Research on Vibration Test Conditions in Particle Impact Noise Detection

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Abstract. Particle Impact Noise Detection (PIND) test is a kind of reliability screening technique which is used to detect free particles in hermetical components and is specified in MIL-STD-883E method 2020.7. Some vibration test conditions are defined which aren't always appropriate in practice. The particle's mean velocity equation is derived based on dynamics and simulations analysis. It disclosures the proportional relation between the particle's mean velocity and vibrator's one. It also shows that the particle's mean velocity is in direct ratio to vibration acceleration and is in the inverse ratio of vibration frequency. It shows how do vibration acceleration, vibration frequency, recovery coefficient and the particle's mass influence its output energy consequently. Furthermore, the best vibration frequency is derived under the constant rated power of vibrator. It shows that the best vibration frequency is in direct ratio to vibration acceleration. Some experiments and simulations are given last.

1. Introduction
All modern systems for military, space and satellite applications use many electronic devices that perform complex control, navigational and monitoring functions. Proper functioning of these devices without interruptions is vital to the success of the missions and safety of the personnel and equipment. Towards achieving this objective, electronic components are manufactured and tested in accordance with the controls and requirements of applicable military standards, specifications and drawings. One critical factor that can cause catastrophic failure is loose particles within the devices. The focus and importance of screening devices for particles occurred when a catastrophic system failure in the Delta Launch Vehicle Program was traced to a loose bit of wire within an electronic component. The significance of screening devices for particles was further elevated because of advances in the manned space vehicle, satellite and missile programs. As a result, space-level devices (Class S) and Class B devices that are used in flight and missile applications must be particle-free. NASA, McDonnell Douglas and Texas Instruments developed and constantly improved techniques of detecting particles audibly and visibly within device cavities. 1960, a finalized version of the audible technique was adopted as a Particle Impact Noise Detection Test procedure "PIND" in MIL-STD-883, Test Method 2020. For the past forty years, the PIND test with its series of mechanical shocks and vibrations has been employed by component manufacturers to screen electronic components. A significant trend in the modern manufacture of these components is to build larger and larger packages resulting in changing requirements for the venerable PIND test equipment. Despite progress in regard to test concepts, PIND tester design, methods and media of attachment, there still is a lack of correlation
between equipments, inconsistency in the test results and conditions, lack of repeatability and false
detections. As a result, there is a general tendency by manufacturers to question the reliability of the
PIND test. Still PIND test remains the key measuring indicator for controlling and maintaining a
reliable process line relative to particle contamination. It is a useful tool to continuously refine and
improve the assembly process.

Figure 1 represents the PIND system of MIL-STD-883E method 2020.7. Vibrator generates a
series of impacts and vibrations. Impacts release the particles (remainders) and vibrations make
the particles to collide with the component’s walls. The collided energy is outputted in the forms of
sounds and voltage, which can be used to estimate whether the particles exist.

![PIND System Diagram]

**Figure 1.** The PIND system of MIL-STD-883E.

MIL-STD-883E method 2020.7 regulates that PIND system must use an oscilloscope whose
frequency response should exceed 500 kHz and whose sensibility is 20 mV/cm and acoustic frequency
detection system which is used to detect collision sounds. MIL-STD-883E method 2020.7 also
regulates sinusoidal vibration and its three vibration frequencies, viz. 27 Hz, 40 Hz and 100 Hz, under
the constant acceleration, for example, 5g (g is the acceleration of gravity). Even though today’s PIND
instruments can carry through frequency sweep under the constant acceleration, vibration mechanisms
still haven’t been explained distinctly. So users have no option but to observe it that prevents the
improvement of PIND test.

R. Schuste studied how did test programs infected test results and discuss how to improve
reliability of electronic components [1]. J. Robinson suggested that it should use proper techniques to
prevent remainders from integrate circuit in the course of packaging [2]. C. M. Vicroy analyzed the
reasons caused PIND faults and presented some principles to follow [3]. L. J. Scaglione adopted
neural network to identify remainders and the accuracy reached 98% which was only acceptable for
transistors [4]. R. R. Prainie studied PIND test for transistors and created the statistical model between
omission factor and test number [5]. Zhang Xu sheng tried to use wavelet analysis to detect
remainders in relay [6]. In fact, all of these researches are almost completed under a given condition
(including cavity height, vibration acceleration, vibration frequency, particle material, etc) which is
regulated by MIL-STD-883E method 2020.7, and assume that different kinds of electric components
have the same output results under the same PIND test condition and output results aren’t concerned
with particle’s characteristics and cavity height, which isn’t practical. It is the most important that they
can’t answer under which test condition output results are the best. Zhang Hui created the particle's
dynamics models in PIND first, and analyzed particle's motion map in phase space, and studied
PIND's test conditions when particle does period-1 motion, and also obtained the particle's stability
conditions of period motion of in PIND [7-10]. But the particle's modes of motion aren't periodical
commonly, so it is essential to research the applicable test conditions of PIND.

