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Identification of the viscoelastic properties of soft materials using a convenient dynamic indentation system and procedure

Hasan Koruk *, Salih Berk Yurdaer, Hayati Omer Koc, Ayca Besli

MEF University, Mechanical Engineering Department, Istanbul, 34396, Turkey

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ABSTRACT

The responses of soft structures such as tissue depend on their viscoelastic properties. Therefore, the knowledge of the elastic and damping properties of soft materials is of great interest. This paper presents the identification of the viscoelastic properties of soft materials using a convenient dynamic indentation system and procedure. Using an electromagnet, a force is applied to a rigid sphere located at the soft-material interface and the dynamic response of the sphere is recorded using a high-speed camera. The recorded video is processed to identify the displacement of the sphere as a function of time. The dynamic response of the sphere located at the soft-material interface is predicted using an analytical model that considers the shear modulus and density of the soft sample, the radiation damping due to shear waves, and the radius and density of the sphere. By matching the measured and predicted steady-state displacements of the sphere, the shear modulus of the soft sample is determined. The viscous damping ratio of the soft sample is identified by using an equivalent viscous damping ratio for the soft sample in the analytical model and matching the measured and predicted oscillation amplitudes of the sphere. Experiments and analyzes are performed using gelation phantoms with different mechanical properties, spheres of different materials and sizes, and different force levels to verify the system and procedure. Three experiments are performed for each gelation phantom, sphere, and external force, and the repeatability of the results is presented. The results show that the dynamic indentation system and procedure presented in this study can be conveniently used to determine the viscoelastic properties of soft materials in practical applications.

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1. Introduction

The behaviour of soft materials such as tissue or tissue-mimicking materials is dependent on their viscoelastic properties (i.e., their elastic and viscous characteristics). Therefore, the knowledge of the elastic and damping properties of soft materials is of great interest. There are various procedures to identify the mechanical properties of soft materials, such as tensile testing [1], indentation method [2,3], the method based on the use of a bubble or sphere located inside the soft material [4,5], and the technique based on the use of a bubble located at the soft-material interface [6–10]. Tensile testing and indentation method are quite common to identify the static mechanical properties of materials, such as Young's modulus [1,11]. Furthermore, the indentation systems can be quite complicated and high-cost [12,13], they provide only the identification of the elastic properties of materials [14] and the mathematical models do not take into account the inertia of the soft material involved in motion and the radiation damping [14,15]. For the method based on the use of a bubble or sphere located inside the soft material [4,5], inserting an object inside the soft material is not effective and this operation can alternate the mechanical properties of the soft material. For the technique based on the use of a bubble located at the soft-material interface [6–10], it can be difficult to precisely manipulate the bubble and correctly measure the force applied to the bubble. In recent years, advanced mathematical models for a sphere located at the soft-material interface were proposed [16–18]. These models that consider the shear modulus, Poisson's ratio and density of the soft sample, the radiation damping due to shear waves, and the radius and density of the sphere are very promising for the identification of the viscoelastic properties of soft materials.

* Corresponding author.
E-mail address: korukh@mef.edu.tr (H. Koruk).

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It should be noted that, for material identification purposes, the response of a system exposed to a dynamic force can be determined by processing the video captured using a camera [6,10] or by analyzing the data captured using a vibration sensor such as an accelerometer [19–24].

This paper presents the identification of the viscoelastic properties of soft materials using a convenient dynamic indentation system and procedure. Unlike different complicated indentation systems in the literature, the system presented here is very simple and low-cost and its implementation is very straightforward. In addition to the elastic properties of the soft material and the size and mass of the indenter, the mathematical model exploited in this study takes into account the inertia force of the soft material involved in motion and the radiation damping due to shear waves. The procedure provides the determination of both elastic and damping properties of the soft material. For this purpose, using an electromagnet, a force is applied to a rigid sphere located at the soft-material interface and the dynamic response of the sphere is recorded using a high-speed camera. The displacement of the sphere as a function of time is identified by processing the recorded video. The dynamic response of the sphere located at the soft-material interface is estimated using the analytical model. By matching the measured and predicted steady-state displacements of the sphere, the shear modulus of the soft sample is determined. The viscous damping ratio of the soft sample is identified by using an equivalent viscous damping ratio for the soft sample in the analytical model and matching the measured and predicted oscillation amplitudes of the sphere. Experiments and analyzes are performed using gelation phantoms with different mechanical properties, spheres of different materials and sizes, and different force levels to verify the system and procedure. Three experiments for each gelation phantom, sphere, and external force are performed and the repeatability of the results is presented. The results show that the dynamic indentation system and procedure used in this study can be conveniently used to identify the viscoelastic properties of soft materials in practice.

