Monitoring Heart Health and Structural Health: mDFA Quantification

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ABSTRACT

The aim of this study was to make a method for an early detection of malfunction, e.g., abnormal vibration/fluctuation in recorded signals. We conducted experimentations of heart health and structural health monitoring. We collected natural signals, e.g., heartbeat fluctuation and mechanical vibration. For the analysis, we used modified detrended fluctuation analysis (mDFA) method that we have made recently. mDFA calculated the scaling exponent (SI) from the time series data, e.g., R-R interval time series obtained from electrocardiograms. In the present study, peaks were identified by our own method. In every single mDFA computation, we identified ~2000 consecutive peaks from a data: "2000" was necessary number to conduct mDFA. mDFA was able to distinguish between normal and abnormal behaviors: Normal healthy hearts exhibited an SI around 1.0, which is a phenomena comparable to 1/f fluctuation. Job-related stressful hearts and extrasystolic hearts both exhibited a low SI such as 0.7. Normally running car's vibration—recorded steering wheel vibration—exhibited an SI around 0.5, which is white noise like fluctuation. Normally spinning ball-bearings (BB) exhibited an SI around 0.1, which belongs to the anti-correlation phenomena. A malfunctioning BB showed an increased SI. At an SI value over 0.2, an inspector must check BB's correct functioning. Here we propose that healthiness in various cyclic vibration behaviors can be quantitatively analyzed by mDFA.

Keywords: Heartbeat, Heart health, Modified detrended fluctuation analysis, Structure health, Scaling Time series,.

1. INTRODUCTION

A healthy-looking heart would stop all of sudden. It is the worst-case scenario in the cardio-vascular system. Sudden collapsing of a tunnel and a bridge is another disaster in structural health. Physical mechanisms leading to damage develop at a tiny scale. For example, unprovoked venous thromboembolism is known to cause coronary occlusion that leads heart attack. As for the structural health, tiny crack would spread through the composite material: The aircrafts are known to experience fatigue [1]. Do all such damages could be predicted? Answer to the question is: Yes. It would be possible if we have a method that can see if it suffered small-scale damage. However, relevant studies have not yet been completed: building many prototypes and conducting many physical tests are currently still needed [1].

Traditionally, a vibration sensor records the vibration change and alerts inspectors that the vibration is approaching a safety limit determined by the regulation. In the aircraft, for example, damage to a system disrupts or changes the signal patterns from the baseline communication signals and software measures and analyses any changes and sends an alert to an inspector. However, for predicting failure as a complex system, we first require to isolate each failure mode among various elementary signals. Every single element is unique, because every elements has eigenfrequency.

We adopted a nonlinear way of thinking.

We are individually different. Every single person has a different set of DNA that makes up the person's own structure of the cardio-vascular system (CVS). Meanwhile, nonlinearly speaking, CSV is not unique. CVS all share one architecture, determined by the way information flows. In the CVS, a pump (the heart) is controlled by a controller [i.e., the autonomic nervous system (ANS) cardiac center]. If CVS functions properly, heartbeat fluctuates in a manner so called 1/f rhythm as documented by Kobayashi and Musha [2].

The underlying principle is: "healthy hearts exhibit 1/f rhythm." Using this principle, we have reported that detrended fluctuation analysis can distinguish between isolated hearts and intact hearts only from electrophysiological data of heartbeat recordings [3]. The analytical method simply works without checking individual elements composing the CVS, because elements interact nonlinearly each other. It might be possible to monitor any systems' health quantitatively if we properly use detrended fluctuation analysis [4, 5]. The novel method was invented decades ago by physicists, Peng et al. [6, 7, 8, 9, 10], and is a testable hypothesis for checking structural health as well as biomedical heart health.

In this study, we evaluated whether our modified detrended fluctuation analysis (mDFA) technique is useful. mDFA computes the scaling exponent (SI). With SI, we can identify patients/objects/structures in whom a possible danger approach to them and they encounter elevated risk for malfunction of then, i.e., the heart and/or material structures.

Literary, effective regulation of emotion (biological health) and/or stress (both biological and structural issues) requires the ability to voluntarily mange/control, paying attention by everyday life monitoring by the owners of the system. In biological health issues, people with the low ability might fail to disengage attention from threats of environments. This failure might increase anxiety/fear by increasing awareness of "potential" dangers. People without this failure might effectively disengage from those stimuli and regulate anxiety. In structural healthiness, this failure surely increases risks and sometimes induces life-threatening matters in our daily activity.

