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MEASUREMENTS BASED MATERIAL CHARACTERIZATION FOR A PLASTIC HAND TOOL HOUSING

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Abstract: *The goal of the present paper was to propose an approach based on measurements, correlation, optimization and sensitivity study for the characterization of the material of a hand tool housing. The considered material is a hard plastic for which the material properties were initially unknown. The measurements were performed on specimens, and small finite element models were used for tuning the properties by means of correlation and update methods. Further tuning was performed via an optimized sensitivity study, and correlation was done with experimental data. The resulting tuned properties were used in real application, a hand tool housing made of the studied material, in an orthotropic approach.*

Keywords: *material characterization, correlation, optimization, sensitivity*

1. INTRODUCTION

paper presents the development of a numerical model that simulates the structural dynamic behavior of a plastic material of unknown composition and structure, based on dynamic measurements performed on specimens of this material. This material is used for the housings of a hand tool. The final goal of the properties identification is the simulation of the behavior of the hand tool assembly (made of housings, gearbox, internal electrical parts and harness, connections, added damping material) and identify the possibilities of improving this final assembly's dynamic behavior in a frequency range that goes up to 2500Hz. In order to achieve this, the behavior of each component has to be separately studied, both by test and by simulation, and then test and simulation has to be performed on the final assembly, and the results have to be correlated in order to obtain a baseline model. On this correlated baseline model, modification are then made and the effect of these modifications on the dynamic behavior of the model are assessed.

The process of correlation and update ensures a rapid and reliable validity of a finite element model, which requires that the models (of parts, components, assemblies) are compared with experimental data or validated models of similar structures.

This comparison, which forms the basis of the material properties identification procedure, is based on the fact that the dynamic system responses (modal frequencies and shapes, frequency function responses, deflection shapes) can be calculated for a finite element model, and also measured on specimens or real components, and processed with specific methods. The primary request is that the simulation model and the real specimens or components have compatible shapes and structures, and that the conditions in which the simulation and measurement are performed (loading, boundary conditions, environmental conditions where necessary) are compatible.

The sensitivity study is performed on the simulation model, and is based on the fact that the behavior of the model is influenced by geometrical and material parameters, and the influence of these parameters can be easily assessed via an optimization like process. This process implies the initial definition of the design parameters and values (or ranges of values) that are considered important for the given application, that will be used as inputs and browsed in the simulation process, so that corresponding outputs are obtained. An optimization process usually requires also the definition of a target function, for example minimizing the mass of a component while keeping the stress within acceptable limits, in order to obtain as result the summarized influence of the input parameters that satisfy the target condition. For the sensitivity process, a specific target like the one described above is not necessary. The influence of the input design parameters over the computed result (mode shapes, relative frequencies) will be represented in comparative graphs on which the relevant trends and influences can easily be identified.

The present papers presents the process of the properties characterization of a hard plastic material which is used for hand tools housings, by experimental and simulation data correlation, and also the identification of the parameters which influence the most the overall behavior of this material. These properties are then used for the study of a component made of the studied material, and the dynamic behavior of this component is again validated against experimental data. The result of this double correlation and sensitivity process is an accurate representation of the behavior of the real component that was studied, very suitable for the necessary baseline model definition of the final assembly of the hand tool.

2. THE PLASTIC MATERIAL CHARACTERIZATION

The determination of the material properties for the hard plastic is necessary for the reliable further usage in a finite element model. The material properties of the samples that were tested are considered to be temperature and direction dependent. Static measurements were performed on two directions for the determination of the Young's modulus. Damping information were not available. The measurements were performed at room temperature (20°C).

The approach consists in the following: on the experimental side, an experimental modal analysis was performed on a specimens of the studied material, and then, on the simulation side, normal modes and frequency response functions were calculated using refined finite element models, in compatible conditions. Correlation was done between experimental and computed data.

2.1. Measurements setup

The measurements were done using the roving hammer technique, in free-free conditions. Difficulties are present due to the fact that the tested specimen is small and light, making the accurate simulation of the free-free conditions quite difficult. The test setup and the position of the accelerometers and hammer excitation (input) points are visible in Figures 1 and 2.

