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Operational modal analysis and fatigue life estimation of a chisel plow arm under soil-induced random excitations

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ABSTRACT

Chisel plow is an important implement for primary tillage when the soil is dry and firm. In this research, fatigue life of a prototype of chisel plow arm under soil induced random excitation is analyzed. For this purpose, first, the field test is carried out on the chisel plow arm under soil-induced random excitations and operational modal analysis of the chisel plow arm is performed using stochastic subspace identification approach. In addition, a finite element model is constructed and successfully validated by stochastic subspace identification results. Then, the validated finite element model and power spectral density results of the measured random responses are used to achieve a process of the Mises stress in the arm needed for fatigue analysis. Finally, the fatigue life estimation of chisel plow arm is carried out in frequency domain using Wirsching-Light and Dirlik methods for different values of geometrical variables. The results of operational modal analysis demonstrate the possibility of identifying modal model of chisel plow arm in its operating condition on a basis of output-only data and the results of fatigue life estimation show that Wirsching-Light method provides a marginally safer prediction for chisel plow.

1. Introduction

Fatigue failure in metal structures could emanate from a process of permanently-occurring progressive micro-cracks (damage) happening for a structure subjected to conditions producing stress/strain fluctuations at some points. It might culminate in cracks or a complete fracture after a sufficient number of fluctuations. Accurate prediction for fatigue life of structures under operational loading is very important for both safe and economic design aspects that are applied in case studies of civil and mechanical engineering structures [1–3].

The fatigue analysis may be performed in the time or frequency domains. In the time domain, the rain flow method is implemented for identifying stress cycles, which are the stress range and mean stress for each cycle [4,5]. Fatigue analysis methods in the frequency domain, such as Wirsching-Light method [6] and Dirlik method [7] are appropriate approaches for large-scale structures under random vibrations, offering a direct connection between the concept of power spectral density (PSD) of stress process and the damage intensity or the cyclic distribution of loading [8]. In general, measuring stress time history is not possible in an early design stage. Thus, the stress history in most of projects could solely be constructed by a finite element model (FEM) of the structure [9,10]. Therefore, modal analysis approaches should be applied for validation of FEM.

During recent years a large number of efforts has been expended for the development of experimental modal analysis (EMA) approaches, requiring measurements of both input excitations and the corresponding output dynamic responses [11,12].

For a great number of structures, response data are the only measurable ones, while the actual loading time histories remain unknown. For instance, civil structures under wind-induced and earthquake excitations, and vehicle suspension systems over different road profiles are excited by stochastic loadings [13,14]. Therefore, operational modal analysis (OMA) approaches are used for extraction of the modal parameters from the output responses without the need for input information [15]. The frequency domain decomposition (FDD) [16], stochastic subspace identification (SSI) [17], and maximum likelihood [18] are OMA approaches for the system identification.

Vibration modeling of agricultural machinery in field conditions is one of the case studies of operational modal analysis [19,20]. The dynamic behavior of farm machines could be affected by different operational conditions *in-situ*, such as the forward speeds, unevenness of roads, and soil types [21]. An example of agricultural machinery is harvesting machinery. In the previous work operational modal analysis of the cutting platform in a harvest combine machine was carried out by frequency domain decomposition (FDD) approach and structural modification was applied to the combine cutting platform [22].

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Table 1
Material parameters for the fatigue life calculation [30]

Material	C (MPa^k)	k	S_u (MPa)
Steel	1.934×10^{12}	3.324	725
Aluminum	6.853×10^{19}	7.30	446
Spring steel	1.413×10^{37}	11.76	1850

The chisel plow is another example of agricultural machinery used for mulch-tillage farming. It helps prevent wind erosion, water runoff, and promoting water infiltration by breaking soil layers below normal tillage depth [23,24].

The effects of soil parameters on a laboratory experimental setup of a vibrating bulldozer blade, chisel and moldboard plow were investigated by Szabo et al. [25]. The tests were executed for different frequencies and amplitudes. The results indicated that the draft force of the vibratory chisel plow was far less than other.

The effects of frequency and amplitude of vibrating tillage tools on draft force have been reported in [26]. A draft force reduction was observed with increasing frequency and amplitude.

From above literatures it can be seen that there is no published research considering mechanical and structural aspects of chisel plow. Accordingly, in the present work, the FE model of a chisel plow arm is created in ABAQUS software and OMA of the chisel plow arm in field test conditions is carried out by SSI approach. The SSI results are then used for the validation of the constructed FEM. After that, the Mises stress process in the chisel plow arm is obtained using the PSD results of the field test and the validated FEM. Then, the fatigue life of the chisel plow arm is estimated in frequency domain using Wirsching-Light and Dirlik methods. Finally, the sensitivity of the estimated fatigue life to changes in some design parameters is investigated and the conclusions of the study are summarized.

