A Survey of the Detection and Measurement of Contact Forces at the Head/Disk Interface in Hard Disk Drives

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ABSTRACT

Some interaction, contact or impact, between sliders and disks exists in almost all current hard disk drives. They can result in head crash, wear failure, power consumption, and even disturbance of MR read-back signals. There are many techniques available to detect contact and impact in the interface, and to measure the interactive forces. Here we describe and compare these experimental techniques.

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1. INTRODUCTION

One of the most important aspects of reliability of hard disk systems is the head/disk interface. Better understanding and control of the contact and impact (C&I) occurring in the interface are of utmost concern. Contact and impact occurs during the contact-start-stop (CSS) procedure and possibly also in the ramp load/unload process. Intermittent contact and impact also occur in the normal operational state of current systems because of the low flying heights. Therefore, contact and impact occur in almost all current hard disk drives. They can result in head crash, wear failure, power consumption, and even disturbance of MR read-back signals. There are several techniques available to detect contact and impact in the interface, and to measure the interactive forces. Detection is mainly performed by using transducers such as acoustic emission (AE), piezoelectric (PZT), laser Doppler vibrometer (LDV), laser interferometer, electrical resistance, and electrical capacitance. The AE signal, force identification and direct measurement are applied to measure the forces. Here we mainly survey the experimental techniques of detecting and measuring the contact and impact between the sliders and disks.

There is no clear definition of contact or impact in the published papers concerned with this issue. For convenience, we call the interaction between sliders and disks contact if the interactive forces are always compressive, and the forces are considered as quasi-static in the application. We call the interaction impact if the forces are not always compressive, and the forces must be considered as dynamic forces. In actual situations, contact may be a superposition of a series of separate impacts.

2. DETECTION OF CONTACT AND IMPACT

For the various techniques used to detect contact and impact between the sliders and disks, a major difficulty is the requirement of a threshold value. If the value is too small, the noise level will result in erroneous detection, and if the value is too large, some impact and contact events will not be detected.

2.1 LDV and laser interferometer method

Although the LDV and laser interferometer (Zhu and Bogy, 1987; Jeong, 1991) can be used to detect interactions between a disk and slider, their signals are not very sensitive to weak contacts, because this method is used to measure the motion of the entire slider. However, Jeong (1991) has shown that the LDV velocity signal can give a clear indication of the interaction in the dynamic loading process.

2.2 Electrical capacitance method

The method (Hoyt et al., 1987; Hamaguchi and Matsumoto, 1990; Suk et al., 1992) typically isolates each of the four corners of the slider to serve as one capacitor plate to measure the distance above the disk surface, which acts as the opposing plate. This method allows the determination of the rigid body motion of the slider. Yeack-Scranton (1986) compared the electrical capacitance with PZT signals, and found that light impacts can not be detected by the electrical capacitance method.

2.3 Electrical resistance method

This method uses the contact electrical resistance between the slider and disk surface to determine whether contact has occurred. Tseng and Talke (1974) first introduced the electrical resistance method to evaluate characteristics of the head medium interface. They measured the contact frequency utilizing a specially prepared metal disk and metal tri-pad slider, and compared the results with the slider flying characteristics. Kishigami et al. (1990) used the method to accurately evaluate the contact characteristics between a slider and the medium. The number of contact pulses per unit time was measured, and the results were compared with those measured by the conventional PZT method. They found that the resistance method is more sensitive than the PZT method in contact detection. Hatamura et al. (1990) measured the electrical resistance as well as the frictional force and slider motion during the CSS process. They considered the electrical resistance as the physical quantity corresponding to the real contact area between a slider and disk. Jeong and Bogy (1992) used this method to detect contact during the CSS and dynamic loading processes, and they compared it with the LDV and AE methods. They studied the effects of the driving voltage and electrical resistance to obtain the optimal use of the method. They found that a long sample time or the existence of the lubrication film on the disks can prevent this method form detecting all the contacts.

