Vibration Effects on the Performance of a Single-Shank Subsoiler

R. Karoonboonyanan[1], V.M. Salokhe[1], T. Niyamapa[2] and Hiroshi Nakashima[3]

[1] ASE Program, Asian Institute of Technology, PO Box 4, Klong Luang,
Pathumthani 12120, Thailand
[2] Department of Agricultural Engineering, Kasetsart University,
Kamphaengsaen Campus, Nakhorn Pathom 73140, Thailand
[3]Graduate School of Agriculture, Kyoto University, Japan
Corresponding author: salokhe@ait.ac.th

ABSTRACT

A single-shank subsoiler, mounted on a 61-kW 4WD tractor was tested with induced vibrations in the longitudinal and vertical planes. Tests were carried out in a sugarcane field with sandy loam soil one month after sugarcane was harvested. The draft, vertical force, and power required at different forward speeds were measured. The vibrations at operator seat were also measured. The subsoiler was tested in non-vibrating and in vibrating modes at two different speeds. The subsoiler vibrations showed significant ($p \leq 0.05$) effects on draft force, vertical force, total power requirement and total power per unit soil failure area. But it did not show any effects on the soil failure area and draft force per unit soil failure area. Compared to the non-vibrating mode of the subsoiler, the vibrating mode was found to have 29% and 34% reduction in draft force, but 227% and 400% increase in vertical force, and 100% and 66% increase in total power requirement. Also, 127% and 112% increase in total power requirement per unit soil failure area at the plowing speed of 2.5 km/h and 3.0 km/h respectively. The vibrations at oscillating frequency were transferred from the implement to the operator seat. In vibrating mode, the vibrations at operator seat in vertical direction were within 1-h fatigue-decrease proficiency boundary (fdp) at 10-Hz one-third octave band. In transverse direction, the vibrations were within 2.5-h fdp at the 1.6-Hz band, while the longitudinal vibrations were within allowable range.

Keywords: Subsoiler, seat vibration, draft force, power, soil failure area, power

1. INTRODUCTION

The problems of soil compaction and hardpan formation are common in sugarcane fields due to the traffic of tractors during cultivation and trucks after harvesting. The fields are subsoiled annually using conventional subsoilers to improve drainage for the next crop.

The use of vibrating or oscillating subsoiler is one technique that can reduce the draft force when the maximum velocity of oscillation is greater than the velocity of the tool carrier (Yow and Smith, 1976). However, despite the reduced draft force, the developed vibrating or oscillating subsoilers required more overall power than the conventional subsoilers since they require higher power for driving the vibration mechanism and for soil fragmentation. It was also recognized that the tractor body vibrates severely and that the power requirement of a vibrating subsoiler increases by two to three times than its use in non-vibrating mode. Several researchers have studied various parameters to minimize the draft force and total power.

List of Symbols and Notations Used

A	- zero-to-peak amplitude of vibration in the horizontal direction, m
a_x (r.m.s.)	- frequency-weighted root-mean-square of longitudinal acceleration
a_y (r.m.s.)	- frequency-weighted root-mean-square of transverse acceleration
a_z (r.m.s.)	- frequency-weighted root-mean-square of vertical acceleration
fdp	- fatigue-decreased proficiency boundary
g	- gravitational constant, m/s^2
Hz	- frequency in cycles per second
h	- hour
K	- the ratio of vibration acceleration to gravitational acceleration
kW	- kilo watt
SEM	- standard error of mean
T	- parameter including both the effects of velocity and acceleration
V_t	- forward velocity of the tractor, m/s
λ	- the ratio of vibration speed to forward speed
ω	- angular speed of the tool, rad/s
ρ	- the ratio of vibration acceleration to forward velocity
$\bar{x}$	- average value
1-L gear	- tractor gear speed selection 1-Low
2-L gear	- tractor gear speed selection 2-Low
4WD	- four-wheel drive tractor

Of the various design factors for the vibratory subsoiler the shape of the tine, the shape of the shank, the direction of oscillation, the oscillation frequencies, and the oscillation amplitudes were found to have effects on both draft force and total power requirement (Hendrick and Buchele, 1963; Kofoed, 1969; Wolf and Shmuelevich, 1977; Sakai et al., 1993; Niyamapa and Salokhe, 1993; Bandalan et al., 1999; Niyamapa and Salokhe, 2000a; Niyamapa and Salokhe, 2000b; Raper and Sharma, 2004). Four parameters attempted to relate the effects of a vibrating tool on the soil to an index of operating variable: $\lambda = A\omega / V_t$, the ratio of vibration speed to forward speed; $\rho = \omega^2 A / V_t$, the ratio of vibration acceleration to forward velocity; $K = \omega^2 A / g$, the ratio of vibration acceleration to gravitational acceleration; and $T = \lambda K$. Butson and MacIntyre (1981) reported no draft reduction when λ was less than 1.

