LESM: An interactive-graphics open-source educational software in MATLAB for static and dynamic structural analysis

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Abstract. This paper highlights the latest advancements in LESM (Linear Elements Structure Model), an educational software designed to analyze frames, trusses, and grillages. Developed as an open-source project using MATLAB, LESM boasts a user-friendly Graphical User Interface (GUI) that facilitates modeling and post-processing. The primary focus of the latest version of LESM centers around dynamic analysis, which necessitated substantial modifications to the program's analysis module. The notable enhancements encompass integrating inertial and damping effects, robust support for time-dependent load conditions, and introducing a transient analysis solver that accommodates multiple time integration schemes. The upgraded GUI is one of the most significant improvements, empowering users to leverage the dynamic analysis features interactively. This development holds immense potential in academic applications, offering students and researchers a valuable tool for exploring and understanding structural dynamics.

Keywords: Structural analysis, structural dynamics, educational software, MATLAB

1 Introduction

The challenge in teaching structural analysis lies in striking a balance between manual techniques and computer tools. Integrating software, particularly educational-focused platforms, with theoretical instruction enhances course relevance, making it more appealing and current for students. The incorporation of graphical-interactive resources amplifies these advantages, allowing students to model real-world structures, grasp equation interpretations, understand parameter sensitivity, and visualize and criticize results. Additionally, hands-on programming with access to source code offers a unique learning opportunity, fostering method implementation using high-level languages.

The LESM (Linear Elements Structure Model) program was developed for engineering education by Rangel [1]. The first version of the software [2] was originally conceived as a non-graphical tool for static linear-elastic analysis of structural models comprised of linear elements, i.e. prismatic uniaxial members including bars (exhibiting axial behavior exclusively) and beams (characterized by axial, flexural, and torsion behaviors). These models encompass 2D/3D frames, trusses, and grillages. The primary objective was to provide an instructional source code, facilitating the initiation of students into the matrix-based structural analysis methodologies. The program later evolved to its second version to include a Graphical User Interface (GUI), developed by Lopes et al. [3]. That version [4] integrated an intuitive GUI replete with sophisticated mouse capabilities for modeling and post-processing that allowed the program to be used in a much more user-friendly way. Additionally, new analysis features were also included by Marques et al. [5] and Assunção et al. [6]. However, the demand for dynamic analysis led to the development of a new version of the software [7], addressing shortcomings in existing educational computer programs.

This work presents the new version of LESM for dynamic structural analysis developed by Resende et al. [8]. It incorporates inertial and damping influences, temporal load considerations, and a transient solver housing diverse time integration schemes in addition to analytical solutions from modal decomposition [9]. Furthermore, it takes into account Euler-Bernoulli and Timoshenko theories to handle flexural behavior of beam elements. The software's modular code structure and graphical capabilities were crucial for these advancements. The new version was also incorporated into the curriculum a structural dynamics course at the Pontifical Catholic University of Rio de Janeiro (PUC-Rio) to facilitate students' learning process. Its availability, both in installation files and source code, facilitates accessibility and promotes collaborative learning via a website [1] and a public Git repository [2].

The subsequent sections of this paper are structured as follows. Section 2 provides an overview of related literature. Section 3 elucidates the novel attributes integrated into the dynamic version of LESM. Section 4 presents a numerical example and its outcomes. Finally, Section 5 encapsulates concluding remarks and outlines ideas for future research.

2 Related work

In the field of structural analysis, the need to encompass dynamic effects for the investigation of structural vibrations is of great importance as this type of analysis is pertinent in diverse engineering contexts. However, the landscape of educational software endowed with graphical-interactivity and unrestrained modeling flexibility, where parameters like geometry and degrees-of-freedom (DOFs) are not confined to predefined templates, remains relatively sparse.

Much of the existing software in this domain is specialized for seismic engineering applications, such as those introduced by Charney and Barngrover [10], Kumar et al. [11], Munipala et al. [12], Gao et al. [13], Sim et al. [14], Panagiotopoulos and Manolis [15], Katsanos et al. [16], Clarke [17]. In addition to that, a significant portion of the educational tools is restricted to elementary models, such as single degree-of-freedom (SDOF) and multiple degrees-of-freedom (MDOF) systems, as the ones developed by Charney and Barngrover [10], Kumar et al. [11], Munipala et al. [12], Clarke [17], Silva et al. [18], Sonparote and Mahajan [19], Mahajan and Sonparote [20], or frames constrained by parametric presets, including those presented by Gao et al. [13], Sim et al. [14], Panagiotopoulos and Manolis [15], Katsanos et al. [16].

