Thermodynamic Damage Measurements of an Operating System

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Key Words: Thermodynamic damage, damage entropy, differential entropy, entropy damage noise

SUMMARY & CONCLUSIONS

Degradation in materials leads to some sort of irreversible damage. Sometimes it is difficult to detect the damage. Often we wait for catastrophic failure to occur. From an energy standpoint, any degradation causes disorder, this disorder causes the entropy of the system to increase. The key is, can we measure the disorder prior to catastrophic failure. In theory, any disorder can disrupt the overall energy flow of an operating system. It is this telltale aspect that we seek to measure. Whether the system is, an amplifier, an engine, the human body, or even the earth's atmospheric system, in theory, when the operating system of interest has degraded, disorder has increased that is associated with irreversible thermodynamic damage that occurred and the entropy has in fact increased. The system's useful free energy is diminished. How best can we measure this change and what state variables should we look at? In this paper we will specifically look at system level noise which is commonly overlooked as a measurement tool. Like a wobbly fan making noise, system level noise is potentially a great tool for measuring certain kinds of thermodynamic damage. Noise in this sense, can be detected using a sensitive instrument which might be measuring electron current noise, fluid flow noise, or even thermal noise. We will also discuss exactly how to make such entropy measurements. Such measurements can potentially help in assessing the system's state warning of potential issues. Results provide a specific method of noise degradation measurements that exemplifies how one can assess thermodynamic damage at the system level by looking at system's operating energy state over time. It may or may not be the best variable depending upon the degradation process. We also cite an example of human heart rate noise degradation failure to help illustrate these concepts. Once we accept the notion of entropy damage in aging systems, we open up opportunities to look at such new ways for assessing degradation. Our ability to make new and improved measurements is only hindered by our creativity and our instruments that we use to resolve and detect entropy damage. In this paper we introduce the concepts and propose looking at the system's active energy state proving an actual design for assembling thermodynamic noise damage measurement equipment.

1. *ENTROPY DAMAGE CONCEPT*

There are a number of reasons that entropy can increase in a device, one reason is due to degradation. This entropy that is generated due to degradation is irreversible and we can term this as entropy damage [1].

Entropy is an extensive property, so that the total entropy between the environment and the device is the sum of the entropies of each. Therefore, the device and its local environment can be isolated to help explain the entropy change. We can write that the entropy generated S_{gen} in an aging process as

$$S_{gen} = \Delta S_{total} = \Delta S_{device} + \Delta S_{env} \geq 0 \quad (1)$$

Now in a degradation process, the device and the environment can both have the entropies changed. For example, matter that has become disorganized, such as a phase change, that affects device performance. In theory, "damage entropy" is separable [1] in the aging process related to the device (system) such that

$$\Delta S_{device} = \Delta S_{damage} + \Delta S_{non\text{-}damage} \geq 0 \quad (2)$$

By this definition, *damage entropy* change ΔS_{damage} must be greater than zero or aging in the device is not measurable. And non-damage entropy increase $\Delta S_{non\text{-}damage}$ is then more disorganization occurring in the device that is not currently affecting the device performance, for example vibration in the lattice of a crystal might increase when heat is added but no permanent disorder to that area of the device that is effecting its performance.

1.1 Entropy of a complex system

Entropy is an extensive property, thus the total entropy of a system is equal to the sum of the entropies of the parts of the system. The parts may also be subsystems. If we isolate an area enclosing the system and its environment such that no heat, mass flows, or work flows in or out, then we can keep tabs on the total entropy. In this case the entropy generated from the isolated area is [1, 2]

$$S_{Gen} = \Delta S_{Total} = \sum_{i=1}^{N} \Delta S_i = \Delta S_{Sys} + \Delta S_{Surroundings} \geq 0 \quad (3)$$

where the equality holds for reversible processes and the inequality for irreversible ones. *This is an important result*. If we can keep tabs on ΔS_{Total} over time, we can determine if aging is occurring even in a complex system. In this paper we refer to complex systems as any system whose entropy is the sum of its parts and its damage entropy is measurable. To assess and track system damage, we will need a repeatable method or process to make aging measurements at different times. If we find that the entropy has changed over time from a

978-1-4799-6703-2/15/$31.00 ©2015 IEEE

repeatable quasi-static measurement process, then we are able to measure and track the aging that occurs between the systems initial, intermediate, and final states. We can call this the entropy of an aging process. (Note that during system aging, we do not have to isolate the system. We only need to do this during our measurement process.)