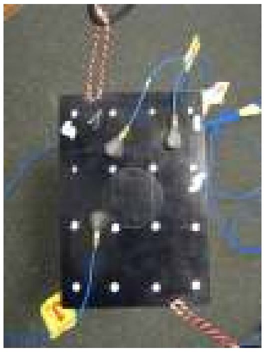


Figure 1: Test setup

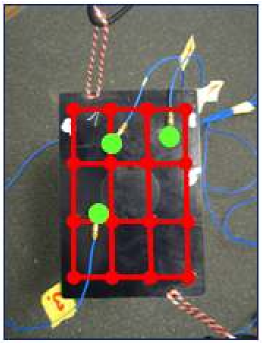


Figure 2: Input points (red) and accelerometers (green) positions

The accelerations are measured on a limited number of fixed positions (three, in this case) and that the structure is excited (with a hammer impact) on the 'measurement' grid. Because of the reciprocity principle, the set of recorded frequency response functions can be inverted, and thus represent the data as if the structure would have been excited at the three accelerometer locations and measured on the measurement grid. This set of frequency response functions were then used for the modal analysis (estimation of the poles of the system).

Measured and inverted frequency response function, resulted by summing up the resulted functions for all three response points, is represented in Figure 3. A number of peaks are visible, and also the fact that at high frequencies noise appears, due to the difficulties in exciting a soft material like plastic, and to the fact that the part is small and light, thus very sensitive. The measurements were repeated a number of times and the most coherent and stable results were kept for further processing.

The measured data processing software provided for this record the set of mode shapes , modal frequencies and damping ratios. After the animation, the main mode shapes were identified, as follows: first torsion mode at 269Hz, first bending around Y axis (short specimen edge) at 416Hz, first bending around X axis (long specimen edge) at 687Hz, second torsion mode at 743Hz, second bending around Y axis at 1166Hz, second bending around X axis at 1835Hz.

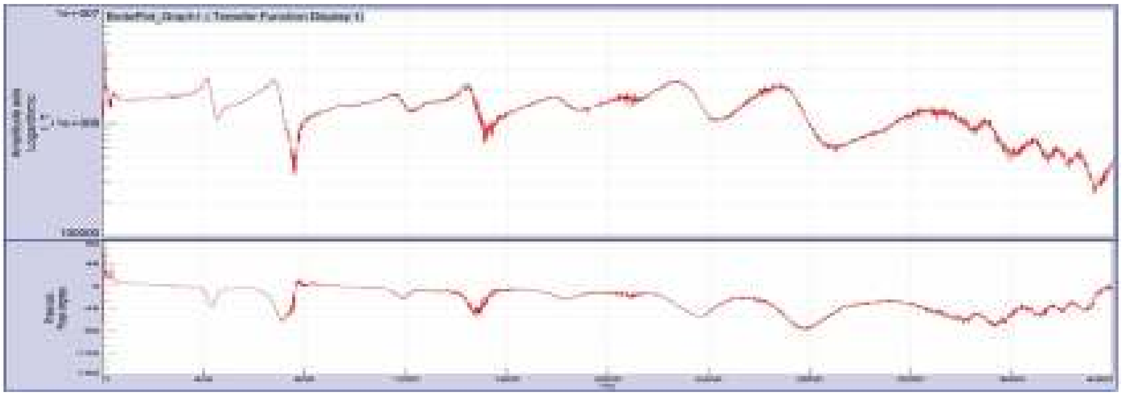
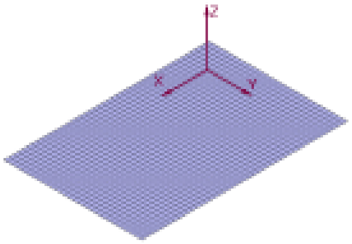


Figure 3: Measured frequency response functions sum

2.2. Simulation model

The geometry of the finite element model for the tested specimen was derived from measured dimensions and are 60mm over 102mm. The model was meshed with shell elements with a thickness of 2.1 mm. The longitudinal direction (fiber direction, corresponding to the longest edge on the specimen) is the X-axis of the model, exactly as in test. The Z-axis is perpendicular to the surface. The model is represented in Figure 4.



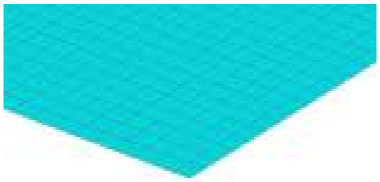


Figure 4: Simulation model

Figure 5: Material orientation

In order to be able to correlate data, the measurement and excitation points must be defined as output and input points in the finite element model (Figure 6).