Bandalan et al. (1999) studied vibrating subsoilers and found that draft ratio decreased rapidly when the velocity ratio increased to 2.25. The draft ratio decreased slowly, however, when the velocity ratio was grater than 2.25. The draft force correlated best to the parameter T (Kang et al., 2001). The torque and the total power requirement correlated best with the parameter K. The value of $T \geq 2.0$ and $K \geq 2.0$ were recommended as a minimum design criterion for a vibrating digger (Kang and Wen, 2005). The reduction of draft was the most important performance indicator of subsoilers. However, a tractor body vibrates severely by the fluctuating soil cutting forces acting on the tine (Sakai et al., 1988). The vibration of tractor-subsoiler system developed by Niyamapa and Rangdaeng (1996) showed effects on the tractor driver via the operator seat. The vibration from the engine and the inertial forces of the tine and shank might have an effect on the tractor vibration. The figures of vibration effect and riding comfort were not presented. To investigate this, in this study, performance of a single-shank subsoiler was investigated in terms of draft force, vertical force, total power requirement, draft force per unit soil failure area, and vibrations at implement, base of seat, and tractor operator's seat.

2. MATERIALS AND METHODS

Description of the Test Site

The experiments were conducted in a sugarcane field, one month after harvesting and one week after burning the crop residues, at an experimental station of Agricultural Extension Department at Phitsanulok, Thailand. The crop had an inter-row spacing of 1.4 m. The soil was sandy loam, consisting of 73% sand, 8% silt and 19% clay. The soil liquid limit was 39.8% and the plastic limit was 29.2%. The average soil moisture content in the top 10-cm depth was 18.3%, and it slightly increased (19.4 to 20.4%) below that depth. The average soil bulk density was 1.38 Mg/m^3 for the top 30-cm depth and it slightly increased with the depth. The average soil penetration resistance on the sugarcane row over the 20-cm depth was 2.18 MPa, while the resistance between the rows was 1.90 MPa. A network of superficial roots may have helped to maintain the integrity of the soil, causing high penetration resistance after drying.

Machine and Instrumentation

A single shank subsoiler developed by Niyamapa and Rangdaeng (1996) was tested in a soil bin and in the field. The optimum operation for least energy expenditure was obtained at a 36 mm oscillating amplitude and 9.5 Hz frequency (Bandalan et al., 1999). The preliminary test of the vibrating subsoiler in the field indicated that the tractor vibrations were not comfortable to the operator. The data of effects of vibrations on the operator were not recorded. Thus the single-shank subsoiler was selected to study the performance and riding comfort.

The single shank vibratory subsoiler vibrates in the longitudinal-vertical plane through a crankshaft and connecting rod on the frame as shown in Figure 1. The tine was 400 mm long, having a cutting edge of 70 mm width and a lift angle of 30 degree. The machine weight was 433 kg. The subsoiler was tested at 36 mm oscillating amplitude, 9.5 Hz frequency and 40 cm depth. A four-wheel drive tractor, powered by a 61-kW engine, with category-II rear hitch was used as the prime mover.

A four-bar linkage mechanism with eccentric shaft connected to the upper end of the shank was designed to produce the required amplitude. The kinematic diagram of tool motion is shown in Figure 2. The vibrating path at the tip of tine is shown in Figure 3. The equations of the tool motion at the tip of tine are:

$$X = V_t t + L_5 \cos\phi$$
$$Y = -L_5 \sin\phi$$

Where X is the movement of the tip of the tine in the x-direction,
Y is the movement of the tip of the tine in the y-direction,
V$_t$ is the forward velocity of the tractor, ϕ is the angle, and
L_5 is the length of side O$_4$C.

