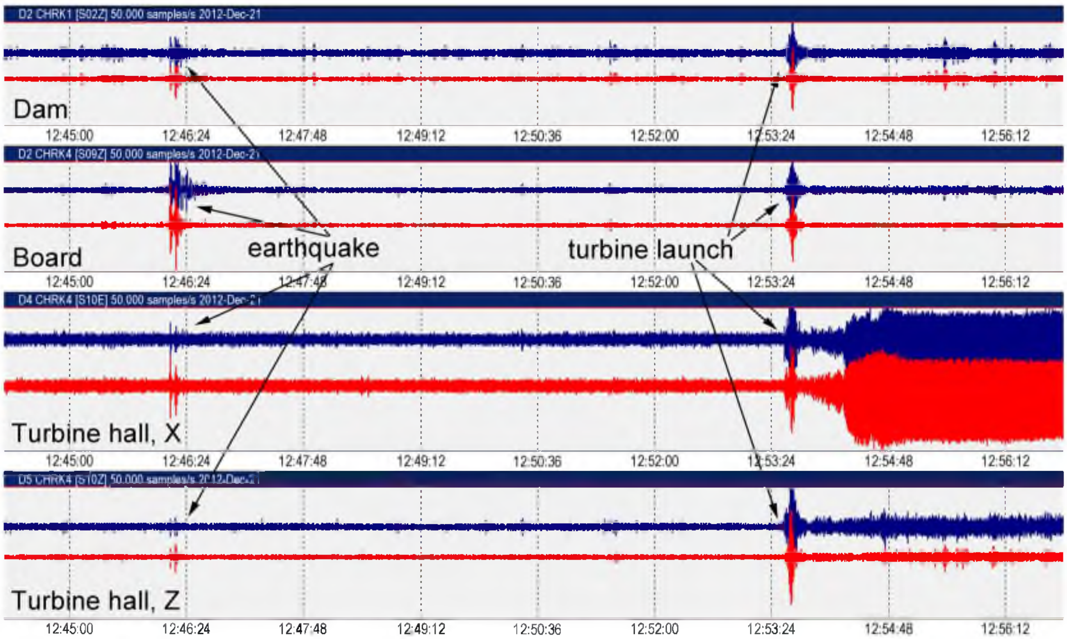


Fig. 9 Seismic records by Chirkey monitoring system with the turbine launch and an earthquake

these signals to a single dimension. STAN diagrams, however, enable such comparison if the temporal flow of the signal is considered. This is due to rotational motion at the cavitation vortex-core flow frequencies.

4.1.2 Identification of hydrodynamic pulsations

STAN diagrams for regimes 5, 6, and 7 in Fig. 11 contain signals from sensors, which measure acceleration and rotational oscillation velocity near the turbine and vibration displacement on the turbine. A detailed image is shown for component 2 of the latter—rotation in a plane perpendicular to the water stream. According to STAN diagrams, linear sensors barely distinguish operation regimes while rotational sensors indicate differences between regimes clearly. Rotation frequency is always present as a vertical line. An additional line at 7–8 Hz appears in regime 7 and is not present in regime 6, and chaotic spots appear at this band in regime 5. This frequency is not seen on STAN—diagrams of linear sensors but some power surges are.

Coherent-temporal analysis (CTAN) is similar to STAN; it calculates coherence function of two records in a sliding time window. In case of two records in a point (i.e., two components of the three-component sensor), it is the measure of phase correlation for components (Yudakhin et al. 2013). CTAN diagram of the rotational sensor reveals another striking feature—Fig. 12.

A turbine wheel rotates around the axis 3; it does not create water circulation in other planes and thus

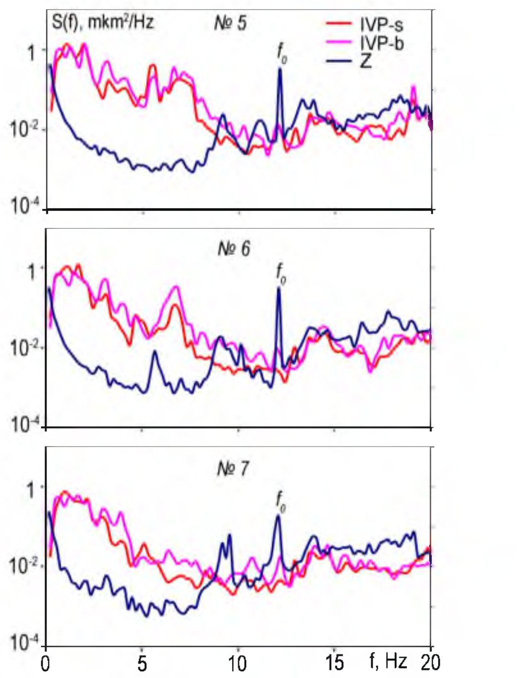


Fig. 10 Power spectra for regimes 5–7 recorded by *Z* component of CMG-5T, IVP-05-0.8/200 at the side (IVP-s) and at the back (IVP-b) of the exit pipe

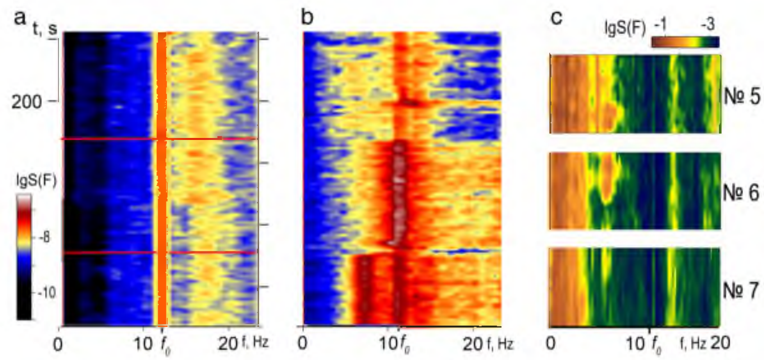


Fig. 11 STAN diagrams for simultaneous recording by accelerometer CMG-5T (**a**), rotational METR-03 (**b**), and IVP-05-0.8/200, back of the pipe (**c**), regimes 5, 6, and 7