2. Theoretical aspects

The following sections describe briefly some of the theoretical aspects related to the presented work.

2.1. Stochastic subspace identification (SSI)

Stochastic subspace identification method directly works with the recorded time histories. It should be beyond the scope of this article to explain in details the stochastic subspace identification method. The interested researcher is referred to [27–30]. The discrete time state space equations for a vibrating structure that is linear and excited by white noise are given by:

$$\{x_{k+1}\} = [A]\{x_k\} + \{v_k\} \tag{1}$$

$$\{y_k\} = [C]\{x_k\} \tag{2}$$

The vector $\{x_k\}$ is the state vector of dimension n, at a discrete time instant k. The vector $\{v_k\}$ is the Gaussian white noise process, driving the system. The vector $\{y_k\}$ is the measurement vector and is obtained by a pre-multiplication of $\{x_k\}$ by an observation matrix $[C]$. The dynamics of the structural system are fully characterized by its eigenvalues and the eigenvectors of the state matrix $[A]$. The eigenvalue decomposition of $[A]$ is given by:

$$[A] = [\phi][\Lambda][\phi]^{-1} \tag{3}$$

The eigenvalues λ_r on the diagonal of $[\Lambda]$ can be transformed into system poles μ_r by using the following equation:

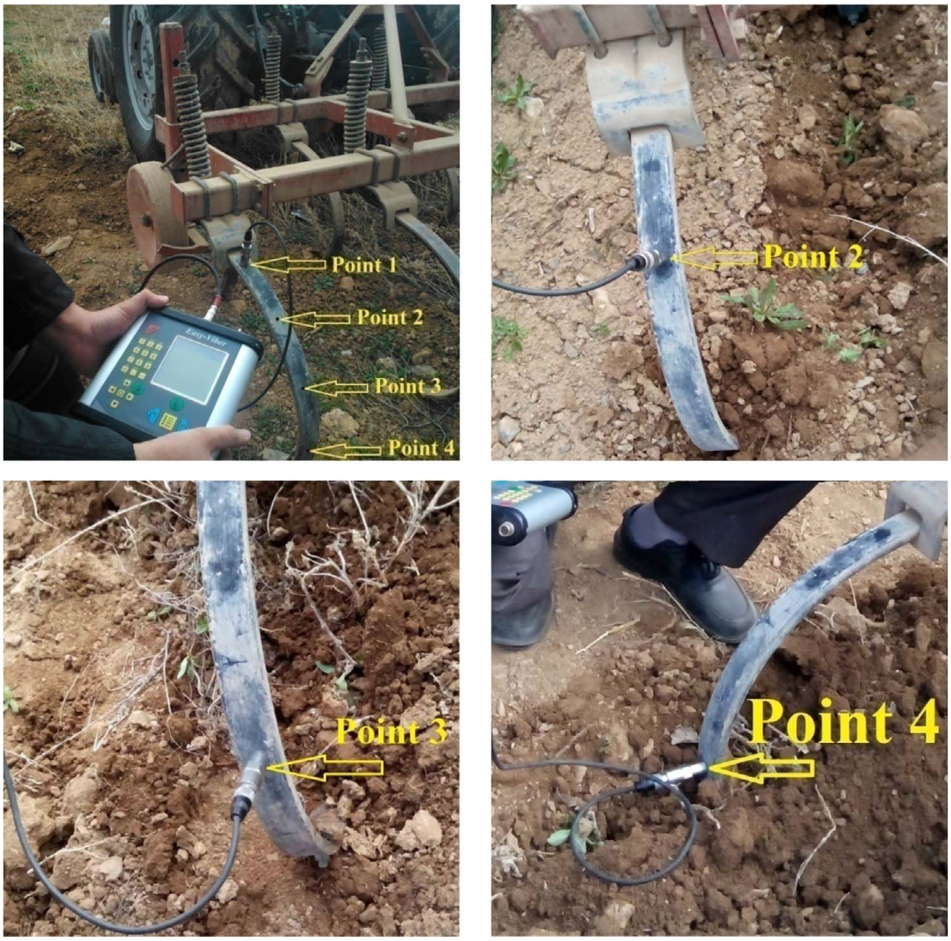

Fig. 1. Photographs of the measurement locations at the chisel plow arm, data acquisition system and accelerometer used in the random vibration test.