It seems that we still might not have a good method to quantify them. Therefore, we conducted experiments to quantify the healthiness and risks using mDFA method that we invented recently.

2. RESULTS

Biomedical health

Heartbeat recording and ethics. For recording heartbeats, we used a Power Lab System (Australia). For electrocardiogram (EKG), EKG electrodes, a set of ready-made three Silver / Silver Chloride electrodes (+, -, and ground; Nihonkoden Co. Ltd. Vitrode V) were used. Wires from EKG electrodes were connected to our newly made amplifier [4]. These EKG signals were then connected to a Power Lab System. Finger pulse recordings were also used with a Power Lab System.

Heartbeats were recorded outside of the hospital; university laboratory, convention hall (Innovation Japan Exhibition) etc. All subjects were treated as per the ethical control regulations of our universities (Tokyo Metropolitan University).

Human heartbeat. We have already demonstrated that normal heart exhibits a normal SI, 1.0, in both invertebrate hearts and human hearts (data not shown here), as mentioned by Kobayashi and Musha [2]. We have proved that abnormal hearts shows abnormal SI that is "not" 1.0. According to SI, therefore, we can check if the cardiovascular system functions well or not. Normal heart exclusively exhibits a normal SI in terms of its rhythm and fluctuation pattern. However, we are not able to identify the reason why it is abnormal in terms of physiology even if SI is "not" 1.0. In such abnormal case, the subjects might possible to be recommended to see a doctor. But, it is obvious that mDFA is useful because mDFA can tell you that something is wrong with your system.

Figure 1 shows a subject (3rd January 2015 four PM) who had quite unique arrhythmic pattern. He mentioned that he is taking a high blood pressure medication, although he did not have any other serious symptoms. He told that he has taken EKG-test recently while health checking, but the checking (only 6 or 7 beat recording with lying position) did not detect his funny heartbeat pattern, he said. Figure 2 shows time series, in beat per min (BPN) for about one hour. It shows that a lot of 2 beats appeared while the subject was sitting and talking. Figure 2 also shows the results of mDFA, SI is 0.74, which strongly suggests that the subject is better to see a doctor, and he did so next day. I currently know his doctors opinion that his heart health alright. Although I worry about his heart health in terms of mDFA, the new method is still not well accepted.

This funny rhythm is so called as alternans, which was first documented in 1872 by German physician Traube. This abnormal rhythm often appears when the subjects were approaching to a terminal condition [11] or extremely excitatory state [11]. This phenomena were found in both invertebrate heart EKGs, for example, the hornet, Vespa sp. and the sea lice, Ligia exotica, and human EKGs [11]. This abnormality was caused by abnormal control of potassium ionic concentration in the blood as proved by our simulation study [11]. We proved hyperkalaemia associated with alternans. From Figure 1 and Figure 2, it is obvious that alternans rhythm is extremely abnormal. Premature ventricular contractions are also known to lower SI that we have already proved [12].

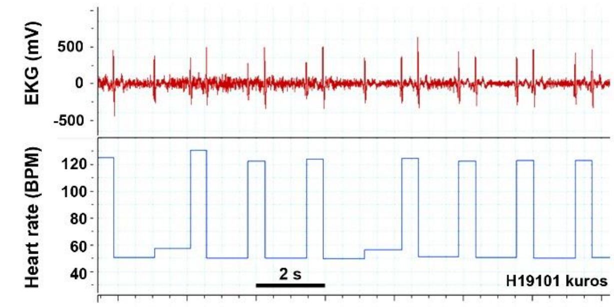


Figure 1. An abnormal heartbeat. Male 63. Sitting chair and talking. Two-beat rhythm, alternans, can be seen.

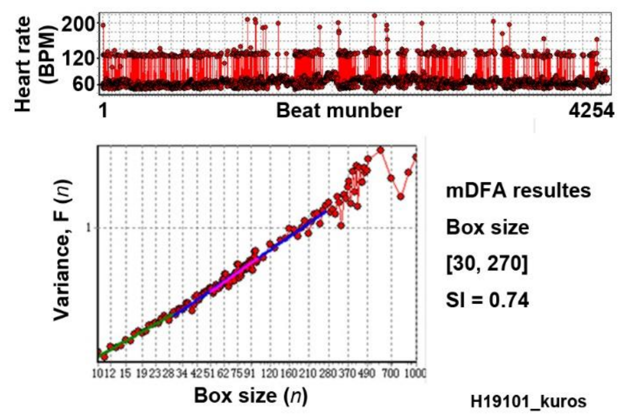


Figure 2. mDFA results. The same subject shown in Figure 1.