Among the limited range of educational software options that offer unrestricted modeling, some rely on non-graphical inputs, as demonstrated in the works of Paultre et al. [21], François et al. [22], Gavin [23], and only a few exhibit an interactive interface aimed at enhancing the efficiency of both pre-processing and post-processing, as exemplified by Yuan and Teng [24], Almeida Barretto et al. [25], Ziemian and McGuire [26], and Rangel and Martha [27–33]. However, even within the latter group, models are typically limited to two-dimensional configurations, while dynamic analysis alternatives remain somewhat restricted. Furthermore, the open-source characteristic remains a rarity within this software panorama. Therefore, the third version of LESM emerges with the purpose of redressing these gaps and deficiencies, aiming to provide an open-source platform that not only offers versatile modeling freedom of frames but also extends to comprehensive 3D dynamic analysis capabilities while keeping the educational purpose.

3 New features on LESM dynamics

In order to accommodate the new dynamic analysis functionalities, the GUI of LESM underwent a series of modifications in comparison to its antecedent version [4]. These improvements include the integration of supplementary dialogues for configuring dynamic analysis parameters, crafting time functions, and generating graphical representations. Furthermore, the scope of available result options has been broadened to encompass the visualization of animated depictions and envelope diagrams detailing internal force distributions. Additionally, subtle refinements have been made to the interface layout to optimize its arrangement and provide a level of user-friendliness for both novice students and experienced engineers. The main interface of LESM is presented in Fig. 1, highlighting the newly introduced buttons designed to facilitate the launch of auxiliary dialogues pertinent to dynamic analysis, alongside a demonstrative three-dimensional truss model.

[1] https://web.tecgraf.puc-rio.br/lesm
[2] https://gitlab.com/rafaelrangel/lesm

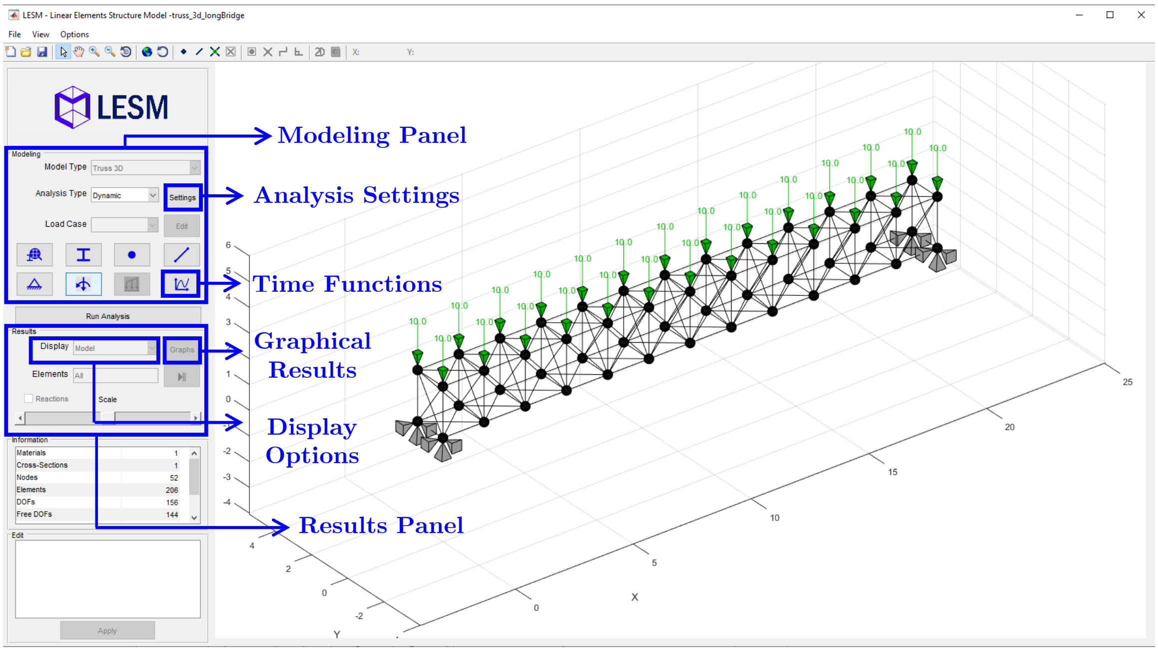


Figure 1. Main dialog of the graphical user interface.