2.4 Acoustic Emission (AE) Method

This method has the major advantage of simplicity and convenience for interaction detection. The AE sensors can be placed either directly on top of the slider or at the base of the suspension assembly. As long as the slider is flying, there is little or no AE to be measured. However, if the slider is impacted by an asperity, then the slider will vibrate, and the signal can be easily detected by the sensor. The use of acoustic emission for interaction detection was first documented in a paper by Kita et al. (1980). In this application, the AE sensor was attached to the test fixture and the electronics consisted of a 100 kHz to 500 kHz band-pass filter, an amplifier, and RMS measurement circuitry. Kita demonstrated its ability to characterize different elements of a slider take off profile in both the time and frequency domains. O'Brien and Harris (1996) used a similar method to detect contact with an experimental system designed on the basis of the natural frequencies of the slider. Yeack-Scranton (1986) suggested a method in which small piezoelectric sensors are mounted on top of the slider. The signals from these sensors are the results of the rigid body motion of the slider, the natural modes of vibration of the slider and the induced elastic waves in the slider. The acceleration of the slider can be deduced from the low frequency (<100 kHz) band of the signal. Above this frequency the natural modes and elastic waves are measured to detect the impact. She also showed that the RMS of the AE signal increases as the disk speed is increased because of the disk roughness effects. Jeong and Bogy (1989, 1991) employed not only the AE sensor but also piezoelectric plates attached to a slider and a LDV to aid in the interaction detection. They (1992) also simultaneously applied the AE sensor, the LDV and the electric resistance method to detect the interaction during the dynamic loading process. Their results show that the AE sensor is very sensitive and can detect the interaction at the slider-disk interface even when it is attached to the suspension holder. But it is subject to other mechanical noise such as the dimple separation slip. If only the AE sensor is used, and the spectrum of the AE signal is not analyzed, this slip could be improperly interpreted as an impact between the slider and the disk. Also, the AE signal has a relatively long delay time, so that the impacts that are very close to each other become difficult to distinguish.

2.5 PZT Method

In this method, a small piezoelectric transducer (PZT) is attached to the back of the slider. This approach has been used by many researchers: Yeack-Scranton (1986); Mochizuki et al. (1989); Kishigami et al. (1990), Hayashi et al. (1989); Jeong (1991). Using a low pass filter, one can measure the rigid body motion of the slider with the PZT. That is similar to use of the LDV and electrical capacitance methods. Using a high pass filter, one can measure the vibration of the slider body with the same PZT. That is similar to use of the AE method. Therefore, the PZT method is very effective for the detection and measurement of the interaction between the slider and the disk. The major disadvantage is the side effects of the sensors on the system properties.

3. MEASUREMENT OF THE CONTACT AND IMPACT FORCES

3.1 Definition of the problem

Quantitatively measuring the contact and impact forces is much difficult than detecting whether a contact or impact occurs. Figure 1, illustrates the forces acting on a slider during operation of the disk drive. The major problems and requirements are as follows.

1) The position of the force action is variable and unknown. We need to determine the position first.
2) This is an impact type force. The root-mean-square (rms) of the force is small, but the peak amplitude is relatively large.
3) It is difficult to separate the contact force from the air bearing force, especially in the lower frequency band.
4) A very wide measurement frequency, from 0 to 10MHz or even 100MHz, is required

5) A wide dynamic range or high force resolution is required. For example, the rms of the contact force in contact recording is much smaller than the air bearing force. Therefor very high resolution is needed to provide an accurate contact force measurement.
6) Calibration is very difficult for such small parts with a wide frequency range, and small force.
7) The current 50% and 30% sliders are too small to attach any measurement devices without inducing side effects to the system. Even several very thin wires attached to the slider will obviously affect the properties of the system. So, non-contact measurement is preferred.
8) To determine the position of the force, a multi-channel measurement is required.

The available methods can be divided into three categories—AE method, identification method (inverse problem method) and direct measurement method.

3.2 AE method

The AE-signal was initially used to detect a slider/disk interaction rather than to measure the magnitude of the forces. Nevertheless, the rms value of the signal, after filtering out the lower components, was shown to provide a possible measurement of the forces. Two representative works have been presented by Ganapathi, et al. (1995), and Khurshudov and Talke (1997).