1.2 Measuring Damage Entropy Processes

We can theorize that any irreversible process that creates increases or decrease to the change in entropy in a system under investigation cause some degradation to the system. However, if we cannot measure this degradation, then in our macroscopic world, the system has not actually aged. In terms of entropy generated from an initial and final state we have [2]

$$S_{Gen}=S_{initial}-S_{final} \geq 0 \tag{4}$$

Where the equal sign is for reversible process and the inequality is for irreversible one. However, what portion of the entropy generated causes degradation to the system and what portion does not? To clarify

$$S_{gen}= S_{damage}+S_{non\text{-}damage} \tag{5}$$

There is really no easy way to tell unless we can associate the degradation through a measurable quantity. Therefore in thermodynamic damage we are forced to define S_{damage} in some measurable way.

We typically do not measure absolute values of entropy, only entropy change. Let us devise a nearly reversible quasi-static measurement process *f*, and take an entropy change measurement of interest at time t_1

$$\Delta S_f(t_1)= S(t_1 +\Delta t)-S(t_1) \tag{6}$$

The measurements process *f* must be consistent to a point that it is repeatable at a much later aging time t_2, we can observe if some measurable degradation has occurred to our device where we record the entropy change

$$\Delta S_f(t_2) = S(t_2 +\Delta t)-S(t_2), \text{ where } t_2 >>t_1 \tag{7}$$

Then we can determine if damage has occurred. If our measurement process *f* at time t_1 and t_2 is consistent, we should find the entropy damage that has occurred between these measurement times as

$$\Delta S_{f\text{-}Damage}(t_2,t_1) =\Delta S_f(t_2)-\Delta S_f(t_1) \geq 0 \tag{8}$$

where the equality occurs if no device degradation is measurable [1]. (Note, we anticipate any non damage part of the entropy change in our consistent measurement process will subtract out or be negligible.) If we do generate some damage entropy during our measurement process $(t_i+\Delta t_i)$, it either must be minimal compared to what is generated during the actual aging process between time t_1 and t_2. Then, our entropy measurement difference should be a good indication of the device aging/damage that is occurring between times t_1 and t_2. The actual aging process to the system between time t_1 and t_2, might be a high level of stress applied to the system. Such stress need not cause a quasi-static. However, the stress must be limited to within reason so that we can repeat our measurement in a consistent manner at time t_2. That is, the stress should not be so harsh that it will affect the consistency of the measurement process *f*.

One might for example have a device aging in an oven in a reliability test, then remove it and make a quasi static entropy measurement *f* at time t_1 and then put the device back in the oven later do another measurement at time t_2. Any resulting measurement difference is damage entropy.

2. *MEASURES FOR SYSTEM LEVEL ENTROPY DAMAGE*

We next ask what state variables can be measured as an indicator at the system level for the entropy of aging. In this paper, we will explore the state system variables of system noise. However, other good candidates include temperature, pressure, strain rate, charge capacity, magnetic flux change, and so forth.

2.1 Measuring System Entropy Damage Noise

Operational noise [1] is a key state variable that is often overlooked as an important measurable thermodynamic quantity. We tend to think first of temperature change as an indication of the system degradation state. However, noise measurements are not limited to say vibration noise, there are many types of measurable noise issues in systems that increase due to degradation, this can include electronic noise current, fluid flow current noise, vibration noise spectral change and so forth. In a mechanical or an electrical operating system, system noise increase is a sign of disorder and increasing entropy. Simply put, if entropy damage increases, so should the system noise. We can term this as entropy damage noise as it originates from the aging process. For example, an electrical fan blade may become wobbly over time. The increase in how wobbly it is can be thought of as entropy damage noise. Not necessarily in the acoustic sense but its degree of how wobbly it is provides a measure of its increasing "noise level". Noise is a continuous random variable of some sort. The entropy of a continuous variable is treated in thermodynamics using the concept of differential entropy. For example the statistical definitions of entropy for discrete and continuous variable X are well defined in thermodynamics as [3,4]

Discrete *X, p(x):*

$$S(X) = -\sum p(x) \quad \log_2 P(x) \tag{9}$$

Continuous *X, f(x):*

$$S(X) = - \int f(x) \ \log \ (f(x)) \ dx = -E[\log \ f(x)] \tag{10}$$

Note in differential entropy, the variables are usually dimensionless. So if X=voltage, the solutions would be in terms of X=V/Vref, a dimensionless variable.