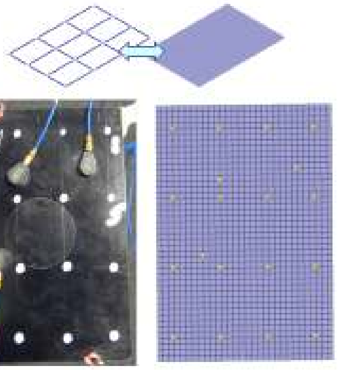


Figure 6: Test and finite element model correspondence

The material was found to have a different behavior in each direction, so orthotropic material definition was used in the FE model (NASTRAN MAT8 card), with the following initial values material properties:

- The density was derived from the weight of the test specimens, that was measured to be 24g, and was calculated as $\rho = Mass/Volume = 1432.7 kg/m^3$;
- The starting values for elasticity moduli, Poisson ratio and structural damping are: $E_1 = E_{longitudinal} = 6200MPa$, $E_2 = E_{lateral} = 1425MPa$, $G_{12} = G_{inplane} = 950MPa$, $v = 0.3$, $GE = 0.2$.

The experimental mode shapes from test were compared with calculated normal modes. The mode shapes were compared using a technique that is called "the modal assurance criterion", or MAC.

After correctly identifying the corresponding test modes for the appropriate mode shapes, the frequencies can also be compared by using the relative frequency difference, defined as: $abs(freq_{FE} - freq_{test}) / freq_{test}$.

Frequency response functions can also be calculated with the finite element model and then compared to the functions measured during the experimental modal analysis. This comparison is mainly used to evaluate the damping in the model, by visually comparing the peaks heights.

2.3. Sensitivity study

As the intention was to perform a sensitivity analysis over the finite element model, the material parameters E_1, E_2 , G_{12} and GE were defined as input design parameters. GE has no influence over the modal correlation, so it will not be used in the first step, of the modal correlation, but only in the second step, of frequency response functions correlation.

The effect of the input stiffness parameters on the (relative) frequency difference and on the MAC value can be assessed using a DOE (design of experiments): the parameters are given random values within a certain range, and the MAC values and frequency differences (Δf) are measured for each mode shape "i". The results of the DOE are graphs, having on the horizontal axis one of the material parameters (E_1 , E_2 or G_{12}) and on the vertical axis one of the correlation characteristics (MAC_i or Δf_i), one point in the graph represents one experiment.

Results for the relevant modes for the MAC and Δf targets are presented in Figure 7 and 8.

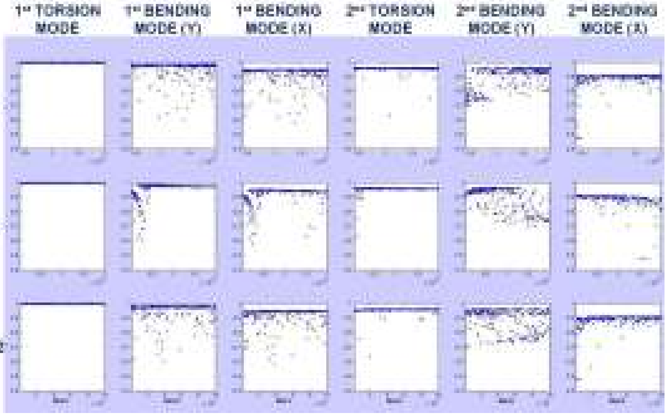


Figure 7: Sensitivity results, impact over the modal assurance criterion MAC

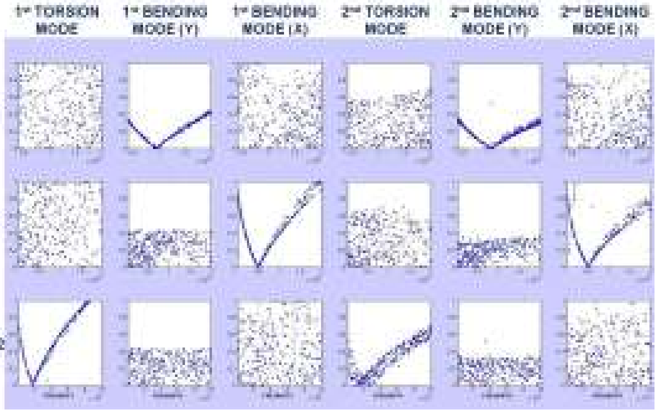


Figure 8: Sensitivity results, impact over the relative pressure difference Δf

From the sensitivity study, it is visible that the torsion modes frequencies are influenced by the in-plane shear modulus G_{12}. The bending modes around the secondary axis (Y-axis) are influenced by the Young's modulus in longitudinal direction (fiber direction), E_1. The Young's modulus in lateral direction E_2 influences only the bending modes around the primary axis (X-axis).