Ganapathi et al. (1995) assumed that the slider vibration energy is a function of the contact force and the disk velocity. For a finite contact force, asperity impact will take place and, based on the Greenwood-Williamson model, the number of asperities contacting the slider will increase linearly with contact force. Each asperity can be thought of as transferring a packet of kinetic energy to the slider. The "kinetic energy" of the asperity will be a function of the velocity squared. So, they used the following functional form

$$V_{rms} = kF_c v^2 \tag{1}$$

Where V_{rms} is the rms voltage of the AE signal, k is a constant of proportionality, F_c is the contact force, and v is the velocity. In their case study, at 250 RPM speed ($v=250$) the friction is still at a maximum, insuring the contact load equals the suspension load ($Fc=34.34\ mN$), and the measured rms of the AE signal is 10.1 ($V_{rms}=10.1$). Then, the contact force at 4500 RPM (v=4500, $V_{rms}=291.9$) is calculated as follows

$$F_c = \frac{291.9}{\left(\frac{10.1}{34.34 \times 250^2}\right) \times 4500^2} = 3.061 mN \tag{2}$$

Although the estimated force seems to be of a reasonable order of magnitude, questions remain concerning the functional form of Eq. (1) and the determination of the constant k therein. Clearly, based on dimensional analysis of Eq. (1), the constant k has a velocity unit.

Khurshudov and Talke (1997) proposed the following different functional form

$$V_{rms} = kF_c v \tag{3}$$

where k is a constant of proportionality. In the low speed region ($v \approx 0\text{-}1$m/s), they assumed the contact force is equal to the suspension load. By curve fitting, the constant k was obtained experimentally for each given slider. Typical values of the contact force are in the range from 1mN to 2.5 mN in the velocity range from 3 to 23 m/s for sub-ambient pressure tri-pad sliders.

Comparing Eq.(3) with Eq.(1), we can see important differences. From the dimensional analysis view, it seems that Eq. (3) is more reasonable than Eq. (1). The two methods have a common point. That is they both use the AE signal measured in the low speed region and assume the contact force is equal to the suspension load to obtain the constant in the equation. Then, they use the equation to predict the contact force in the high speed region. But they ignore a severe problem. The contact force serves as an excitation force for the slider vibration. The locations, on which the contact force is applied, are different in the two speed regions. Figure 2 shows the forces acting on the slider in the Z direction in the two states. In the low speed region, the contact force is a distributed force, and in the high speed region, the contact force is a concentrated force (for tri-pad sliders). Even if the sum of the distributed force is equal to the concentrated force, the response of the slider will be much different in the two states. Therefore, the use of the constant k obtained from the low speed state to predict the contact force in the high speed state as described in these two papers is questionable.

Because the AE method is very convenient and has no obvious side effects on the system, it can be used to qualitatively evaluate the contact force. However, we can only obtain the static part or rms of the force by using the AE method. Selecting a suitable functional form and determining the unknown parameter is still questionable. Further research is definitely required to improve this method.

3.3 Identification Method

If we can assume the system is linear, the input identification method can be used to indirectly measure the interactive forces. If we know the transfer function *H(ω)* and response *V(ω)* of the system, the excitation, interaction force *F(ω)*, can be identified as follows

$$F(\omega) = \frac{V(\omega)}{H(\omega)} \tag{4}$$

Matsumoto et al. (1993) measured the response of four sensors (one on each corner of the slider), as shown in Figure 3 a), after applying a known input force (breaking pencil load) at the air bearing surface, and from that they calculated a transfer function of the system. With this transfer function, the interaction force waveform was calculated from the measured responses. They found two types of impact forces between the slider and the disk, as shown in Figure 3 b) and c). One has an amplitude of about 20mN and an interaction time of about 5 μs. The other has an amplitude of about 4 mN and an interaction time of about 22 μs. This is the only paper we have found in which the measured waveform of the interaction force are presented.

Briggs et al. (1992) performed the finite element modeling of the slider and presented the need for using slider body vibration modes for proper force identification. They discussed how to determine suitable sensor locations to obtain the impact locations and magnitudes of the forces. Briggs (1991) also suggested that the magnitude of vibration of the modes can be used like a “fingerprint” to estimate the force location along the slider rails. The magnitude of the impact can be determined from the overall vibration level. The method was found to work well on an enlarged model of the slider using ball drops to simulate asperity impacts. Streator and Bogy (1992) applied the force identification method to determine the friction force acting at the end of a cantilever-mass transducer from the measurement of a periodic strain signal.

The major advantage of the force identification method is the capability of obtaining the waveform of the force. The major problem is that the method is ill-conditioned with small errors in the measurements leading to large errors in the identified forces. It is also difficult to find the transfer function of the system because it is difficult to apply a measurable force for such small sliders.