In the paper, the particle's mean velocity equation is derived based on dynamics and simulations
analysis. It disclosures the proportional relation between the particle's mean velocity and vibrator's one.
It also shows that the particle's mean velocity is direct ratio to vibration acceleration and is inverse
ratio to vibration frequency. Furthermore, the best vibration frequency is derived under the constant
rated power of vibrator. It shows that the best vibration frequency is direct ratio to vibration
acceleration. Some experiments and simulations are given last.
2. The particle's mean velocity
During the PIND test, noises reduce the detection accuracy seriously. Namely, usable signal (the particle collision signal) is inundated in the noises, so it is difficult to recognize it. It can control the particle's motion behavior by controlling vibration test conditions of vibrator (including vibration acceleration and vibration frequency) in order to control the particle's kinetic energy. The particle's motion behavior is also affected by recovery coefficient. So the particle's velocity is the function of vibration acceleration, vibration frequency and recovery coefficient. In view of the complex motion behavior of the particle [11], it thinks of the particle's motion as stationary random process. So the particle's mean velocity should exist as statistical average value that is proved in simulations and experiments.

In researches it assumes: (1) the component has the cavity which is ideal cuboid and in which there is a particle; (2) the particle is regarded as a rigid ball which has the certain recovery coefficient $e$; (3) vibrator is horizontal and the ball does vertical motion; (4) gravitational field is constant and the acceleration of gravity $g$ is 9.81 m/s$^2$; (5) the ball's motion keeps to Newton's laws and dynamics laws; (6) the gas in component has no effects on the ball; (7) vibrator does sinusoidal motion and its displacement equation $S(t) = A_m \sin(\omega t)$, $A_m$ is amplitude, $\omega$ is angular frequency; (8) positive direction of displacement and velocity is ascending.

2.1. Relation between the ball's mean velocity and vibrator's one
Figure 2 is the ball's motion map in cavity. Let $V_k'$ and $V_k$ be the ball's velocities immediately before and after the $k$th collision with the nether wall of cavity respectively. Let $U_k$ be vibrator's velocity at the $k$th collision with the nether wall of cavity, $k=1,2,\ldots,\infty$. It can derives

$$V_k - U_k' = -e(V_k' - U_k)$$  \hspace{1cm} (1)

Rewriting equation (1) and it gives the velocity $V_k'$ after the $k$th collision as

$$V_k' = (1 + e)U_k - eV_k$$  \hspace{1cm} (2)

Figure 2. The ball and the vibration table’s motion map.

The ball's motion is stationary random process when collision number is enough big. Equation (2) will become

$$V_{avg} = (1 + e)U_{avg} - eV_{avg}'$$  \hspace{1cm} (3)

$V_{avg}$ is the mean value of $V_k$, $V_{avg}'$ is the mean value of $V_k'$, and $U_{avg}$ is the mean value of $U_k$. If the ball's bounce height is greater than vibrator's amplitude ($A_m$), the ball's motion will be determined by the so-called "standard map" model [11], and therefore

$$V_k = -V_k' \text{ or } V_{avg} = -V_{avg}'$$  \hspace{1cm} (4)

Substituting equation (4) into equation (3),
Setting \( \rho = (1+e)/(1-e) \), equation (5) becomes

\[
V_{\text{avg}} = \frac{1+e}{1-e} U_{\text{avg}}
\]  

Equation (6) shows that the ball's mean velocity is in direct ratio to vibrator's one and the ratio is the increasing function of recovery coefficient.

2.2. Approximate equation of the ball's mean velocity

From the preceding analysis, the ball's mean velocity \( V_{\text{avg}} \) should be the function of vibration acceleration \( a_m \), vibration frequency \( f \) and recovery coefficient \( e \).

\[
V_{\text{avg}} = F(a_m, f, e)
\]  

Instantaneous velocity of vibrator can be got by differentiating displacement equation

\[
U(t) = A_m \cos(\omega t)
\]  

Rewriting equation (8)

\[
U(t) = \frac{a_m}{\omega} \cos(\omega t)
\]