2. System and procedure for material identification

A rigid sphere (with a radius R and density ρ_s) located at the soft-material (with a shear modulus G, density ρ and viscous damping ratio ζ_m) interface is pushed using a magnetic force (f) and the displacement of the sphere (u) is measured using a high-speed camera (resolution: 1920 × 1080 pixels at 240 fps, aperture: f/1.8, optical stabilization: available and flash: truetone multi-LED). A small magnet is attached to the sphere to apply a force by an electromagnet to the sphere located at the soft-material interface. The videos are recorded at 240 fps and the resolution is 0.1 mm/pixel. The displacement of the sphere from the videos as a function of time (t) is tracked using the Matlab software (MathWorks, Natick, MA, USA). The scale used to measure the force amplitude has a sensitivity of 1 mN. The schematic picture for the experimental setup is shown in Fig. 1a. The frames from a sample recorded video for the sphere located at the soft-material interface, when there is no force (the top panel), force is applied and maximum deformation is reached (the middle panel), and the load is removed and the sphere goes back to the original position (the bottom panel), are shown in Fig. 1b. It is seen that the deformation of the soft material is reversible.

The mathematical model that takes into account the shear modulus, Poisson's ratio and density of the soft sample, the radiation damping due to shear waves, and the radius and density of the sphere [18] is used to predict the dynamic response of the sphere located at the soft-material interface. The model is valid for both small and large sphere displacements. Based on this model, the dynamic response of the sphere located at the soft-material interface to a rectangular pulse with amplitude f_0 and duration τ is given by:

$$u(t) = \frac{f}{k} - \frac{f}{k\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t}\cos(\omega_d t - \varphi) \text{ for } 0 \le t \le \tau \tag{1a}$$

$$u(t) = \frac{f e^{-\zeta\omega_n t}}{k\sqrt{1-\zeta^2}} \left\{ e^{\zeta\omega_n \tau}\cos[\omega_d(t-\tau) - \varphi] - \cos(\omega_d t - \varphi) \right\} \text{ for } t > \tau \tag{1b}$$

Here, $u(t)$ is the displacement of the sphere as a function of time, k is the equivalent stiffness coefficient, f is the effective force, ζ is the equivalent viscous damping ratio due to radiation of shear waves, φ is the phase angle, and ω_n and ω_d are the undamped and damped natural frequencies, respectively. The expressions for these parameters are given as following:

$$k = \left(1 - 0.1\frac{u_0}{R}\right) 1.5 \left(\frac{4E^*\sqrt{R}}{3}\right)^{2/3} f_0^{1/3} \tag{2}$$

$$c = \frac{1}{2}\left(0.5 + \frac{u_0}{R}\right)\left(\sqrt{\frac{\rho}{G}}R\right)\left(1 - 0.1\frac{u_0}{R}\right)1.5 f_0^{1/3}\left(\frac{4E^*\sqrt{R}}{3}\right)^{2/3} \tag{3}$$

$$m = \frac{1}{3}\pi R^3\left(4\rho_s + \frac{u_0}{R}\rho\right) \tag{4}$$

$$f = \left[1 + 0.5\left(1 - 0.1\frac{u_0}{R}\right)\right] f_0 \tag{5}$$

$$\zeta = \frac{c}{2\sqrt{km}} \tag{6}$$

$$\varphi = \tan^{-1}\frac{\zeta}{\sqrt{1-\zeta^2}} \tag{7}$$

$$u_0 = \left(\frac{3f_0}{4E^*\sqrt{R}}\right)^{2/3} \tag{8}$$

$$\omega_n = \sqrt{\frac{k}{m}} \tag{9}$$

$$\omega_d = \omega_n\sqrt{1-\zeta^2} \tag{10}$$

where E^* is the reduced Young's modulus given by $E^* = \frac{E}{1-\nu^2}$ and ρ_s is the density of the sphere. Here, E is the Young's modulus of the soft material given by $E = 2G(1+\upsilon)$ where G and υ are the shear modulus and Poisson's ratio of the soft material, respectively. The equivalent density of the sphere is calculated by considering the masses of the sphere and the small magnet. In this study, the shear modulus of the soft sample is determined by matching the measured and predicted steady-state displacements of the sphere. The viscous damping ratio of the soft sample is identified by using an equivalent total viscous damping ratio (ζ_t) in the analytical model and matching the measured and predicted oscillation amplitudes of the sphere. The viscous damping ratio of the soft-material is found using $\zeta_m = \zeta_t - \zeta$ where ζ is the equivalent viscous damping ratio due to radiation of shear waves.