3.4 Direct measurement method

Burger (1995) applied MEMS technology in the design and realization of an impact sensor array. As shown in Figure 4 a), the array was integrated in a silicon slider that can be used to measure slider disk interactions. The impact sensor array consists of thin film piezoelectric sensor elements that are placed close to the ABS. The local deformations due to the impact force are measured, which results in a high sensitivity and wide measuring bandwidth.

The experiment showed the feasibility of detection of slider disk interactions. However, the measured signal, shown in Figure 4 b), indicates a large contribution from the natural modes of the slider. Direct measurement of the impact forces and measurement of the elastic waves in the slider could not be realized due to the large depth of the sensor array and the low bandwidth of the amplifiers. The slider is not a real slider, and the effects of the wires (the sensor array needs many wires to connect the electronics) would be severe for current 30% sliders. Calibration would be another difficult task.

4. CONCLUSION

Comparing all of the previously used methods, we have concluded that the AE signal and electrical resistance methods are the two best choices for the interaction detection between the slider and the disk. The AE method, based on the slider body vibration by using band-pass filters, is very sensitive, reliable and convenient. The method that is force based would fail to detect some very weak or very close interactions. The electrical resistance method is another very sensitive and reliable method. The parameters, such as driving voltage, the resistance and sample frequency, are very important for the optimal use of this method.

There are three types of interaction force measurement methods – AE, identification and direct measurement methods. The successes of these methods have been limited. Comparing them to each other, we conclude that the AE method is most convenient for industrial application, and the identification method shows more potential. In any case additional research is certainly required to successfully measure the interaction forces between sliders and disks in hard disk drives.

ACKNOWLEDGMENTS

This study is supported by the Computer Mechanics Laboratory at the University of California at Berkeley and the National Storage Industry Consortium (NSIC).

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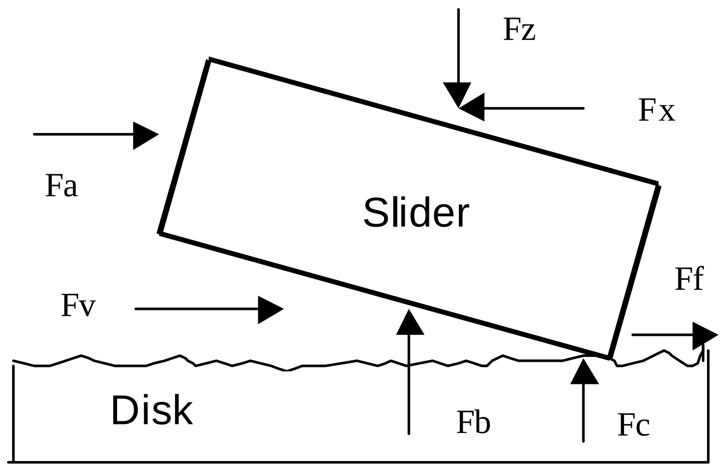
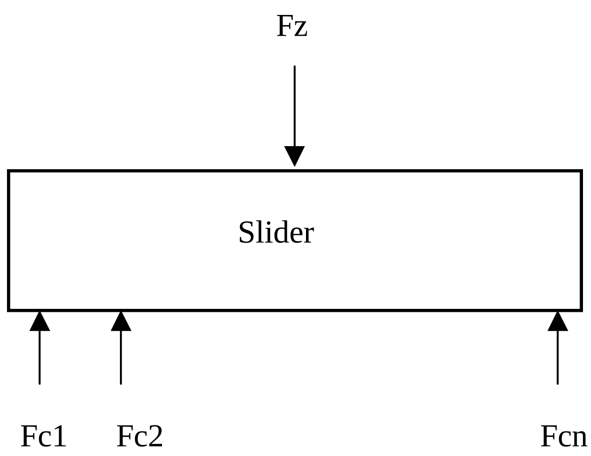
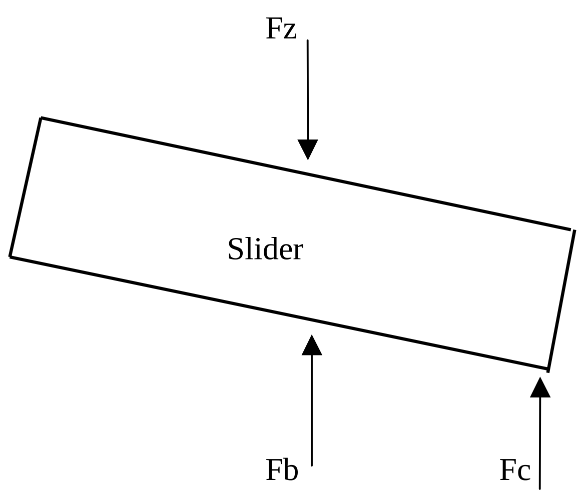