Here we are concerned with the continuous variable x having probability *f(x).* Noise is often considered Gaussian. For example, Gaussian white noise is one common example and often reflects many real world situation (note not all white noise is Gaussian). When we find that a system has Gaussian white noise, the function *f(x)* pdf is

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \tag{11}$$

When this function is inserted into the differential entropy equation, the results is given by [4]

$$S(X)=\frac{1}{2}\log(2\pi \quad e \quad \sigma(x)^2) \qquad (12)$$

This is an important finding for the system entropy damage noise. We see that entropy for a Gaussian noise system, the differential entropy is only a function of its variance σ^2 (it is independent from its mean μ). For a system that is becoming nosier over time the damage entropy can be measured in a number of ways where the change in the entropy at two different times t_2 and t_1 is [1]

$$\Delta S_{Damage}(t2,t1)=S_{t2}(X)-S_{t1}(X) \\ =\frac{1}{2}\log(\frac{\sigma_{t2}^2}{\sigma_{t1}^2}) \qquad (13)$$

Interestingly enough noise engineers are quite use to measuring noise with the variance statistic. That is, one of the most common measurements of noise is called the Allan Variance. This is a popular way to measure to measure noise and is in fact very similar to the Gaussian Variance given by [5]

$$\text{Allan Variance:} \quad \sigma^2(\tau)=\frac{1}{2(n-1)}\sum_i(\bar{y}(\tau)_{i+1}-\bar{y}(\tau)_i)^2 \qquad (14)$$

By comparison the true variance is

$$\text{True} \quad \text{Variance:}\sigma^2(y)=\frac{1}{n}\sum_{i=1}^{n}(y_i-\bar{y})^2 \qquad (15)$$

We note the Allan Variance, commonly used to measure noise, is a continuous pair measurement of the population of noise values where the true variance is non pair measurement over the entire population. The Allan variance is used often because it is a general measure of noise and is not necessarily restricted to Gaussian type noise.

The key results here are that entropy of aging for system noise goes as the variance which is also historical way for measuring noise and is likely a good indicator of the entropy of aging of a complex system. There are a number of historical options on how noise can be best measured.

Example:

Prior to a system being subjected to a harsh environment, we make an initial measurement M1+ of an engine vibration (fluctuation) profile. Then the system is subjected to an unknown harsh environment. We then return the system to the lab and make a measurement M2 + in the exact same way that M1 was made.

M1: Engine exhibits a constant PSD characteristic of $3G_{rms}$ content in the bandwidth from 10 to 500 Hz

M2: Engine exhibits a constant PSD characteristic of $5G_{rms}$ content in the bandwidth from 10 to 500 Hz

Then system noise damage ratio is then: (note Standard deviation=G_{rms} for white noise with mean of zero.)

$$Damage_{noise\_ratio} = Log(5^2)/Log(3^2)=1.47 \qquad (16)$$

3. *AUTOCORRELATION FUNCTION AS A MEASURE OF ENTROPY DAMAGE NOISE*

Another method of entropy damage noise assessment is the autocorrelation function that describes how a signal is changing in time, i.e. how it correlates the signal at two different points is time. The autocorrelation function is [6]

$$R_{yy}(\tau)=\lim_{T\to\infty}\frac{1}{T}\int_0^T y(t)y(t+\tau) \quad dt \qquad (17)$$

This is similar to Equation 10. In the case of band limited Gaussian white noise signal *y(t)*, the G_{RMS} content values of its Fourier transform $S_{yy}(\omega)$

$$S_{yy} \quad (\omega) \quad =\frac{1}{2\pi}\int_0^T R_{yy}(\tau)e^{-j\omega\tau}d\tau \qquad (18)$$

is given by the Gaussian standard deviation for mean zero white noise. Thus we can look at the variance at two different times as suggested by Equation 13. Alternately, we can find R_{yy} by capturing the noise wave form $y(t_1)$ and much later at $y(t_2)$ after aging. This second method has a nice advantage as the engine noise increase, we would anticipate that autocorrelation average value will become more and more uncorrelated and approach zero amplitude.