\( a_m \) is the amplitude of vibration acceleration and is equal to \( A_m \omega^2 \). Because \( U_{\text{avg}} \) is determined by \( U(t) \), \( U_{\text{avg}} \) is also in direct ratio to \( a_m/\omega \). Considering equation (6), \( V_{\text{avg}} \) is direct ratio to \( a_m/\omega \) too. Equation (7) becomes

\[
V_{\text{avg}} = \frac{a_m}{f} P(e)
\]

To verify equation (10) and to get the expression of \( P(e) \), "standard map" model program is made to simulate the ball's motion map in Matlab. Lots of simulations show that \( V_{\text{avg}} \) and \( U_{\text{avg}} \) will always tend to the corresponding values gradually, and the ratio of them is determined by equation (6). Collision number \( N \) is 10000 in simulations. A group of data is as follow. Vibration acceleration is 5g, recovery coefficient is 0.9 and vibration frequency is 50Hz. Figure 3 exhibits the variety of \( V_{\text{avg}} \) along with the collision number \( N \). When \( N \) exceeds 2000, \( V_{\text{avg}} \) tends to 0.5956. Figure 4 exhibits the variety of \( U_{\text{avg}} \) along with \( N \). When \( N \) exceeds 2000, \( U_{\text{avg}} \) tends to 0.0313. The ratio of \( V_{\text{avg}} \) to \( U_{\text{avg}} \) is \( 0.5956/0.0313 \approx (1+0.9)/(1-0.9) = 19 \), which is determined by equation (6).

![Figure 3. \( V_{\text{avg}} \) reaches a stable value.](image)

![Figure 4. \( U_{\text{avg}} \) reaches a stable value.](image)

More simulations are as follow. Just one parameter of \( a_m, f \) and \( e \) is changed in simulations and it analyzes the relation between \( V_{\text{avg}} \) and the changed parameter.

2.2.1. Relation between \( V_{\text{avg}} \) and \( f \). Table 1 lists \( V_{\text{avg}}, U_{\text{avg}} \) and \( f \) in three instants and shows: (1) The ball's mean velocity is in the inverse ratio of vibration frequency (2) the ratio of \( V_{\text{avg}} \) to \( U_{\text{avg}} \) is equal to \( \rho \).
Table 1. Relations between mean velocity and vibration frequency.

| Vibration Conditions | f (Hz) | 30   | 50   | 100  | 150  | 200  | 250  |
|----------------------|--------|------|------|------|------|------|------|
| \( a_m = 5g \)      | \( V_{avg}(m/s) \) | 0.9262 | 0.5956 | 0.2885 | 0.1887 | 0.1467 | 0.1165 |
| \( e = 0.9 \)       | \( U_{avg}(m/s) \) | 0.0485 | 0.0313 | 0.0148 | 0.0099 | 0.0076 | 0.0062 |
| \( a_m = 5g \)      | \( V_{avg}(m/s) \) | 0.6566 | 0.3943 | 0.1939 | 0.1329 | 0.0720 | 0.0706 |
| \( e = 0.8 \)       | \( U_{avg}(m/s) \) | 0.0739 | 0.0430 | 0.0213 | 0.0146 | 0.0114 | 0.0096 |
| \( a_m = 5g \)      | \( V_{avg}(m/s) \) | 0.5155 | 0.3070 | 0.1583 | 0.1044 | 0.0790 | 0.0628 |
| \( e = 0.7 \)       | \( U_{avg}(m/s) \) | 0.0906 | 0.0548 | 0.0274 | 0.0183 | 0.0136 | 0.0108 |

2.2.2. Relation between \( V_{avg} \) and \( a_m \). Table 2 lists \( V_{avg}, U_{avg} \) and \( a_m \) in three instants and shows: (1) The ball’s mean velocity is direct ratio to vibration acceleration; (2) the ratio of \( V_{avg} \) to \( U_{avg} \) is equal to \( \rho \).

Table 2. Relations between mean velocity and vibration acceleration.

| Vibration Conditions | \( a_m \) (m/s²) | 3g   | 5g   | 8g   | 10g  |
|----------------------|------------------|------|------|------|------|
| \( f = 50Hz \)      | \( V_{avg}(m/s) \) | 0.3554 | 0.5956 | 0.9161 | 1.2419 |
| \( e = 0.9 \)       | \( U_{avg}(m/s) \) | 0.0188 | 0.0313 | 0.0479 | 0.0611 |
| \( f = 50Hz \)      | \( V_{avg}(m/s) \) | 0.2608 | 0.3943 | 0.6484 | 0.7909 |
| \( e = 0.8 \)       | \( U_{avg}(m/s) \) | 0.0287 | 0.0430 | 0.0682 | 0.0895 |
| \( f = 100Hz \)     | \( V_{avg}(m/s) \) | 0.1734 | 0.2885 | 0.4504 | 0.6095 |
| \( e = 0.9 \)       | \( U_{avg}(m/s) \) | 0.0090 | 0.0148 | 0.0235 | 0.0320 |