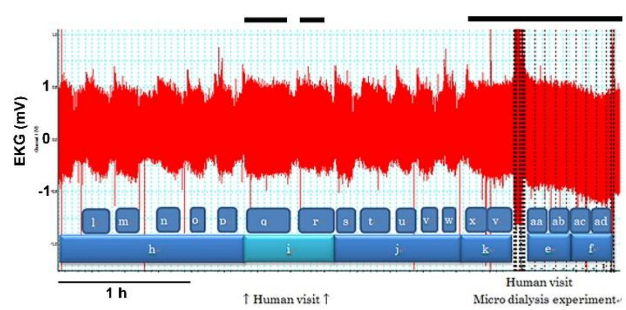
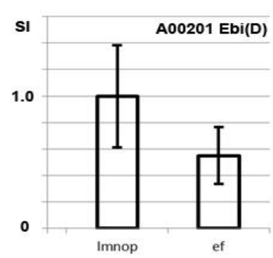


Figure 3. EKGs from freely moving spiny lobster (*Panulirus japonicus*). Bars: Human approaching to the tank. EKG sampling rate: 1 kHz.



	Average	SD
lmnop	0.999	0.38434
ef	0.5505	0.21514

Figure 4. Results of mDFA. Periods [(l, m, n, o, and p) and (e and f)] correspond to those shown in Figure 3.

Invertebrate heartbeat. We have previously recorded lobster EKGs in a tethered condition [13, 14, 15]. Lobsters stayed in sea water tank in freely moving condition. In the study, we found that the heart of lobster changes its beating pattern when human-inspectors approached the lobster tank for feeding and for micro-dialysis blood sampling experiment [13]. Results of the study are briefly shown in Figure 3. One can see two different beating patterns: (1), on/off switching pattern, i.e., repetitive slowdown in rate. We discovered that this pattern occurred only when no human exist in the lobster's room. (2), cyclically beating continuing pattern as shown by three bars in Figure 3. The former pattern only appeared during "no stress" period, and the latter pattern was observable during "stressful" period. In other word, we can read lobster's "fear/anxiety" by heartbeats. SI corresponding to "no stress" period was near 1.0. In turn, SI for "stressful" period was very low, around 0.5 (Figure 4). The lobster experiments proved that mDFA can quantitatively identify the physiological meanings of cyclic behavior of the heart.

Structural health

Vibration of electric motor. A neuro-biologist, without engineering background, got an idea after successful biomedical experimentations: mDFA might be useful for non-biological signals, i.e., structural health checking. Although experiments what we conducted were very primitive, we obtained convincing evidences suggesting that mDFA is useful for monitoring structural health as shown below.

A car (Nissan Cedric VIP) that stayed in a parking was started to run with neutral gear. Vibration was recorded with a piezo sensor (for finger pulse recording, ADInstruments, Australia). The sensor was set on the steering wheel. At idling state, at ~2000 rpm, and at ~4000 rpm, vibration signals always exhibited a constant SI around 0.5 (0.4-0.6) (data not shown). We learned that a car vibrated with the white-noise like fluctuation. We did not test a damaged car because of facility limitation as a biologist.

We met a company (Sanki Consys, downtown Tokyo, Mr. Matsumoto, Director) to test mDFA on electric motors. Conducting experimentations were allowed to do at their facility. Mr. M. managed a lot of air-conditioning/heating machines distributed to hotels and restaurants in the big city. Mr. M. wanted to find a new technology that alarm that motor-system approaches a state of malfunction in advance before it gets sudden stop.

We questioned what SI could be exhibited by a spinning motor before and after breaking down. A 100 V electric motor, and a 200 V electric motor too, were set on the fixed base. Vibrations were recorded with a piezo electric sensor that is made for finger pulse recording (ADInstruments, Austraria) (see Figure 5). Sampling ratio was 20 kHz. A continuous oscillation/vibration recording were made. A set of ~2000 successive peaks were identified and made a peak-to-peak interval time series on which we conducted mDFA.

