Luc Clijmans, Herman Ramon and Josse de Baerdemaeker, Leuven/Belgium

Sensitivity Analysis of the Dynamic Behaviour of Agricultural Machines

Even during normal operation of agricultural machines a number of disturbances occur that can generate excessive vibration levels. The disturbances can come from soil roughness or from rotating elements within the machine. Machine vibrations affect the manual or automatic controls and they reduce the efficiency of the operations to be carried out like for example spraying. In this contribution, an experimental modal model is derived that contains the eigenfrequencies and mode shapes of the machine. A frequency sensitivity analysis on the modal model gives information about the most critical locations on the structure with respect to local parameter changes. In a later stage, this is used to predict frequency shifts owing to structural modifications like local stiffness and inertia changes.

Tractor vibrations reduce the driver comfort and influence the efficient control of machinery [1, 4]. Experimental data of machine vibrations yield information about vibration levels, natural frequencies, damping and mode shapes occurring under real situations. The experimental technique can be utilised for failure detection, structural integrity testing and modelling purposes [3].

Objectives

This work deals with the dynamic behaviour of a tractor and a sprayer. The aim is to build structural dynamic models, based on experimental observations and applying the models to evaluate possible design changes. These design changes are proposed on the basis of a parameter sensitivity analysis carried out on the experimental modal models.

Fundamentals of modal analysis

The experimental modal analysis is used to derive linear modal models of a structure. The most obvious assumptions made in this method of vibration testing is that the system under test is linear and is driven by the excitation input only in its linear range.

Experimental modal analysis uses measured responses of a mechanism to known input excitation forces to calculate the frequency response functions (FRF). A parameter identification applied to these FRFs yields the modal model. These models contain the main characteristics of the system under consideration like natural frequencies, damping ratios and structure motions or mode shapes [2].

Experimental set-up for modal analysis

The hardware components required for experimental modal analysis vibration measurements consist of an excitation source for providing input energy to the structure. The inputs are measured by force transducers. Acceleration transducers are used to measure the response motions of the structure under test. The transducers are connected to a signal conditioning amplifier and filter. All the electrical signals are coupled with a data acquisition system to a computer workstation on which signal processing and modal analysis software runs.

For the excitation, a vertical hydraulic shaker was constructed. The top of the piston rod is connected with two parallel horizontal plates with three calibrated load cells (type PCB-202B) sandwiched in between.

The complete shaker is placed in a pit such that the instrumented horizontal plates are at floor level.

Response accelerations are measured by inductive accelerometers (HBM B12/200). The digital data acquisition system is a DIFA-SCADAS 6-channel acquisition system. LMS CADA-X software controls the data acquisition and analysis. It also is used to visualise the mode shapes. In the report reported here, a conventional agricultural tractor (John Deere 3300 FWD) with a Berthoud Mack 1000 sprayer mounted of which the boom width was 18 m, was utilised.

The vibration study was limited to a bandwidth of 0 to 10 Hz. Higher frequencies do not contribute to large motions of the tractor or of the sprayer. The burst random stochastic excitation signal has a spectrum between 0 and 10 Hz and a length of 5/8 of the measuring period. The complete system of tractor and sprayer was excited under the left rear wheel. An anti-aliasing filter was used and the averaging of 20 time periods cancelled out the influence of the noise on the signals. The coherence between excitation and response was better than 93 %, which ensured a high signal to noise ratio.

The modal model of the tractor with mounted sprayer

The sprayer is depicted by 14 nodes localised on the spray boom, four on the frame of the sprayer and five on the tractor (on the axles and on the pendulum point of the front axle), representing the geometric model of the test structure (*Fig. 1a*). *Figure 1b* represents the visual animation of the first longitudinal mode of the tractor-sprayer combination at 1,92 Hz.

The summed FRF of the sprayer shows four peaks for the horizontal and three peaks for the vertical direction in the frequency range 0 to 5 Hz. Each peak corresponds to a resonant frequency and a mode shape as listed in *Table 1*.