3. Results and discussion

The average of the measured responses of the sphere located at the gelatin-phantom interface for three repeated experiments and

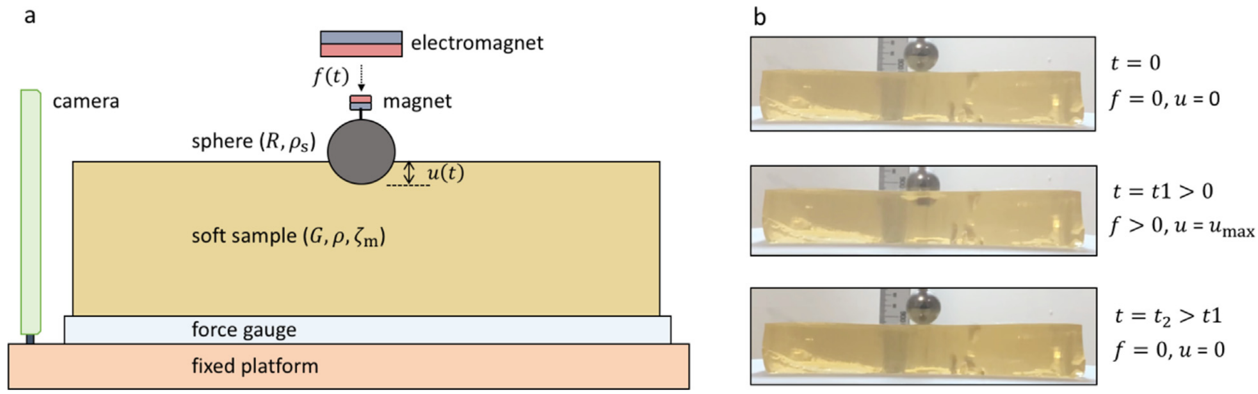

Fig. 1. The schematic picture for the experimental setup (a) and the frames from a sample recorded video for the sphere located at the soft-material interface for three different time instances (b).

the deviations are presented in Fig. 2a. Here, the gelatin phantom is prepared using 100 g gelatin powder and 400 g water. The density of the rectangular gelatin phantom (123.6 mm × 83.1 mm × 29. 2 mm) determined based on its measured mass and volume is 1051.6 kg/m^3. The Poisson's ratio of the soft material is assumed to be around 0.5 in this study, as it is done in practice [25]. The radius of the sphere is 8.15 mm and its equivalent density is 7761.6 kg/m^3. The magnitude of the step input is 297 mN. It is seen that the experiments are quite repeatable and the average deviation for the given time range is 0.05 mm. By matching the experimental and predicted responses of the sphere located at the gelatin-phantom interface, the shear modulus and viscous damping ratio of the gelatin phantom are determined to be G = 1.5 kPa and ζ_m = 0.12, respectively. The response of the sphere located at the gelatin-phantom interface using the identified material properties is shown in Fig. 2b. It is clear that the experimental and theoretical results are quite similar. The average difference between the experimental and theoretical results is 1.4%.

In order to further evaluate the dynamic indentation system and procedure, the same gelatin phantom (i.e., 100 g gelatin powder + 400 g water) is tested using another sphere. The radius of the sphere is 7.45 mm and its equivalent density is 14780.3 kg/m^3. The magnitude of the step input is 364 mN. The average of the measured responses of the sphere located at the gelatin-phantom interface for three repeated experiments and the deviations are presented in Fig. 3a. Again, it is seen that the experiments are quite repeatable and the average deviation for the given time range is 0.05 mm. By matching the experimental and predicted responses of the sphere located at the gelatin-phantom interface, the shear modulus and viscous damping ratio of the gelatin phantom are determined to be G = 1.6 kPa and ζ_m = 0.17, respectively. The response of the sphere located at the gelatin-phantom interface using the determined material properties is shown in Fig. 3b. Again, it is clear that the experimental and theoretical results are quite similar. The average difference between the experimental and theoretical results is 2.4%. The results show that the material properties of the gelatin phantom determined using different spheres and forces are quite close to each other (i.e., G = 1.5 kPa and ζ_m = 0.12 for the first experiment and G = 1.6 kPa and ζ_m = 0.17 for the second experiment). It should be noted that, in general, the identification of damping is not as repeatable as the determination of other properties such as elastic properties, and different analysis methods can produce slightly different damping values even for the same experimental data [10,24,26,27]. There are many reasons for obtaining different damping values, such as friction between the sphere and the gelatin phantom, air friction and the effect of force magnitude on the amount of dissipated energy.