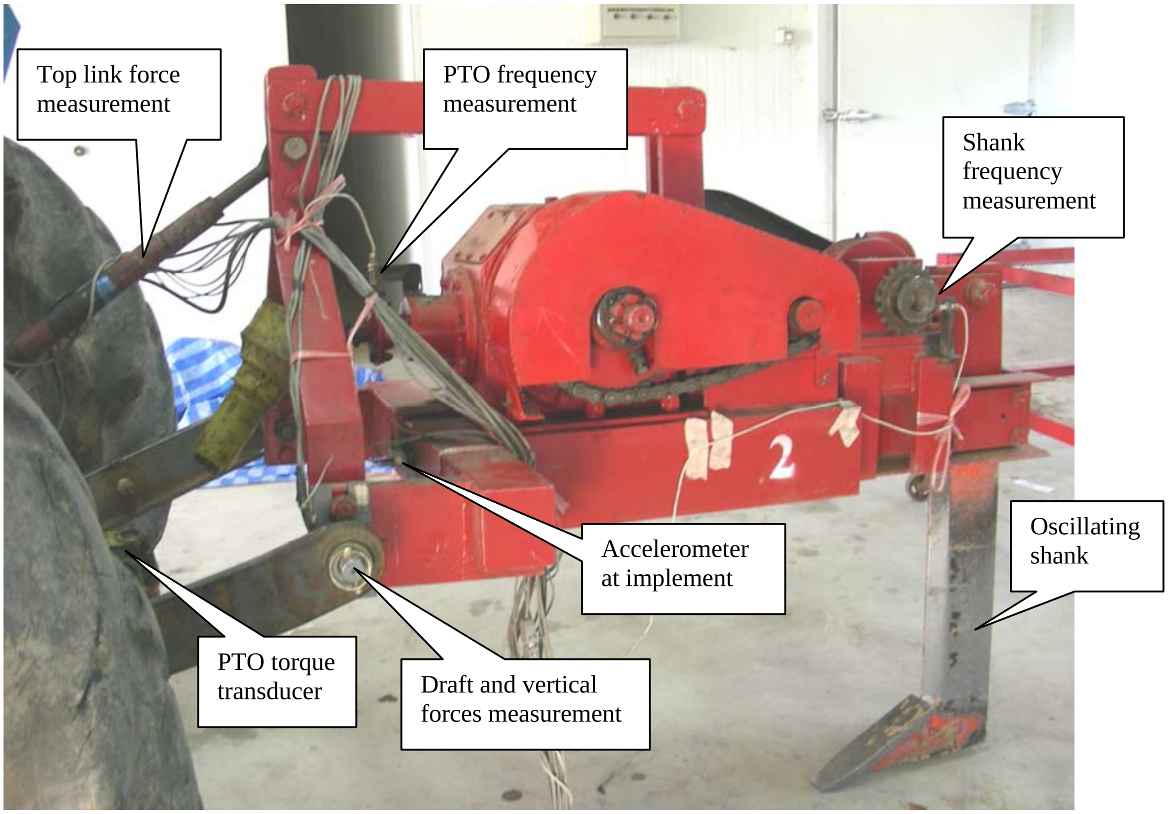

Figure 1. Single shank subsoiler and instrumentation.