Table 1: Resonant frequencies of tractor-sprayer (horizontal motions) and effect of structural modifications on resonance

Mode Nr.	Frequency Hz	Mode participation %	predicted frequencies after adding a mass of 1 kg in points spui: 5 and in spui: 10 Hz	predicted modes after placing a truss between spui: 1 to 2 and spui: 13 to 14 Hz	Description
1	1,92	71,8	1,53	mode disappears	both outer boom sections in phase
2	2,52	18,9	2,68	mode disappears	both outer boom sections in antiphase
3	4,06	9,2	5,40	3,91	third flexible mode shape of entire boom

Ir. Luc Clijmans, Prof. Dr. Ir. Herman Ramon and Prof. Josse De Baerdemaeker officiate as scientifics at the Department of Agro-Engineering and -Economics, Katholieke Universiteit Leuven, Kardinal Mercierlaan 92, B-3001 Heverlee/Belgium.
The authors gratefully acknowledge N.V. Cofabel for providing the tractor and sprayer and M&M and the Van Hemelrijck Foundation for the test equipment. The first author has a doctoral scholarship of IWT (Flemish Government).

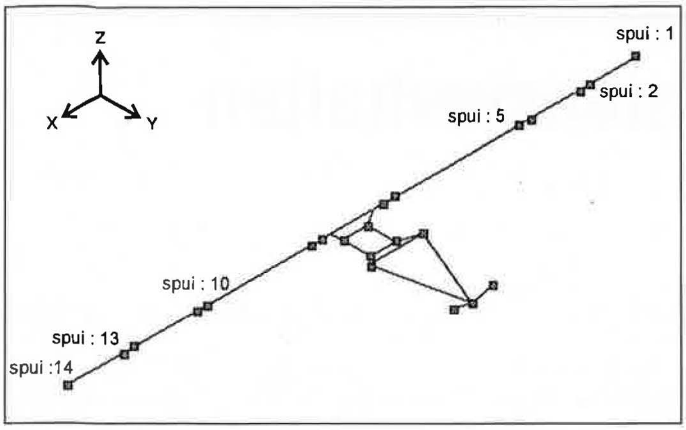

Fig. 1 a: Wireframe representation of the undeformed tractor-sprayer combination

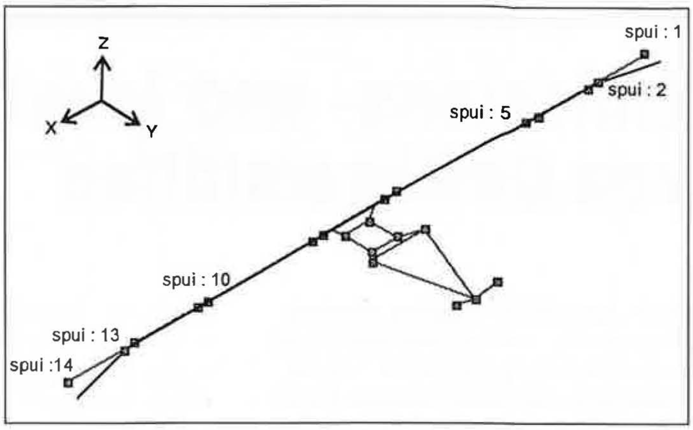

Fig. 1b: First (longitudinal) mode of the tractor-sprayer combination at 1,92 Hz

Sensitivity analysis and structural modification

The modal model will be used to study the influence of small design changes on the dynamics. For this purpose, the sensitivity of the structural dynamics to applied modifications is analysed. A set of equations calculates the sensitivity of the natural frequencies, damping values and mode shape coefficients of the machine to changes in inertia, stiffness and damping distribution. The starting point for the computations is the experimental modal model of the original structure.

Results of a sensitivity study of the natural frequencies of the tractor and the sprayer to inertia (mass) and stiffness changes are displayed in *Figure 2*. For each mode shape, the least sensitive locations are in the nodal points. In the anti-nodes the amplitudes can easily be reduced by structural modifications.

Next, a structural modification was carried out to alter the dynamics of the structures under test. A frequency spectrum of the expected disturbances in the field can be of great help for this design change. For example for proper field work, some of the resonant frequencies of this tractor and spray boom must lie beyond the dominant frequencies of the input spectrum. These frequency shifts can occur by locally increasing the mass or by changing the stiffness of some substructures.