In order to further verify the dynamic indentation system and procedure, another gelatin phantom using 125 g gelatin powder and 375 g water is prepared and similar experiments and analyzes are performed for this phantom. The density of the rectangular gelatin phantom (137.7 mm × 87.6 mm × 22.5 mm) determined based on its measured mass and volume is 1121.9 kg/m^3. The radius of the sphere is 8.15 mm and its equivalent density is 7761.6 kg/m^3. The magnitude of the step input is 275 mN. The

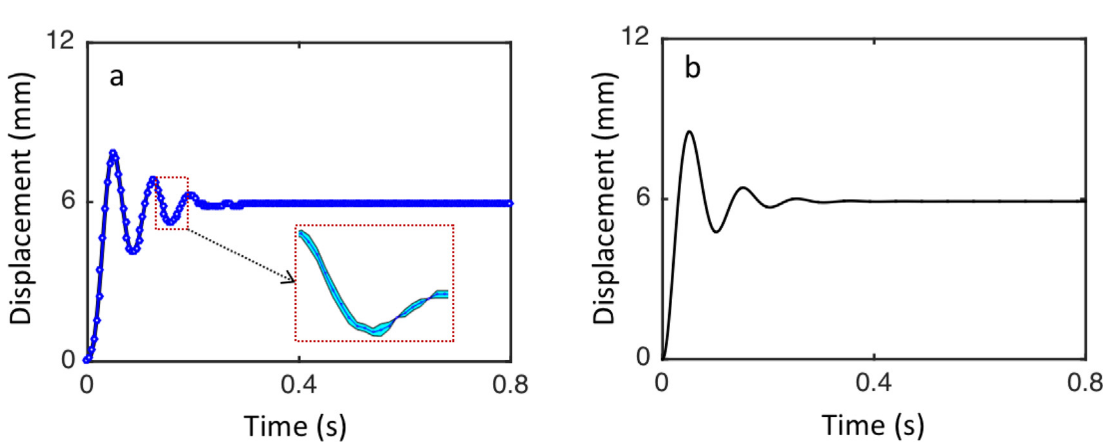

Fig. 2. The measured (a) and predicted (b) responses of the sphere (radius: 8.15 mm, density: 7761.6 kg/m^3) located at the gelatin-phantom (100 g gelatin powder + 400 g water) interface (force magnitude: 297 mN).

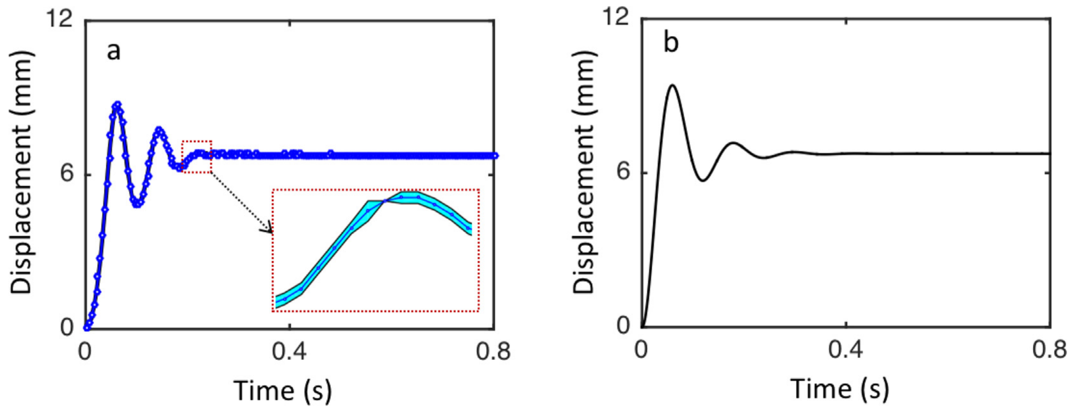

Fig. 3. The measured (a) and predicted (b) responses of the sphere (radius: 7.45 mm, density: 14780.3 kg/m^3) located at the gelatin-phantom (100 g gelatin powder + 400 g water) interface (force magnitude: 364 mN).