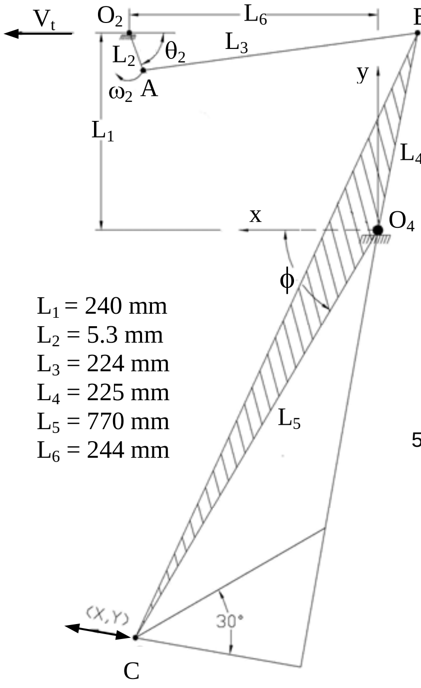

Figure 2. Kinematics of tool motion

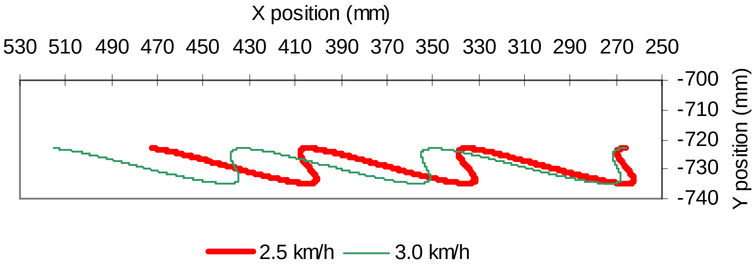

Figure 3. Vibration path of the tine

The draft and vertical forces were measured by bonding four 350-Ohm strain gages of full Wheatstone's bridge at each of the two lower link pins and at the upper link. The draft and vertical forces were determined by the bending action of the lower link pins and axial loading of the top link. The inclination of the upper link and operating depth were measured by a linear potentiometer attached at the tractor roof and fixed to the top pin of vibratory machine. A PTO-torque transducer was used to measure the torque. Two proximity switches were installed to measure the rotational speed and angular displacement of PTO and crankshaft. Nine accelerometers were installed to measure the vibrations at the implement, the base of seat, and the operator seat in the x (longitudinal), y (transverse), and z (vertical) directions. Three accelerometers were set up at each position. The SCXI field point model, NI Automation and Measurement Program on NI-DAQmx was used in this study. The data were recorded on a VI-logger and analyzed by using DIAdem version 10.0. The details of the measurement system are given in Figure 1.

2.3 Experimental Procedure

A preliminary test of single-shank subsoiler was carried out in the field at gear speeds: 1-Low, 2-Low, and 3-Low in both non-vibrating and vibrating conditions. The operating depth of non-vibrating mode at gear 3-Low was less than 30 cm and, therefore, this speed was rejected. Thus the single-shank subsoiler was tested at two tractor forward speeds (at gear 1-Low and 2-Low) and two vibrating conditions (non-vibrating and vibrating) for a 30 m travel. Travel time and wheel rotations were recorded to estimate the speed and wheel slip.

A soil profile meter was used to measure the level of land before and after tilling. Soil section was done by digging out the soil at the predetermined plane and by removing the cracked soil. The soil failure area was calculated from the soil profile before tilling and after removing the tilled soil section.

All the data were statistically analyzed. Comparisons were drawn between the subsoiler performance in vibrating and the non-vibrating modes.

3. RESULTS AND DISCUSSION

Performance Test

The data about the average tractor speed, wheel slip, shank frequency, operating depth, draft force, vertical force, PTO torque, and soil failure area were collected during the field test (Table 1). The performance of subsoiler working in vibrating mode was compared to its non-vibrating mode at two different speeds, 2.5 km/h for 1-L gear and 3.0 km/h for 2-L gear. It was found that draft force, vertical force and total power requirement in vibrating mode were significantly different ($p \leq 0.05$) from the non-vibrating mode. At the above speeds, the draft force was reduced by 29% and 34%, but the vertical force was increased by 227% and 400% respectively. Correspondingly, the total power requirement of a subsoiler in vibrating mode was increased by 100% and 66% at the same speeds. The soil failure area and draft force per unit soil failure area were found insignificantly different ($p \leq 0.05$) at these test conditions. The total power per unit soil failure area was increased by 127% and 112% at the plowing speeds of 2.5 km/h and 3.0 km/h respectively.

The test results revealed that the plowing speed had a statistically significant effect on the total power requirement ($p \le 0.05$), but its effect on the draft force and the vertical force was found to be insignificant ($p \le 0.05$). The draft force in the vibrating mode was lower than that in the non-vibrating mode. On the other hand, vertical force in vibrating mode was higher than that in the non-vibrating mode. The increase in the vertical force in the vibrating mode may be due to lifting up of soil clods during the forward movement of shank and tine. This was the same as revealed by Niyamapa and Salokhe (2000b). In their studies it was noted that the soil surface was cracked due to tool motion showing the characteristics of lifting up of soil clods during the oscillating movement of the implement. However, the resultant forces in vibrating mode were 7.9 kN and 8.0 kN (at speeds 2.5 km/h and 3.0 km/h respectively) lower than those for non-vibrating mode which were 9.9 kN and 11.2 kN at the same speeds.