Fa Aerodynamic drag
Fb Air bearing force
Fc Contact force
Ff Friction force
Fv Viscous shear force
Fx Suspension load in X direction
Fz Suspension load in Z direction

Figure 1 The forces acting on the slider

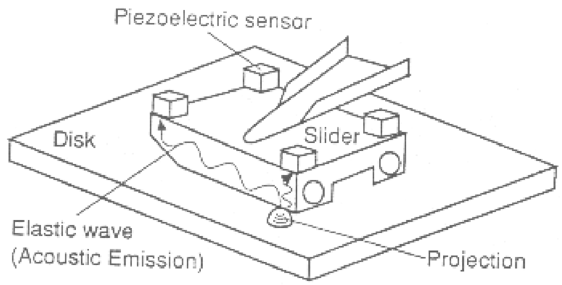


a) In the low speed state

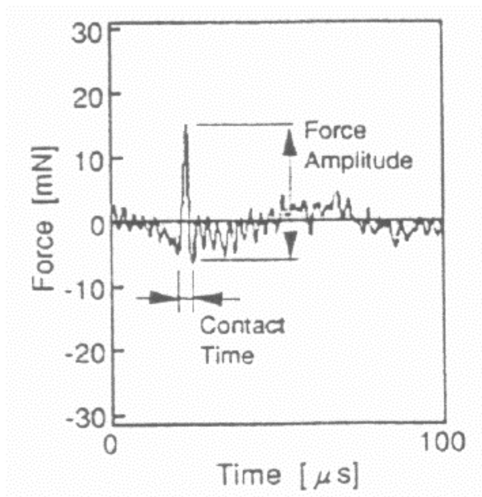


b) In the high speed state

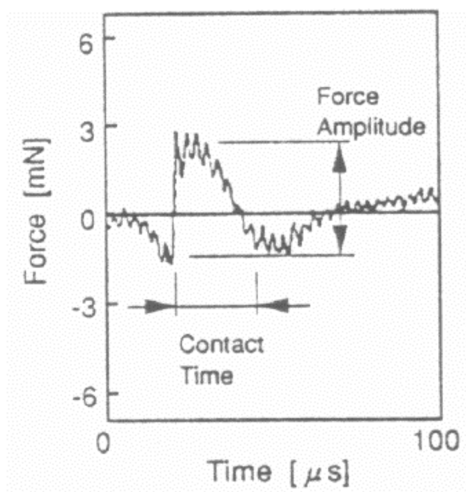
Figure 2 Contact force acting the slider