Motors never got malfunction within a short period of operation experiment. We covered a motor with a glass wool (Figure 5) and finally found that accumulated heat caused malfunction. We observed strong scent and smoke from the motor system shortly (Figure 6).

Vibration signal was analyzed by mDFA. To our surprise, normally spinning motors exhibited a low SI, near zero instead of 0.5 like a car. We finally found that if SI went up over 0.2, it could lead it to a risky state that might induce life threatening phenomena. Figure 7 shows an example of mDFA of a motor. A SI about 0.1 (near zero) is, mathematically, anti-correlation state. We confirmed that the break down motor was broken after the ball bearing was destructed due to excessive heat. At above SI 0.2, we can determine that motor spinning get a malfunction condition. It seems that mDFA is a useful method to inspect structural health

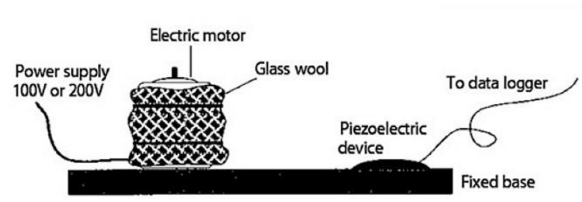


Figure 5. Diagram of vibration recording. AC motor, drying hands at the rest room. Samping rate: 20 kHz. Logger: ADInstruments, Austraria.

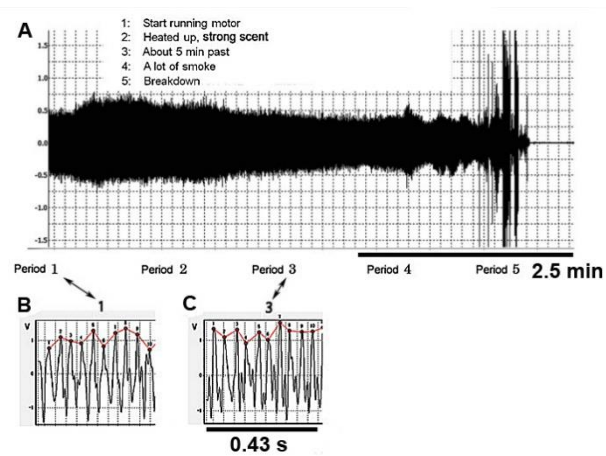


Figure 6. Vibration recording from the setting of Figure 5. A, vibration recording. B and C, peak identification example.

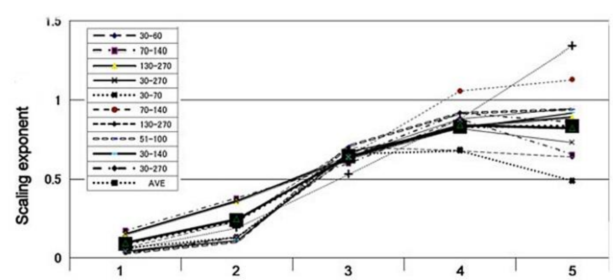


Figure 7. mDFA results of Figure 5 motor.

Vibration of ball bearing. Though it was not sophisticated, experimentation shown in Figures 5, 6, and 7 revealed that normal spinning wheel exhibits a very low SI if the system is "healthy." We tested a ball bearing that has heavy radial load (note: a hollow in Figure 9). The ball bearing was spun at 18000 rpm with a load (1 or 2 kN) of radial force until the test system automatically stop due to excessive vibration. Figure 8 shows an example. The testing system itself was severely received large vibrating motion from a high speed (18000 rpm) spinning, as indicated by the average initial-state-SI value (about 0.35). This SI means that the whole system vibrated significantly when started.

However, experiments gave us new findings more than expected. A heavy radial load force gave ball-bearings a significant damage (widening of hollow-cracks, confirmed later by a microscope lens) at the time point indicated by the double arrows. In turn, we found that our mDFA method is superior to vibration-recording method: As shown in Figure 8, mDFA revealed that malfunction was detected very earlier than vibration measurement method. mDFA detected malfunction at the time point indicated by a thick arrow.

We may conclude that mDFA-incorporated method can detect abnormality earlier than traditional vibration method.