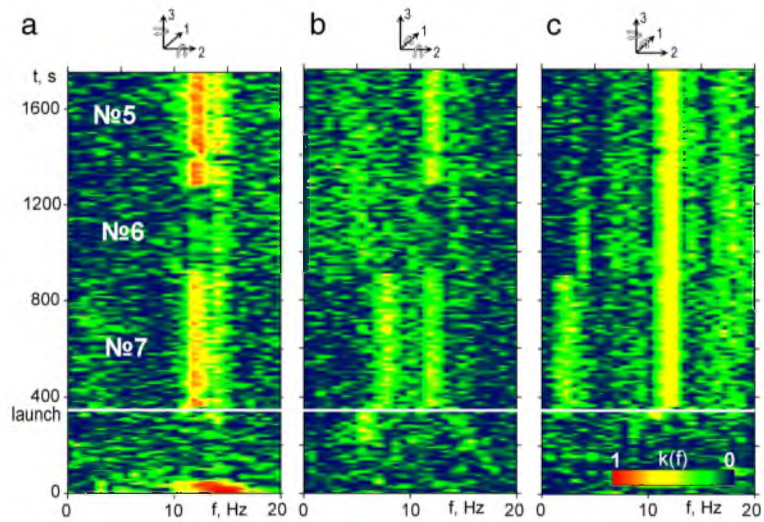


Fig. 12 CTAN diagrams for regimes 5–7. All components of rotational sensor (**a**–**c**) are present, and top schemes show which rotations are analyzed

the coherency cannot exceed 0.5. This is indeed so for regime 6 at the rotation frequency for pairs 3-2 and 1-2. Bench parts produce noise, which disturbs coherency value for pair 3-1. CTAN diagram for pair 1-2, regime 7, has distinct lines at 7-8 and 12 Hz indicating the presence of circular descending

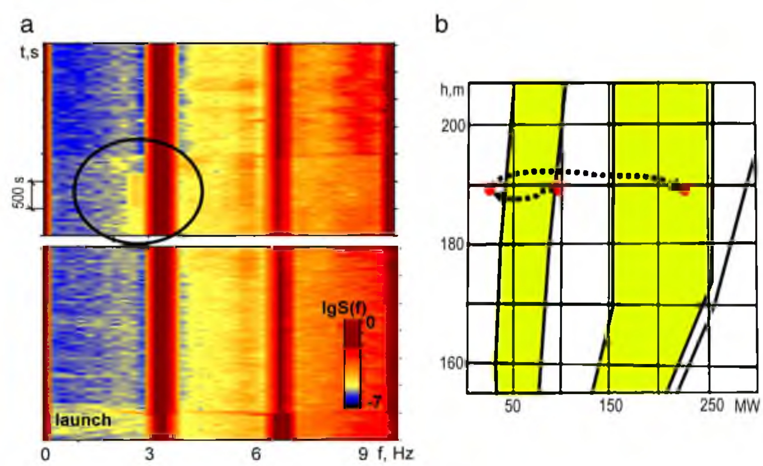


Fig. 13 STAN diagram (**a**) for the turbine hall of Chirkey hydropower plant. Regimes are marked on the operational chart (**b**) of the turbine

rotations. Most likely, this is a cavitation vortex-core flow. Frequencies of these rotations in regime 5 are equal to the rotation frequency.

All these features clearly demonstrate that the rotation oscillation sensor is very efficient at hydrodynamic pulsation detection. Linear sensors, accelerometers, and vibrational displacement detectors can detect it, too, but they are less efficient.

4.2 Turbine operation monitoring at Chirkey hydropower plant

STAN diagram (Fig. 13) for the accelerometer in the turbine hall (component is along the stream) has distinctive main rotation frequencies f_0 = 3.33 Hz and overtones at 6.66 and 9.99 Hz.

In the middle part of the diagram, a circle marks an area with emerging frequency 2.7 Hz, which is most likely associated with a cavitation vortex-core flow. Diurnal variation shows that this event occurred when the power rapidly dropped from the value on the border (between recommended and non-recommended zones) into the non-recommended zone. Consecutive rapid elevation of power prevented further development of the situation and lead to a disappearance of 2.7 Hz oscillations. These low-frequency oscillations were detected across all points on the dam and side joints, though less prominent.

5 Conclusions

The presented new approach of combining different monitoring methods is a first experience in series of monitoring systems to be installed on hydropower plants in Caucasus.

Experiments conducted on test bench prove that vibration diagnostics can complement seismic monitoring of the turbine efficiently.

Prompt detection of hydraulic disturbances in an exit pipe of a turbine is possible.

The system can distinguish earthquake events, turbine launches, and other motions.

Rotation oscillation sensor is a substantial asset, which is installed in conjunction with accelerometer in the turbine hall, can bring the efficiency of cavitation hazard detection to a new level.

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Authors' contributions Galina N. Antonovskaya and Natalya K. Kapustyan designed the experiments and processed the data, and wrote the manuscript. Alexander I. Moshkunov developed physical layer of Chirkey hydropower plant network and data processing software. Alexey V. Danilov took part in data processing and observations.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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