2.2.3. Relation between \( V_{avg} \) and \( e \). Table 3 lists \( V_{avg}, U_{avg} \) and \( e \) in three instants and shows: (1) The ball’s mean velocity \( V_{avg} \) is the nonlinear increasing function of \( e \); (2) the ratio of \( V_{avg} \) to \( U_{avg} \) is equal to \( \rho \). Using polynomial approximation method, it can get the coefficients of \( P(e) \), viz. \((20.21, -41.91, 29.47, -6.7)\). So \( P(e) \) can be expressed.

\[
P(e) = 20.22\ e^3 - 41.91\ e^2 + 29.47\ e - 6.7
\]  

(11)

Table 3. Relations between mean velocity and recovery coefficient.

| Vibration Conditions | \( e \) | 0.9   | 0.8   | 0.7   | 0.6   |
|----------------------|-------|------|------|------|------|
| \( f = 50Hz \)      | \( P(e) \) | 0.6077 × 1 | 0.3988 × 1 | 0.3221 × 1 | 0.2563 × 1 |
| \( a_m = 5g \)      | \( V_{avg}(m/s) \) | 0.2906 | 0.1931 | 0.1583 | 0.1277 |
| \( f = 100Hz \)     | \( P(e) \) | 0.5925 × 2 | 0.3937 × 2 | 0.3227 × 2 | 0.2604 × 2 |
| \( a_m = 5g \)      | \( V_{avg}(m/s) \) | 0.1921 | 0.1328 | 0.1044 | 0.0836 |
| \( f = 150Hz \)     | \( P(e) \) | 0.5875 × 3 | 0.4061 × 3 | 0.3193 × 3 | 0.2557 × 3 |
| \( a_m = 5g \)      | \( V_{avg}(m/s) \) | 0.1921 | 0.1328 | 0.1044 | 0.0836 |

2.2.4. Approximation equation of \( V_{avg} \). In view of equation (11), equation (10) becomes

\[
V_{avg} = \frac{a_m}{f} (20.22\ e^3 - 41.91\ e^2 + 29.47\ e - 6.7)
\]  

(12)

Require mentioned, equation (12) is obtained based on "standard map" model. If recovery coefficient \( e \) is enough big the ball’s bounce height is far greater than displacement amplitude of vibrator that is close to "standard map". On the other hand, if recovery coefficient \( e \) is small (i.e. \( e < 0.5 \)) "standard map" model will be not applicable, the ratio of \( V_{avg} \) to \( U_{avg} \) isn’t equal to \( \rho \) and equation (12) isn’t true.

3. The best vibration test condition of PIND

The larger velocity of the particle the easier it is detected. Equation (12) shows that the ball’s velocity can be controlled by controlling vibration acceleration and vibration frequency. During the experiments of PIND, vibration acceleration is given generally and vibration frequency is optional. However, small vibration frequency will increase vibrator’s output power under the constant vibration
acceleration that means vibration frequency can't be decreased arbitrarily. Therefore, the best vibration frequency exists under the constant rated power of vibrator in PIND.

3.1. Output power of vibrator

Figure 4 is the velocity of vibrator. Suppose the mass of vibration table is $M$, instantaneous energy of vibrator is

$$\frac{1}{2}MU^2(t) = \frac{1}{2}MA_m^2\omega^2 \cos^2(\omega t)$$

(13)

Figure 5. The velocity of vibrator.

The total energy of vibrator in one period is

$$E_v = 2\int_{-T/4}^{T/4} \frac{1}{2}MA_m^2\omega^2 \cos^2(\omega t)dt = \frac{\pi}{2}MA_m^2\omega$$

(14)

$E_v$ is the total energy of vibrator in one period. So output power $P_v$ in one period is

$$P_v = \frac{E_v}{T} = \frac{M}{4}(A_m\omega)^2$$

(15)

Equation (15) shows that output power $P_v$ is in direct proportion to the amplitude of velocity.