a) Schematic of the force identification

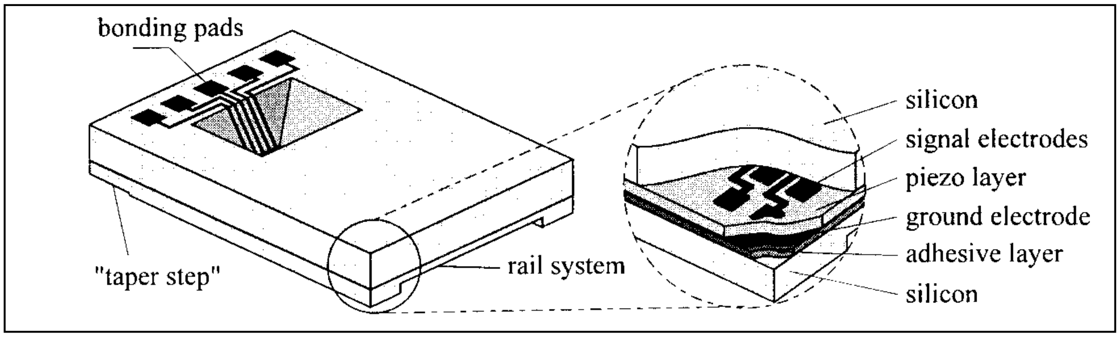


b) Impact force – Type 1

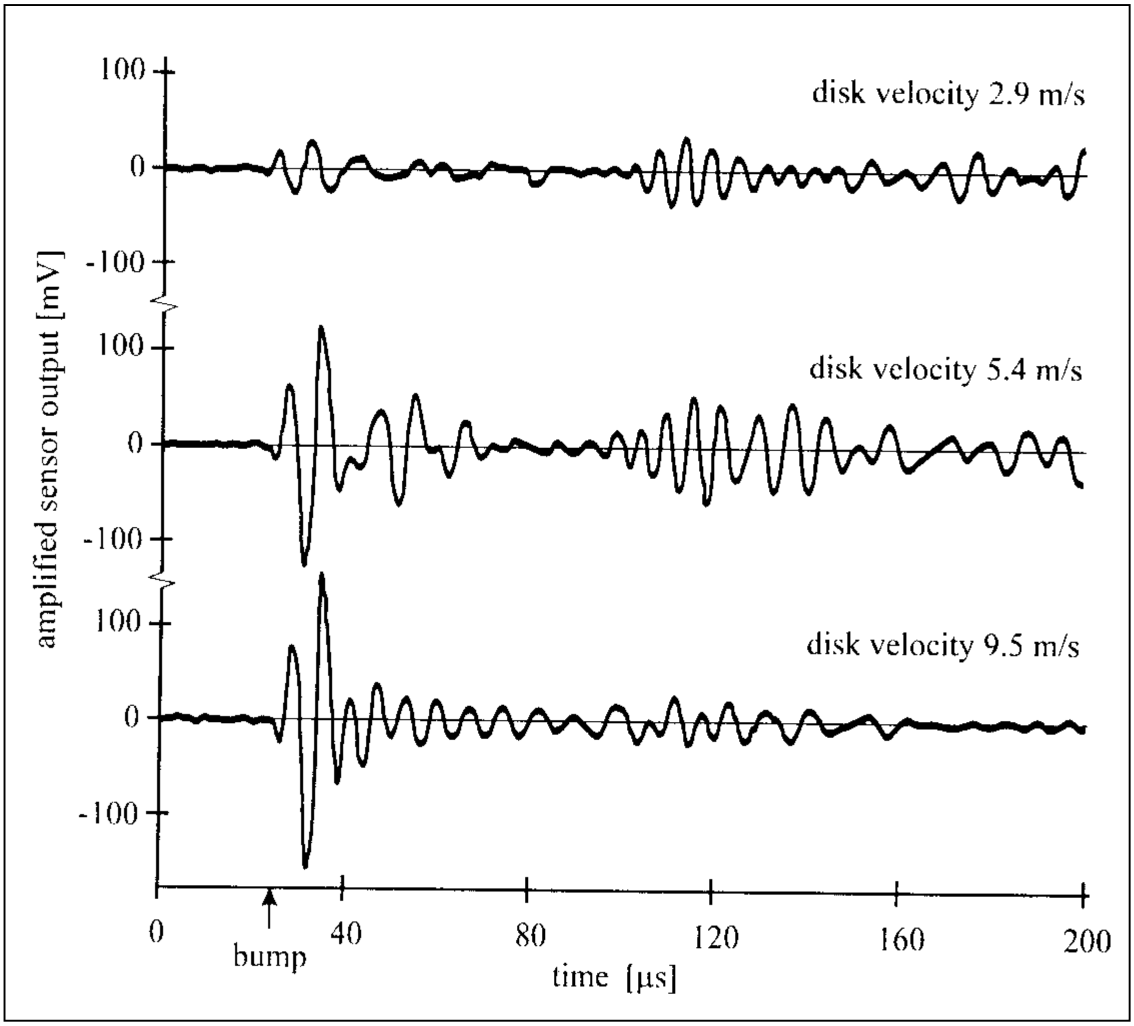


c) Impact force – Type 2

Figure 3 Force identification and results (Matsumoto et al., 1993)



a) The silicon slider with sensor array



b) Typical sensor response on a interaction between the slider and the bump

Figure 4 Slider with sensor array and measured sensor output (Burger, 1995)