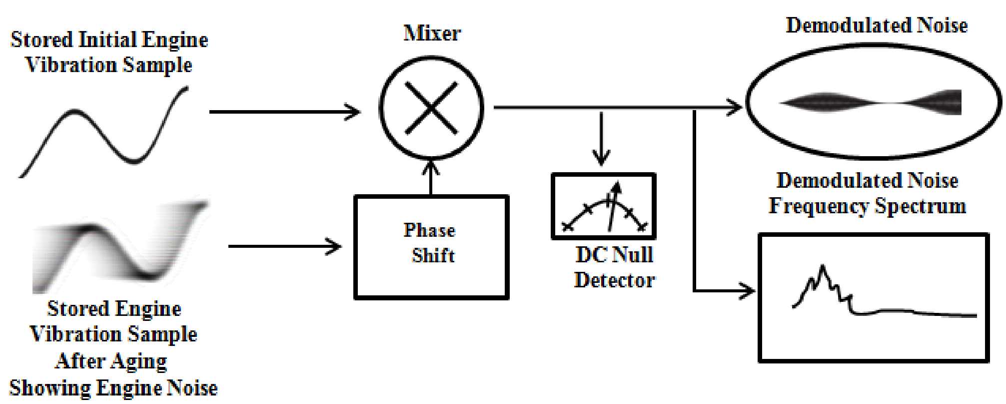

Figure 1 - Active autocorrelation measurement noise demodulation detection

3.1 *Active Autocorrelation On Board Noise Detection Measurement System Example*

As an example of how we can use the autocorrelation method on and active system, we can propose an electronic system for such measurements. Active on-board autocorrelation measurements can be helpful for determining the system wellness in real time. Figure 1 illustrates a proposed active measurement process using an electronic mixer similar to RF demodulation technology

Figure 1 shows an initial engine vibration sample at time *t1*, *y(t1)* and later after engine aging at time *t2*, *y(t2)*, a stored engine vibration sample. The two signals are mixed after phase shifting. The idea is to try and isolate the noise by "nulling" out the initial engine signal. The conceptualized mixing of the initial engine signal will require phase shifting so that after mixing the initial signal is "nulled" out as best as possible so that only the noise remains. This is similar to AM demodulation when removing the carrier wave from a modulated AM radio signal. AM demodulation technology is well established. Therefore this type of mixing is well known and should be very feasible. The key difference here is the added problem of signal storage and their phase mixing for proper autocorrelation of the signals as described by Equation 17. The figure is simplified for conceptual overview. More sophisticated mixing methods exist. The figure shows the entropy damaged noise signal in the time domain as well the noise signal frequency content spectrum can be assessed found per Equation 18. Analysis in the frequency domain can have a number of metrics such as the G_{rms} spectral content, the PSD magnitude by using accelerometers to generate the *y(t)* signals, and possible resonance assessment with Q values found from the spectra observations. Assessment of this type is not limited to engine noise but any type of noise. Noise Measurements can be made to electronic circuits, engines, fluid flow, human health, etc.

Such noise measurement can also include AM, FM or Phase demodulation noise analysis. For example a sinusoidal carrier wave can be written

$$A(t)=Am\ Sin(\omega t+\phi) \qquad (19)$$

where Am is its maximum value, ω is the frequency, ϕ is the phase relation. We see that noise modulation can occur to the amplitude, frequency or phase.

Once noise is captured, one must use engineering/statistical judgment to assess the threshold of the noise issue that can be tolerated before maintenance is warranted.

Statistically, it is easier to judge when maintenance is needed based on a number of such systems. As our experience increase with the type of system we are measuring, the information we obtain is easier to interpret. Therefore analysis of numerous units when assessed will help determine normality and when maintenance is needed. Typical a good sample size is likely 30 or greater.