average of the measured responses of the sphere located at the gelatin-phantom interface for three repeated experiments and the deviations are presented in Fig. 4a. It is clear that the experiments are quite repeatable and the average deviation for the given time range is 0.04 mm. By matching the experimental and predicted responses of the sphere located at the gelatin-phantom interface, the shear modulus and viscous damping ratio of the gelatin phantom are determined to be G = 2.8 kPa and ζ_m = 0.38, respectively. The response of the sphere located at the gelatin-phantom interface using the identified material properties is shown in Fig. 4b. Again, it is clear that the experimental and theoretical results are quite similar. The average difference between the experimental and theoretical results is calculated to be 3.0%. As expected, the shear modulus and viscus damping ratio of the gelatin phantom increase (i.e., from G = 1.5–1.6 to 2.8 kPa and from ζ_m = 0.12–0.17 to 0.38) as the ratio of the gelatin powder increases from 20% (i.e., 100 g gelatin powder + 400 g water) to 25% (i.e., 125 g gelatin powder + 375 g water). It is seen that the dynamic indentation system and procedure presented in this study can be conveniently used to determine the viscoelastic properties of soft materials in practice. The use of this method for the identification of different materials such as tissue, various tissue-mimicking materials, acoustic foams and fabrics is considered as our future studies. Furthermore, by minimizing the sources of errors and performing many experiments for different materials, we plan to further minimize the difference between the experimental and theoretical results for the identification of accurate material properties in future.

4. Conclusion

The identification of the viscoelastic properties of soft materials using a convenient dynamic indentation system and procedure is presented in this study. A force is applied to a rigid sphere located at the soft-material interface using an electromagnet and the response of the sphere is recorded using a high-speed camera. The recorded video is processed to identify the displacement of the sphere as a function of time. The dynamic response of the sphere located at the soft-material interface is predicted using an analytical model that takes into account the shear modulus and density of the soft sample, the radiation damping due to shear waves, and the radius and density of the sphere. By matching the measured and predicted steady-state displacements of the sphere, the shear modulus of the soft sample is determined. The viscous damping ratio of the soft sample is determined by using an equivalent viscous damping ratio for the soft sample in the analytical model and matching the measured and predicted oscillation amplitudes of the sphere. The results of the three experiments performed for each gelation phantom, sphere, and external force show that the experiments are quite repeatable. The shear modulus and viscous damping ratio of the gelation phantom prepared using 100 g gelatin powder and 400 g water are determined to be 1.5–1.6 kPa and 0.12–0.17, respectively, using different spheres and excitation forces. The shear modulus and viscous damping ratio of the gelation phantom prepared using 125 g gelatin powder and 375 g water are identified to be 2.8 kPa and 0.38, respectively. The shear modulus and viscous damping ratio of the gelatin phan-

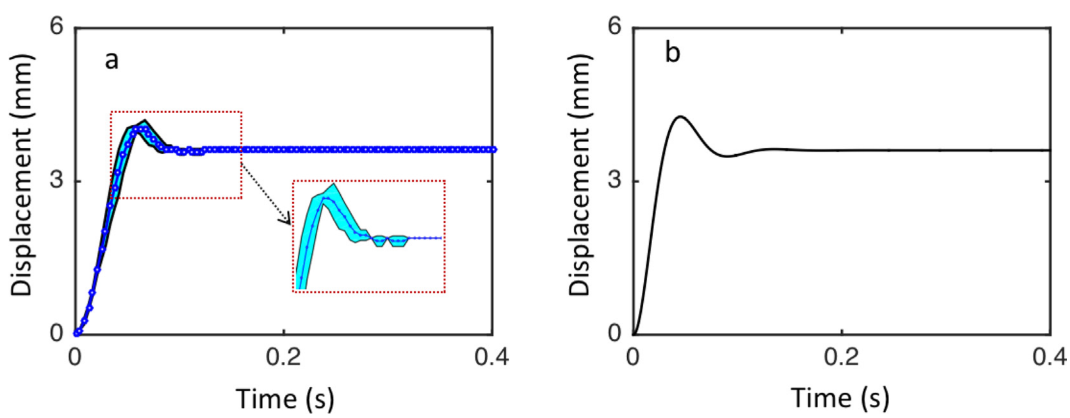

Fig. 4. The measured (a) and predicted (b) responses of the sphere (radius: 8.15 mm, density: 7761.6 kg/m^3) located at the gelatin-phantom (125 g gelatin powder + 375 g water) interface (force magnitude: 275 mN).

tom increase as the ratio of the gelatin powder in the phantom increases, as expected. The results show that the dynamic indentation system and procedure exploited in this study can be conveniently used to determine the viscoelastic properties of soft materials in practical applications.

CRediT authorship contribution statement

Hasan Koruk: Conceptualization, Methodology, Investigation, Data curation, Visualization, Validation, Supervision, Writing – original draft, Writing – review & editing. **Salih Berk Yurdaer:** Investigation, Data curation, Validation. **Hayati Omer Koc:** Investigation, Data curation, Validation. **Ayca Besli:** Investigation, Data curation, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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