For the sprayer, small changes are applied to the structure. The structural modification prediction revealed a great sensitivity to inertia modifications at the extreme points. In addition nodes 5 and 10 (the anti-nodes of mode 3) react to inertia additions. The spray boom is also made stiffener by putting two extra trusses on the outer sections (between node 1 and 2 and between node 13 and 14). This structural modification has great impact on the first two mode shapes, which were moved out from the frequency band of interest. The results of the structural modification on the sprayer boom are summarised in *Table 1*.

Conclusions

In this study, experimental modal analysis is applied to study the dynamics of an agricultural tractor with mounted sprayer. From experimental data of accelerations to stochastic random disturbance forces, frequency response functions are computed. Parameter identifcation tools estimate the modal parameters like resonant frequencies, damping ratios, modal displacements or mode shapes and mode participation factors. These modal parameters are used to design the modal model that describes the dynamics of the structure in the studied frequency band. Good approximations are obtained between the measured and synthesised FRFs. The sprayer model showed seven resonant frequencies, for the rigid body modes, for important longitudinal flexible deformation modes between 0 and 5 Hz and for the vertical modes.

In a next stage, the modal model was subjected to a sensitivity analysis. The most sensitive parts of the tractor and sprayer were localised. The influence of mass and stiffness changes on resonant behaviour was determined. Results show different effects of modifications between the nodal points with small amplitudes and the anti-nodes of the mode shapes with greater amplitudes. The use of structural modification predictions can be helpful for design purposes. Knowledge about the force disturbance spectrum experienced in the field gives information about the condition in which the machine has to operate and can guide the structural modification to reduce undesirable, excessive vibrations under working conditions in the field.

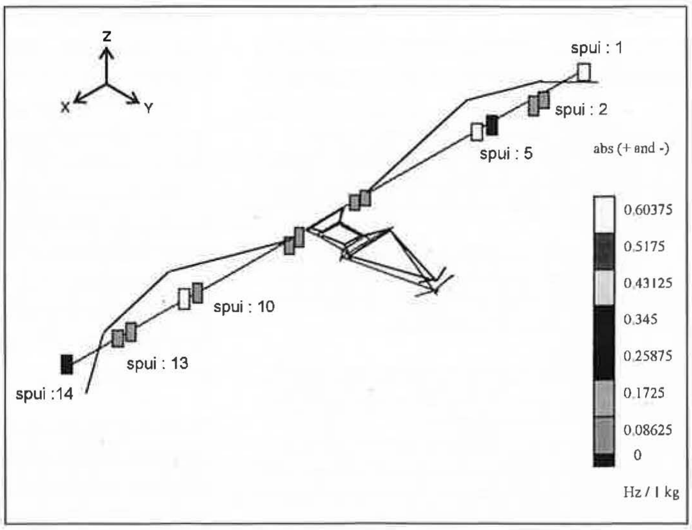

Fig. 2: Frequency sensitivity of the third longitudinal mode of the tractor-sprayer (4,06 Hz) to changes in inertia

References

[1] *Crolla, D.A.*, and *H. Schwanghart:* Vehicle dynamics: steering I. Journal of Terramechanics, 29 (1992), no. 1, pp. 7-17

[2] *Heylen, W., S. Lammens* and *P. Sas:* Modal Analysis, theory and testing. Course experimental modal analysis, Division of Production Engineering, Machine Design and Automation, K.U.Leuven, Belgium, 1994

[3] *Liefooghe, C., J. Leuridan, J* and *H. Van der Auweraer:* Integration of Structural Dynamics and Fatigue Analysis. Proceedings International Conference on Structural Integrity Assessment, Manchester, 1992, Elsevier, ISBN-1-85166-771-7, pp 269-279

[4] *Lines, J.A.:* The suspension characteristics of agricultural tractor tyres. Thesis submitted for the degree of Doctor of Philosophy, Cranfield Institute of Technology Silsoe College, UK, 1991, pp. 20-30

Keywords

Vibrations, experimental modal analysis, mode shapes, sensitivity analysis