2.4. Optimization and correlation

After the DOE, an optimization can be performed with the stiffness parameters as variables and setting as a target (to minimize) function F a combination of the correlation characteristics for the first three modes, defined as:

$$F = 10 \cdot \left[(\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta f_3)^2 \right] + \left[(1 - MAC_1)^2 + (1 - MAC_2)^2 + (1 - MAC_3)^2 \right] \qquad \textbf{(1)}$$

The first three modes are the first bending modes (in the two directions) and the first torsion mode. These modes are enough for the optimization, since they are the primary modes influenced by the three material characteristics.
In Figure 9, the MAC and Δf before and after the optimization process are presented.

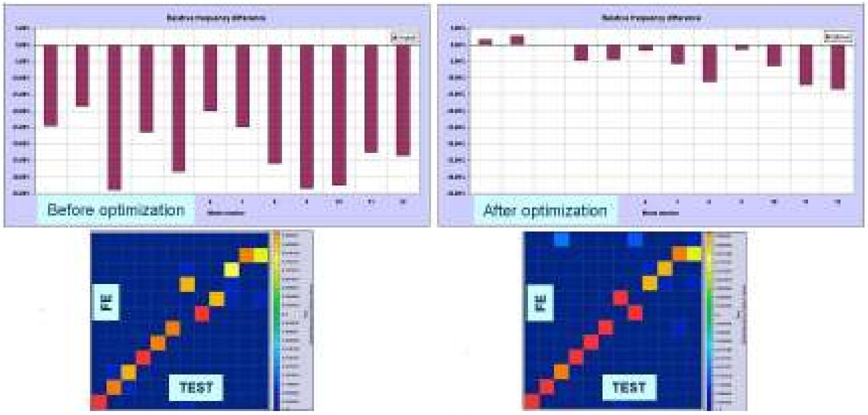


Figure 9: MAC and Δf before and after optimization

The optimized material characteristics are: E_1= 9970MPa, E_2=4850MPa, G_{12}=1850MPa. These values will be used to continue with the frequency response functions correlation, and the tuning of the structural damping coefficient GE.
Frequency response functions for all the input/output points possible combinations were calculated using the finite element model with the characteristic determined above, and the following values for the damping coefficient GE: 0.1, 0.15 and 0.2. Although only one frequency response function is represented below (Figure 10, input position is marked in green, response position in red), the results show that the most appropriate value for GE, that gives the best approximation of the measured function, is 0.15.

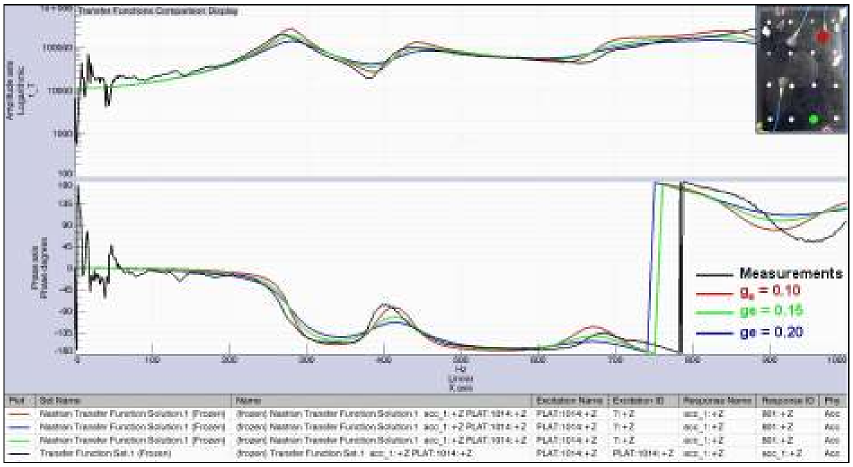


Figure 10: Frequency response function, acceleration in Z direction over frequency range

The resulting material parameters to be used with an orthotropic material definition for the real part are:
ρ=1432.7kg/m^3, E_1=9970 MPa, E_2=4850 MPa, G_{12}=1850 MPa, ν =0.3, GE=0.15.