Table 1. Effect of vibration and speed on subsoiler performance

	Non-vibrating		Vibrating	
	1-L gear	2-L gear	1-L gear	2-L gear
Average speed, km/h	2.5	3.0	2.5	3.0
Average slip, %	10.1±0.3	9.8±0.2	6.6±0.5	7.8±0.9
Average shank frequency, Hz	0	0	10	10
Average operating depth, cm	42.2±1.8	34.2±1.8	33.7±2.2	37.7±2.2
Average draft force, kN	9.8±0.6	11.2±0.6	7.0±0.7	7.4±0.7
Average vertical force, kN	1.1±0.8	0.6±0.8	3.6±1.0	3.0±1.0
Average P.T.O. torque, N.m	0	0	138.9±4.9	159.0±4.9
Average total power, kW	6.7±0.6	9.5±0.6	13.4±0.7	15.8±0.7
Average soil failure area, cm^2	1,335±222	1,444±222	1,184±272	1,338±272
Average draft per unit soil failure area, N/cm^2	7.5±1.4	8.0±1.4	6.0±1.8	6.8±1.8
Average total power per unit soil failure area, W/cm^2	5.1±2.4	6.8±2.4	11.6±3.0	14.4±3.0

$\bar{x} \pm SEM$

It was also found that total power requirement significantly ($p \le 0.05$) increased with the speed. The higher total power requirement in the vibrating mode can be attributed to additional PTO power input for oscillating machine (Bandalan et al., 1999) and for soil fragmentation. Total power ratio decreased from 2.0 to 1.7 as the speed was increased from 2.5 km/h to 3.0 km/h. This agrees with the study by Bandalan et al. (1999) and Niyamapa et al. (2000).

Vibrating condition was found to have a significant effect on the total power requirement per unit soil failure area ($p \le 0.05$) but its effect on the soil failure area was found statistically insignificant. Clod size observed in the vibrating mode was smaller than that in non-vibrating mode. Niyamapa and Salokhe (1993) conducted a study on the soil failure and soil disturbance of sandy loam soil and found that the characteristics of soil disturbance could be divided into two main zones, the deep layer and the near surface zone. In the deep layer zone, the soil was fractured forming small fragments. In the near surface zone, the soil cracked forming big soil clods.

Table 2 shows the corresponding values of the four parameters, λ , ρ , K , and T at the two speeds tested.

Table 2. The parameters for vibrating subsoiler

Parameters	1-L gear	2-L gear
λ	3.3	2.7
ρ	205.8	171.0
K	14.5	14.5
T	47.5	39.4

The results revealed that in the vibrating mode, the values of the average draft force and the average P.T.O. torque increased with increase in the speed of the tractor. However, the average vertical force decreased with increasing speed (Table 1). Also, for the same oscillating amplitude and oscillating frequency the values of parameters $\lambda, \rho,$ and T changed with tractor speed. These values decreased with the increase in plowing speed (Table 2). The plowing speed had no effect on parameter K. This was the same as revealed by Bandalan et al. (1999) and Kang et al. (2001).

Characteristics of Tractor Seat Vibration

The characteristics of tractor vibrations in three directions (longitudinal, transverse, and vertical) with and without the implement were studied in the field. The human exposure to whole-body vibration was also studied. The frequency-weighted root-mean-square (r.m.s.) acceleration as defined in ISO 2631/1 (1985) was used for evaluating vibrations and predicting the working efficiency of subjects when exposed to vibrations. The fatigue-decreased proficiency (fdp) is a function of exposure time and frequency. It was selected for evaluating the results. According to ISO 2631/1, for the human operator, the most sensitive frequency ranges are 4-8 Hz for vertical and below 2 Hz for longitudinal and transverse vibration. The tolerance for vibrations decreases with increased exposure time. The acceleration in three directions at the seat of the tractor operating in the field was investigated (Figures 4 to 7).