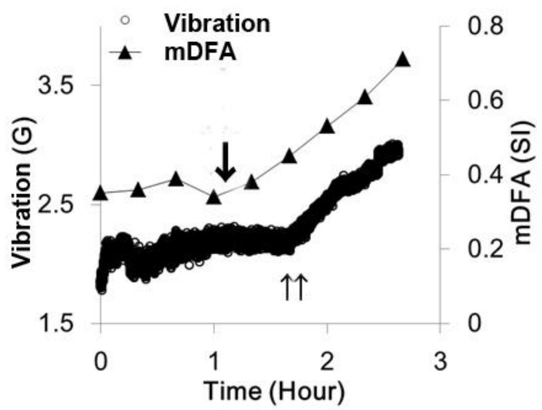


Figure 8. mDFA results obtained from a ball bearing spinning tests. Radial force (1 kN) suddenly let the wheel a malfunction state (see double arrows). Black circle, vibration measurments, 1G = 9.8 m/s2. Traiangles, mDFA results. Data logging, 500 kHz sampling. Normally lubricated with grease. One impression-injured hollow made on orbit bed. Eight balls ball bearing (see Figure 9).

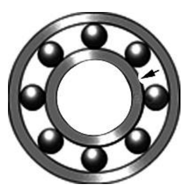


Figure 9. Diagram of a ball bearing. An arrow indicates an artificial hollow that was made in order to induce malfunctioning.

3. DISUCUSSION

We tested the ability of mDFA whether it quantitatively distinguishes healthiness of the heart. It was necessary to get a 2000 beat EKGs without intermission and without missing any heartbeats. Unexceptionally, heartbeats were recorded by our new EKG amplifier (see ref [4]). The amplifier guaranteed stable and reliable EKG recordings: i.e., without scaling out of EKG-trace from screen caused by subjects' movement such as laughing, talking, and walking. This EKG amplifier enabled us to make a perfect heartbeat interval time series, for about 2000 beats. Owing to the contribution of this new EKGs, we were able to accomplish reliable analysis of mDFA (so far, over 350 human volunteer EKGs and over 1000 invertebrate EKGs, since 2002).

Once again, in summary, we succeeded stable EKG recordings. Each recordings last for 30 min to 90 min (Sampling ratio, 1 kHz). This was accomplished by adopting a small time-constant (TC) of input-stage of amplifier, which is ~0.1 s. Normally, TC is set to ~10 s under the International Terms for EKG-machine for medicine. This regulation guarantee an easy observation of S-T elevation caused by ischemic myocardial state, for example. But, mDFA only need to pay attention to the timing of heartbeat recorded in EKG-traces. We preferred stability of EKG-trace instead of following the International Terms, because of carrying out perfect detection of 2000 peaks, and avoiding any equivocal "interval" measurements.

mDFA computes a scaling exponent (SI). We showed that SI was able to quantify the state of vibration and/or fluctuation of natural world signals. Normal healthy subjects exhibits 1/f rhythm, which is comparable to the scaling exponent one (SI = 1.0). We discovered that lobster specimens peacefully staying in a shelter space without human-induced threatening exhibited a SI that was near one. To our surprise, SI significantly decreased when human approached to the lobster tank for the purpose of feeding with clam-meat. Owing to this discovery, we found that mDFA's ability to quantify "stress" from the cyclic behavior of the heart. Thereafter, we applied this quantification method to human heartbeat. Then, we propose that our mDFA can quantify the state of any cyclic movements using SI. For the heart, 1.0 is reference value. This is comparable to 37 degree C for human body temperature as a healthy reference temperature.

In healthy car, vibration exhibited SI = 0.5, which is so called white noise like fluctuation. In a car, a lot of elementary parts vibrate in concert with nonlinear couplings each other. This is why SI is 0.5 for the car vibration. In turn, when a motor's shaft was smoothly spinning, exhibited SI was 0.1 (near zero). We thus found that a reference value for a human-made machined is 0.1, i.e., SI for spinning machines is 0.1. Indeed, we tested mDFA upon electrically generated sigmoidal wave data that was recorded by an amplifier, and we found that SI was near zero (data not shown).

Although biologists are strangers in engineering discipline, we as a biologist would like to propose an idea that mDFA is a new technology and helpful method to quantitatively determine the state of vibration/fluctuation of signals in natural world. We would like to lay stress that it is worthwhile for engineers to learn detrended fluctuation analysis and the scaling exponent, because mDFA method looked like very useful for structural health checking [14, 15].

4. ACKNOWLEDGMENTS

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