3. HAND TOOL HOUSING APPLICATION

The real part to be simulated using the properties determined above was the housing of a hand tool of the common type used for light wood cutting, from the small load and dimensions range, for which experimental data exist, measured in the same way as described above. This part was meshed with shell finite elements. The geometry and the finite element model cannot be disclosed.

The material of this housing was considered orthotropic, with the characteristics determined above, except for the density, which was adjusted for the measured mass of this part, to 1301kg/m^3.

Given this finite element model is relatively large, this the calculation time is also considerable, it is not convenient to have a big number of runs on this (full) model. The usefulness of the properties determined above is obvious: due to the sensitivity and optimization performed for the specimen model, a good match for the first modes, and also a low relative frequency difference were obtained for the housing model (Figure 11), and an acceptable frequency response correlation (Figure 12), after only one NASTRAN SOL103 (modal solution) and SOL 108 (forced response) run.

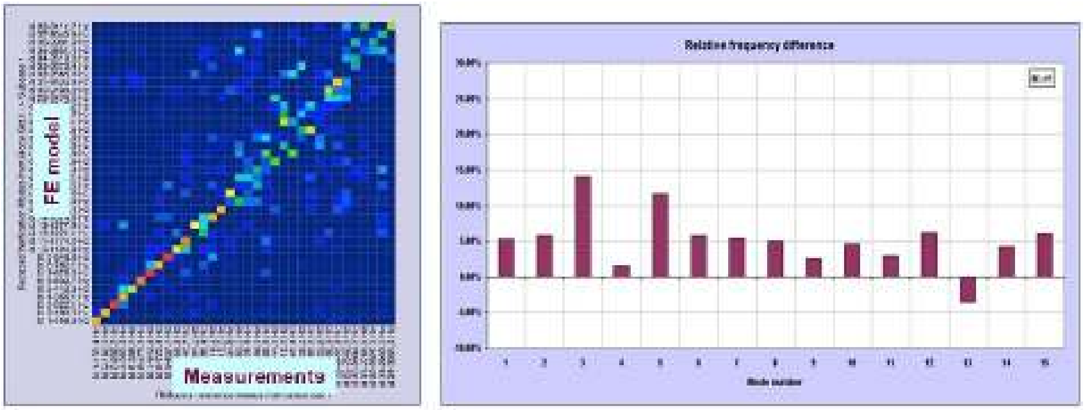


Figure 11: MAC and Δf for the correlated housing

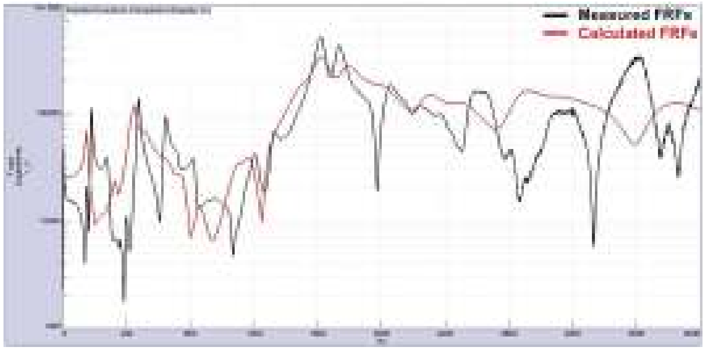


Figure 12: Measured and calculated frequency response functions sum

4. CONCLUSION

The paper presented the development of a numerical model that simulates the structural dynamic behavior of a plastic material of initially unknown composition and structure, based on dynamic measurements performed on specimens of this material. The accurate values of the material properties were identified based on experimental data, on a simulation model and on the following methods and procedures: correlation, optimization and sensitivity. The properties were proven to be accurate enough to allow the efficient correlation, in acceptable parameters, of the model of a real part made of the studied material in only one step.

REFERENCES

[1] Heylen W., Lammens S., and Sas P., Modal Analysis Theory and Testing, K.U. Leuven, PMA, Leuven, Belgium, 1997.