3.2 *Human Heart Rate Noise Degradation Measurement Example*

Although noise degradation measurements are difficult to find, one helpful example of noise autocorrelation analysis of an aging system found by the author is in an article by Wu et. al. [7].

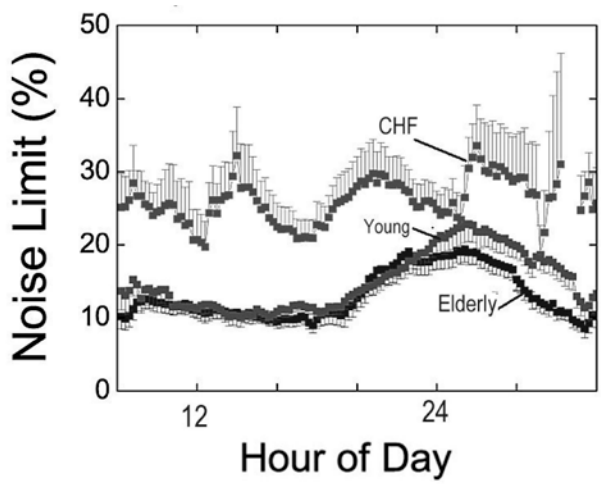

Figure 2 – Noise limit heart rate variability measurements of Young, Elderly and CHF patients Ref 7.

Here heart rate variability was studied in young, elderly and Congestive Heart Failure (CHF) patients. Figure 3 shows noise limit measurements of heart rate variability. We note that heart rate noise limit variability between young and elderly patients are not dramatically different compared to what is occurring in patients with CHF. Although this is not the same system (i.e. different people), such measurements can be compared using noise analysis described in this section.

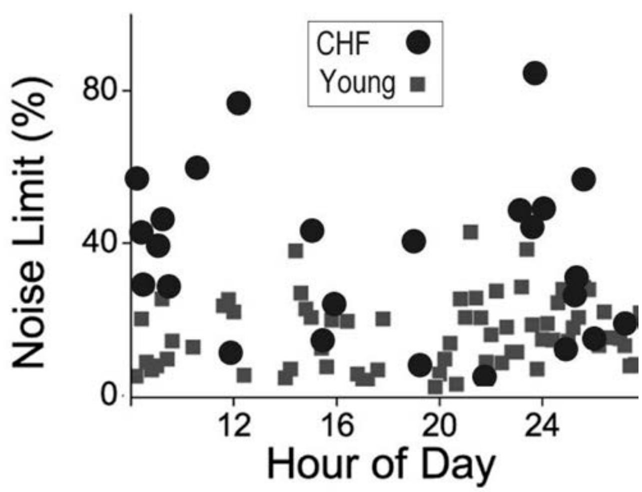

Figure 3 – Noise limit heart rate variability chaos measurements of Young and CHF patients Ref 7.

This is further illustrated in Figure 2 showing noise variability in heartbeats of young subjects compared with CHF patients. This is an example of damage entropy comparison in a complex human heart aging system between a good and a failing system observed well prior to catastrophic failure. This reference shows a variation of how our example in Fig. 1 and damage noise entropy measurements in general can be implemented and would be helpful as a detection method of a system's thermodynamic degradation state.

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Dr. Alec Feinberg is the founder of DfRSoft. He has a Ph.D. in Physics and is the principal author of the book, Design for Reliability. Alec has provided reliability engineering services in all areas of reliability including solar, thin film power electronics, defense, microelectronics, aerospace, wireless electronics, and automotive electrical systems. He has provided training classes in Design for Reliability, Shock and Vibration, Quality, Accelerated Testing, HALT, Reliability Growth, Electrostatic Discharge, Dielectric Breakdown, DFMEA and Thermodynamic Reliability Engineering. Alec has presented numerous technical papers and won the 2003 RAMS Alan O. Plait best tutorial award for the topic, "Thermodynamic Reliability Engineering". Alec is also a major contributing author to the new book on The Physics of Degradation in Engineered Materials and Devices due out this year (Chapter 4, Thermodynamic Damage within Physics of Degradation).