The interface dialog dedicated to configuring dynamic analysis parameters is visually presented in Fig. 2. Within this dialog, users are provided the option of a purely modal analysis to compute the natural vibration frequencies and corresponding modes or, alternatively, performing a transient analysis along with obtaining the modal response. In the context of transient analysis, it is necessary to select the solution algorithm, which consists of a modal superposition or a time discretization scheme. Currently, there are four options of time discretization schemes, including both explicit and implicit methods: Newmark, Wilson-θ, three-step Adams-Moulton, and 4th order Runge-Kutta. Other input parameters include the formulation of the mass matrix, the specification of damping coefficients, and the provision of initial conditions of displacement/rotation and velocity. The latter are relevant to the unconstrained DOFs and are succinctly displayed in tabular format for convenient reference.

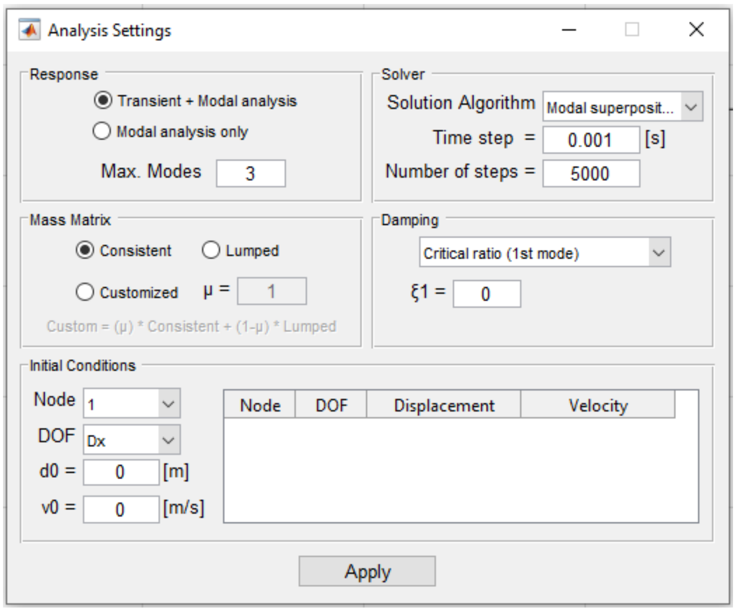


Figure 2. Auxiliary dialog for setting dynamic analysis parameters.

The generation and modification of time functions are accomplished via the interface dialog depicted in Fig. 3. Within this dialog, users are able to incorporate multiple constituents from predefined function categories, such as constant, linear, and harmonic, or from an externally introduced tabular data set. These constituents are overlapped to create the intended time function. The created time functions can be subsequently applied to loading conditions. However, currently, the only type of loading condition that can be assigned a time function is nodal loads. When assigned a time function, each component of the nodal load is multiplied by the function value of the corresponding time step.

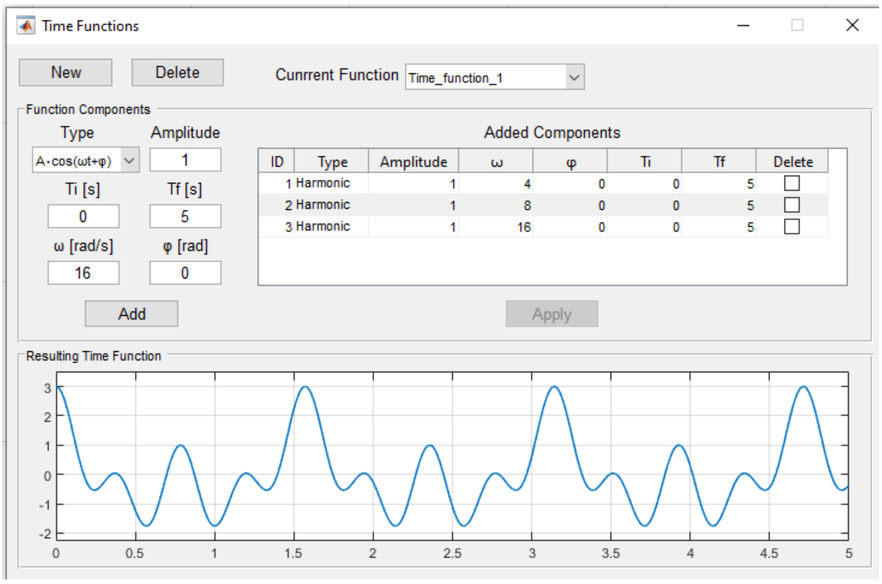


Figure 3. Auxiliary dialog for the definition of time functions.