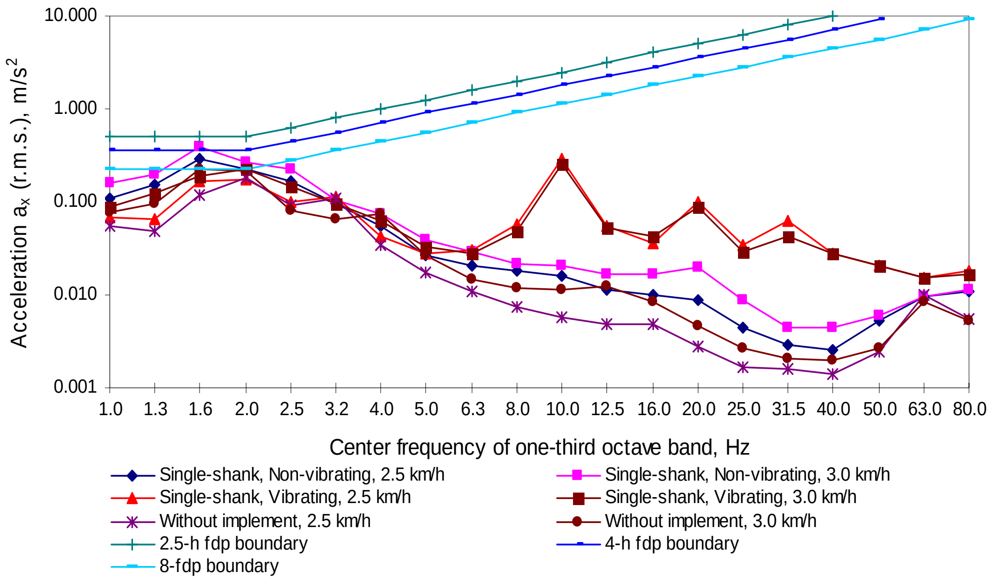

Figure 4. Longitudinal acceleration at seat of tractor in the field.

The vibrations at the operator seat in the longitudinal direction without the implement were below 8-h fdp in all tests. Also, the vibration of a single-shank subsoiler did not affect the longitudinal vibration at the operator seat. For the tractor with non-vibrating single-shank subsoiler running at 3.0 km/h, the longitudinal acceleration at operator seat was within 2.5-h fdp boundary at 1.6-Hz one-third octave band (Figure 4).

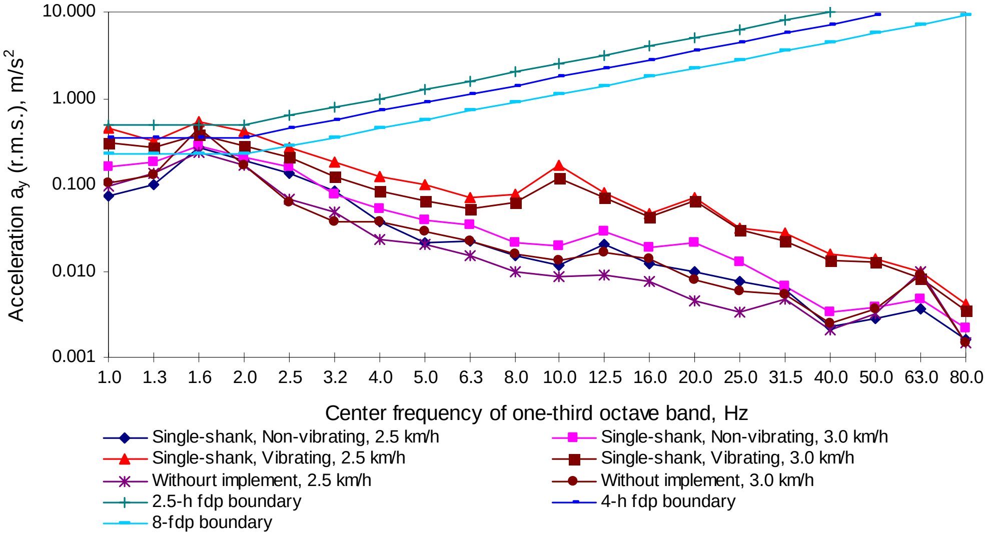

Figure 5. Transverse acceleration at the seat of tractor in the field.

When the tractor was running without the implement in the field at 3.0 km/h, the vibration effect at the operator seat in transverse direction exceeded 4-h fdp boundary at 1.6-Hz one-third octave band. The vibrating condition of the single-shank subsoiler was found to affect the transverse direction vibration at the operator seat. For a vibrating single-shank subsoiler running at either 2.5 km/h or 3.0 km/h, the effect of accelerations in transverse direction at the operator seat was within 2.5 h fdp boundary at 1.6-Hz one-third octave band (Figure 5).