3.2. Relation between output power of the ball and one of vibrator

Setting output power of the ball is $P_B$ and $P_B$ should be in direct ratio to $V_{avg}$. Considering $a_m=\omega^2$, equation (12) becomes

$$V_{avg}=2\pi A_0\omega(20.22\omega^3-41.91\omega^2+29.47\omega-6.7)$$

(16)

It indicates that $P_B$ is in direct ratio to $P_v$, namely,

$$P_B \propto \frac{1}{2}V_{avg}^2 \propto (A_m\omega)^2 \propto U_{avg} \propto P_v$$

(17)

3.3. The best vibration test conditions of PIND

Equation (15) can be rewritten

$$P_v = \frac{M}{4}\left(\frac{a_m}{\omega}\right)^2$$

(18)

Output power of vibrator is in the inverse ratio of the square of $\omega$. If vibration frequency decreases output power of vibrator will increase under the constant vibration acceleration. When output power of vibrator reaches rated power the corresponding vibration frequency is the best vibration frequency. Setting rated power of vibrator is $P_M$, equation (18) becomes

$$f_0 = \frac{a_m\sqrt{\pi M}}{4\pi\sqrt{P_M}} = 0.141a_m\sqrt{\frac{M}{P_M}}$$

(19)

$f_0$ in equation (19) is the best vibration frequency under the constant vibration acceleration and the constant rated power of vibrator. $f_0$ is in direct ratio to vibration acceleration and it is also in direct proportion to the root of the ratio of $M$ to $P_M$. 
4. Experiments

Model 4501L is widely used to do PIND experiments in industry and is also used in our experiments. The data acquisition system is used to get the particle's output energy, whose sampling rate is 500 kHz. A kind of space relay is unpacked and several kinds of particles are put into the relay. These particles include different mass granulated tins and rubbers.

![Figure 6](image1.png) Figure 6. Output energy increases along with vibration acceleration’s increase.

![Figure 7](image2.png) Figure 7. Output energy increases along with recovery coefficient’s increase.

![Figure 8](image3.png) Figure 8. Output energy increases along with the ratio of mass increase.

![Figure 9](image4.png) Figure 9. Varieties of the best vibration frequency.

Figure 6 shows that: (1) the particle’s output energy increases along with vibration acceleration’s increase at the same vibration frequency; (2) the particle's output energy also decreases along with vibration frequency's increase. The particle is granulated tin whose mass is 0.06mg. Figure 7 shows the particle’s output energy increase along with recovery coefficient’s increase under the constant acceleration of 6g. The particles are granulated tin and rubber which have the same mass of 0.06mg. Because the granulated tin's recovery coefficient is greater than rubber's one, output energy of granulated tin is greater than one of rubber. Figure 8 shows the particle’s output energy is in direct ratio to its mass when holding other conditions. Because the particle's mean velocity is independent of mass its kinetic energy is direct ratio to mass. The two kinds of particles are granulated tins whose mass are 0.06mg and 0.11mg respectively. Figure 9 shows varieties of the best vibration frequency. When vibration frequency decreases the particle's output energy will increase. But the particle's output energy isn't always on the increase after vibration frequency is less than a certain frequency which is the best vibration frequency $f_0$, moreover, vibration acceleration will decrease and it is in direct proportion to vibration frequency which can be explained by equation (19). At this time, though vibration frequency is less than the best vibration frequency $f_0$, the particle's output energy will hold the line basically owing to vibration acceleration's decrease.
5. Conclusion
In this paper, PIND vibration test condition is researched in depth. PIND is a reliability screening technique that employs vibration, shock, and acoustics. As a requirement for MIL-STD-883E, PIND test has helped the manufacturers of hermetically sealed electronic components greatly increase the reliability of their product by eliminating contaminants within the cavity over the past forty years. But PIND doesn’t indicate quantitative relation between vibration conditions and output energy of the particle and it also doesn't explain how to obtain the best test conditions. Therefore researching on PIND theory is active demand. The key items covered in the paper are as follow.

(1) The particle's approximate equation is derived based on dynamics. The particle's motion can be thought of stationary random process in "standard map" model. In this way, it derives the expression which shows the relation between the particle's mean velocity and vibrator's one, the ratio of both velocities is determined by recovery coefficient. The particle's mean velocity equation is obtained based on simulations, it is in direct ratio to vibration acceleration, and it is in the inverse ratio of vibration frequency and it is the increasing function of recovery coefficient.

(2) The best vibration frequency is derived under the constant rated power of vibrator. The direct proportion relation between output power of the particle and one of vibrator is analyzed, it indicates output power of the particle is in direct ratio to the amplitude of velocity of vibrator and the best vibration frequency is in direct ratio to vibration acceleration, and is in direct ratio to the root of the ratio of mass of vibrator to rated power of vibrator.

Future work will be directed to study more complex model such as atactic cavity and study new and powerful vibration waveform for PIND.

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