The auxiliary dialog for applying concentrated loads to nodes is shown in Fig. 4. Within this dialog, the values of each component of the nodal load are provided and an associated time function that has been previously created is assigned. In addition, concentrated masses can also be applied to the selected node to add inertia to the translational DOFs (rotational DOFs are not influenced by concentrated masses). Although the concentrated masses are provided in the same dialog of nodal loads, they not affected by time functions.

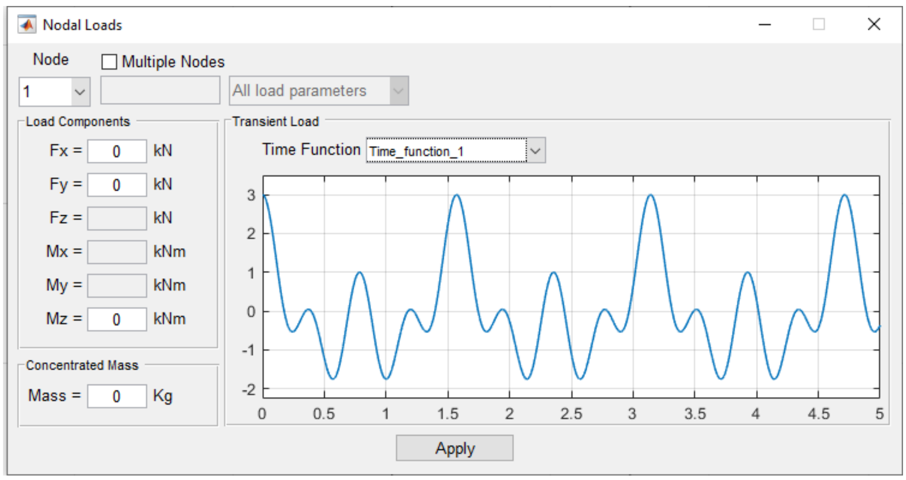


Figure 4. Auxiliary dialog for the application of dynamic nodal loads.

4 Numerical example

The numerical example examined in this paper features a 2D academic frame from Paz and Kim [34], as depicted in Fig. 5. The primary goals of this example are to help users (particularly students) become accustomed to the software, compare its results with those in the referenced book, investigate dynamic properties like damping and mass distribution in structural systems, and explore the effects of different numerical integration methods. The frame comprises two 2.54-meter long Euler-Bernoulli beam elements, with one inclined at 45^o. The material has a Young's modulus of 68948 MPa and density of 7480000 kg/m^3. The cross-sections has an area of 38.7 cm^2 and moment of inertia of 4162 cm^4. The joint node is subjected to a 445 kN horizontal force applied suddenly

— a Heaviside step function — while the other nodes are fully fixed. The system is undamped and a consistent formulation of the mass matrix is used.

The Vibration modes are displayed in Fig. 6. Graphical outcomes concerning the horizontal DOF of the joint node are presented in Fig. 7. The red color represents the overall response, while the black and green colors emphasize the effects of the first and third vibration frequencies, respectively. These visual representations disclose the patterns of displacement, velocity, and acceleration responses. Additionally, the phase portraits are also depicted in that figure (bottom left), unveiling further insights into the dynamic behavior of this model.

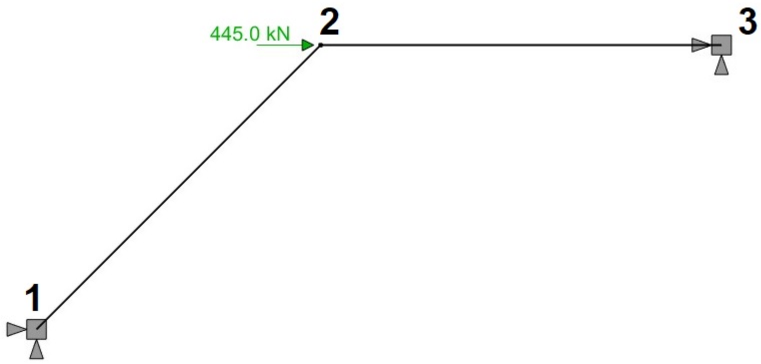
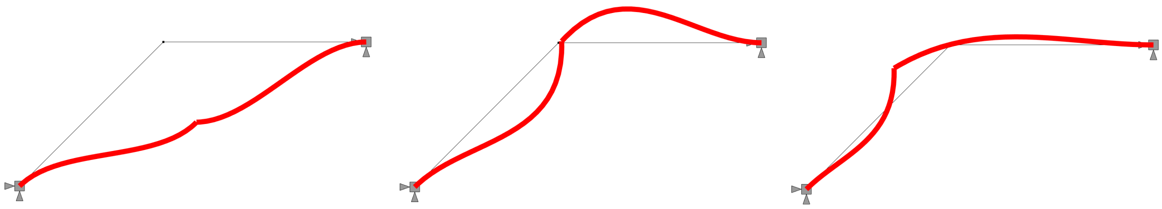