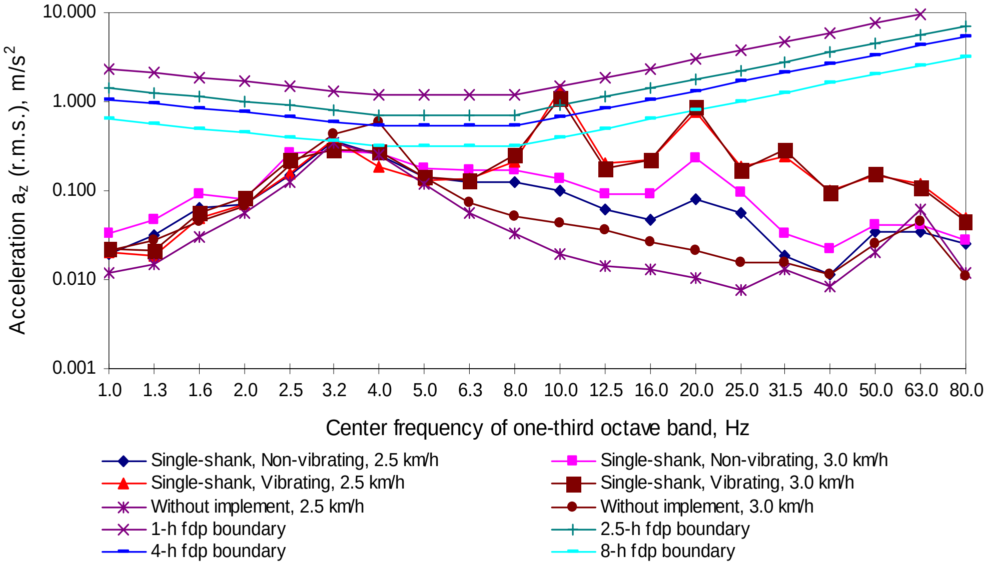

Figure 6. Vertical acceleration at the seat of tractor in the field.

The effect of vertical acceleration at operator seat of tractor without implement running in the field at 3.0 km/h was found to be within the 2.5-h fdp boundary at 4-Hz one-third octave band. This is because the resonant frequency of tractors of this size was around 3-5 Hz (Sakai et al., 1993). For a tractor with vibrating single-shank subsoiler, the effect of vertical acceleration at operator seat was found within 1-h fdp boundary at 10-Hz one-third octave band (Figure 6). The peak amplitude r.m.s. was found to be 10-Hz one-third octave band (interval 8.94 – 11.18 Hz), which covers the working frequencies of the single-shank subsoilers. The second harmonics were found at 20-Hz one-third octave band (interval 17.89 – 22.36 Hz) as the second peak.

Figures 7 to 9 show that the vibrations at the operator seat, the seat base and the implement shared the same frequency distribution pattern with the highest value at the implement, suggesting that the vibrations were transferred from the implement to the operator seat.

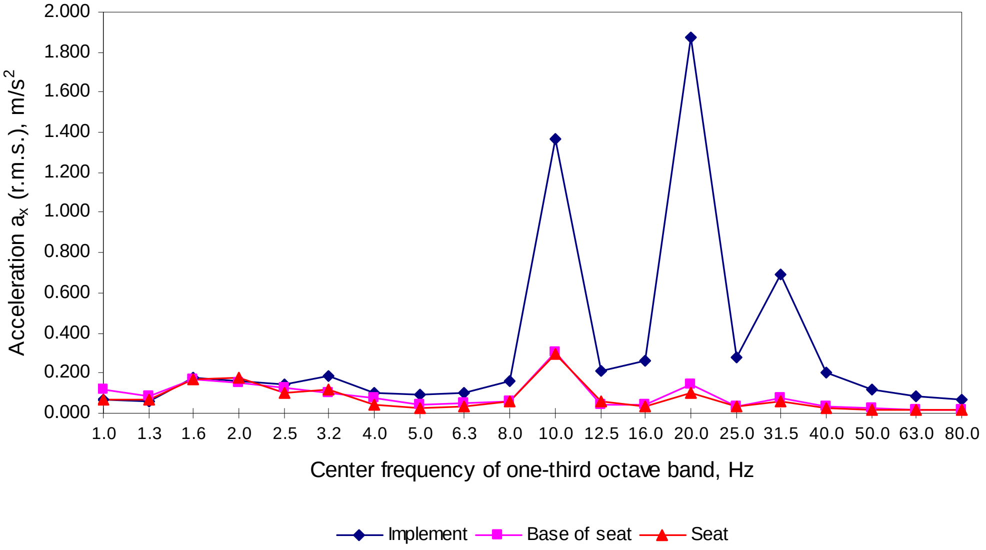

Figure 7. Longitudinal acceleration of vibrating single-shank subsoiler at 2.5 km/h tractor speed.

4. CONCLUSIONS

Based on the experiments conducted on a single-shank subsoiler in a sugarcane field with sandy loam soil, following conclusions could be drawn:

1) Compared to the non-vibrating mode, the vibrating mode of the single-shank subsoiler significantly reduced the draft force but increased the total power requirement. The soil failure areas in vibrating and non-vibrating modes were not statistically different.