Figure 5. Academic 2D frame model [34] to introduce LESM to students.



(a) Mode 1 ($f = 4.02$ Hz). (b) Mode 2 ($f = 4.96$ Hz). (c) Mode 3 ($f = 10.32$ Hz).

Figure 6. Vibration modes and their frequencies.

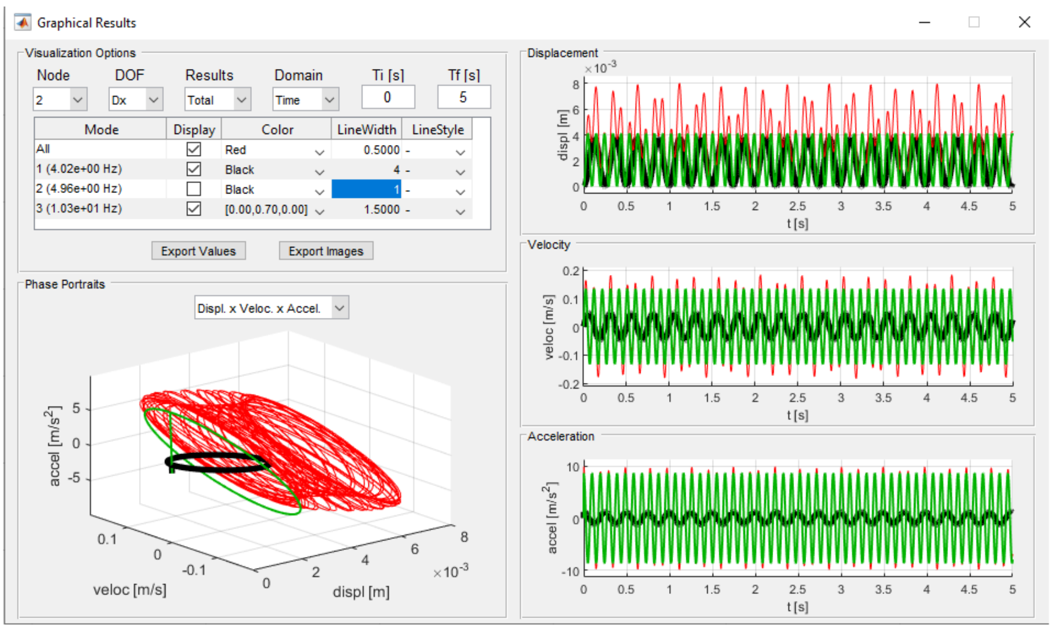


Figure 7. Graphical results dialog analyzing the horizontal displacement (DOF = Dx) of node 2.

5 Conclusions

This paper addressed a new version of LESM, featuring a range of advanced functionalities focused on the analysis of vibration behavior of framed structural models. This version was developed while maintaining the intuitiveness of the program's GUI. Therefore, it stands as a unique graphical-interactive educational tool with free modeling capabilities for dynamic analysis of both 2D and 3D frames and trusses, all while adhering to an object-oriented open-source code. It's important to mention the benefits of using an in-house educational software like LESM compared to commercial options, as it can be customized for course-specific requirements, offering options that transcend the bounds of commercial tools. These adaptations, for example, can include deliberately sub-optimal solution algorithms, thereby enabling students to compare outcomes and gain insights into the numerical stability of the algorithms.

The envisioned developments for the program include the incorporation of time functions for prescribed support displacements to simulate seismic loads and the implementation of stability and nonlinear analyses, making the program more suitable for advanced graduate courses in structural engineering. It is also planned to adopt a learn-by-coding approach for the coming terms of the structural dynamics course. This approach has the potential to foster interest in software development even among students with minimal prior programming experience.

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