2) The average vertical force during the vibrating mode increased due to lifting up of soil clods during the forward movement of the shank and the tine. The difference in the draft force per unit soil failure area was found insignificant for the vibrating mode compared to that for the non-vibrating mode.

3) The vibrations at the operator seat, the seat base and the implement shared the same frequency distribution pattern with the highest value at the implement, suggesting that the vibrations were transferred from the implement to the operator seat.

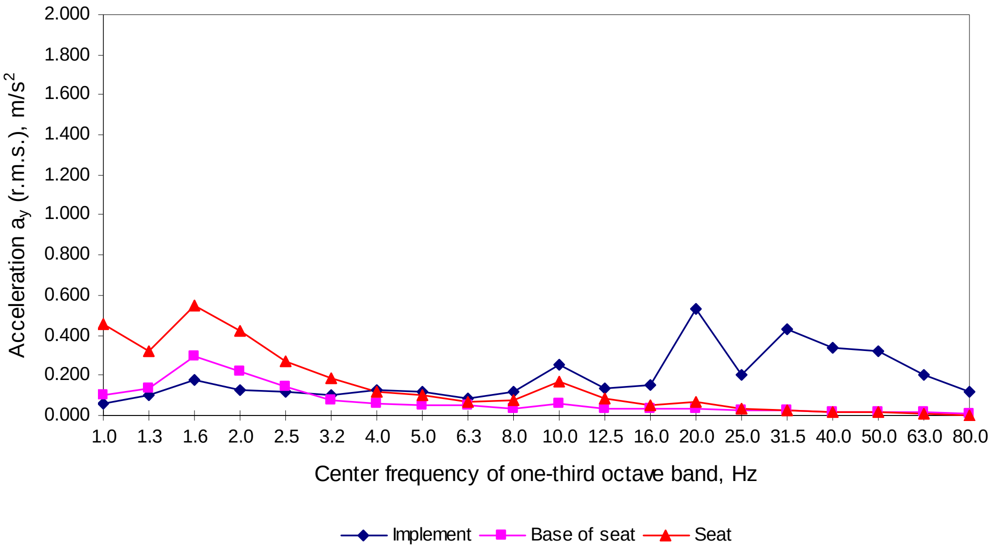

Figure 8. Transverse acceleration of vibrating single-shank subsoiler at 2.5 km/h tractor speed

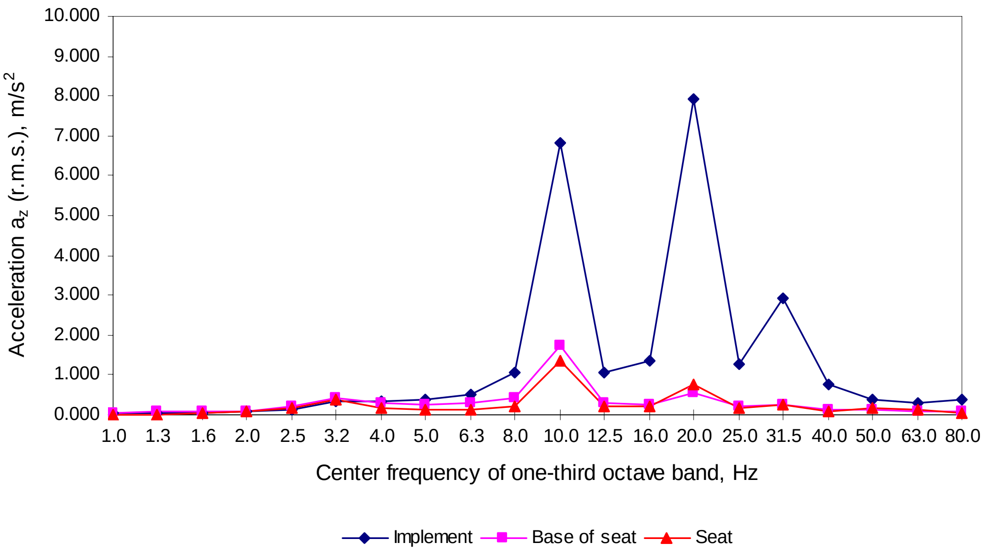

Figure 9. Vertical acceleration of vibrating single-shank subsoiler at 2.5 km/h tractor speed.

The vibrations at the operator seat exceeded the 8-h fdp which is uncomfortable to the operator. Further investigation to reduce these vibrations by using a double-shank subsoiler or by changing the design of seat or subsoiler should be carried out.

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