Model-based Approach to Compensate for the Dynamics Convolution Effect in Nanomechanical Property Measurement†

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Abstract—A model-based approach to compensate for the dynamics convolution effect on the measurement of nanomechanical properties is proposed. In indentation-based approaches to measure the nanomechanical properties of soft materials, an excitation force consisting of multiple frequencies needs to be accurately exerted (from the probe) to the sample material, and the indentation generated in the sample needs to be accurately measured. However, when the measurement frequency range becomes close to the bandwidth of the instrument hardware, the instrument dynamics along with the probe-sample interaction can be convoluted with the mechanical behavior of the soft material, resulting in distortions in both the applied force and the measured indentation, which, in turn, directly lead to errors in the measured nanomechanical properties of the material (e.g., the creep compliance). In this article, the dynamics involved in indentation-based nanomechanical property measurement is investigated to reveal that the convoluted dynamics effect can be described as the difference between the lightly-damped probe-sample interaction and the overdamped nanomechanical behavior of the soft sample. Thus, these two different dynamics effects can be decoupled via numerical fitting based on the viscoelastic model of the soft material. The proposed approach is illustrated by implementing it to compensate for the dynamics convolution effect on a broadband viscoelasticity measurement of a Polydimethylsiloxane (PDMS) sample using a scanning probe microscope.

I. INTRODUCTION

A model-based approach to compensate for the dynamics convolution effect on indentation-based measurement of nanomechanical properties is proposed. Indentation-based approach to measure the nanomechanical properties of soft materials provides unique insights into material properties at nanoscale. These insights are critical to unraveling structure-property correlation of a wide variety of materials, ranging from polymers to live biological samples [1]. Extraneous dynamics, however, can be convoluted with the material response during the measurement, resulting in measurement errors in the obtained material properties (e.g., the creep compliance). Such a dynamics convolution effect has limited the measurable frequency range of existing nanomechanical measurement techniques. The goal of this work is to develop a systematic approach to compensating for the dynamics convolution effect on nanomechanical property measurement, thereby increasing the measurement frequency range and reducing the measurement errors.

The indentation-based approach to measure the nanomechanical properties is limited by the presence of dynamics convolution effect. For example, the rate-dependent elastic modulus of soft materials such as PDMS can be measured by using force-curve measurement under different load/unload rates [2], [3]. The force curve measurement, however, is quasi-static, thereby time-consuming when the measurement frequency range becomes large. Moreover, when the load/unload rate is increased, the instrument dynamics along with the probe-sample interaction can be convoluted with the material response in the measured force signal (e.g., the cantilever deflection when scanning probe microscope (SPM) is used). As a result, the exerted force (from the probe to the sample) may fail to follow the desired profile. The measurement time can be reduced and the measurement frequency range can be increased by using the force modulation method [4], [5]. However, the convolution of the instrument dynamics with the probe-sample interaction still exists in the measurement. Although this dynamics convolution effect on force modulation can be accounted for by using a linear spring-damper mechanical model [6], [7], this method is limited to the relatively low frequency range. The frequency range as well as the sensitivity of the measurement is improved in the recently-developed multi-frequency approach [4], [8]. When the measurement frequency range becomes large, however, the frequency spectrum of the applied force can be severely distorted by the dynamics convolution effect, resulting in low signal-to-noise ratio (SNR) at some frequencies and input saturation at others. Therefore, there exists a need to compensating for the dynamics convolution effect on nanomechanical property measurements.

Compensation for the dynamics convolution effect on nanomechanical property measurements using SPM is challenging. The challenge arises as only the output of the entire deflection dynamics (from the driven piezoeactuator to the material response) can be measured. The convoluted dynamics effect on the excitation force can be substantially reduced by using control techniques, as demonstrated recently [2], [9]. Compensation for the convoluted dynamics effect on the indentation measurement, however, still remains as a challenge. This is because the indentation in the soft material is usually obtained from the difference between the probe deflection on the soft sample and that on a hard reference sample. The difference in the mechanical behavior of these two samples (soft vs. hard), thereby, leads to different probe-sample interactions, resulting in extraneous dynamics effect on the indentation measurements. Therefore, techniques need to be developed to compensate for the dynamics convolution effect on nanomechanical property measurements.

The main contribution of this article is the development of...
a model-based approach to eliminate the dynamics convolution effect on nanomechanical property measurements. The cantilever deflection dynamics of the soft sample and that of the hard reference are measured and compared to reveal that the part of the instrument dynamics convoluted into the measurement is characterized by lightly damped poles and zeros, and the locations of these poles and zeros coincide with those of the piezo-cantilever dynamics. On the contrary, the mechanical behavior of soft materials is characterized as being overdamped, which can be described by for example, a Prony series model [10]. Therefore, the convoluted dynamics effect is distinct from the material behavior, and can be removed through numerical fitting. The proposed approach is illustrated by implementing it to the measurement data obtained in a broadband viscoelasticity measurement of a PDMS sample using SPM [9].

II. MODEL-BASED COMPENSATION FOR INSTRUMENT DYNAMICS CONVOLUTION EFFECT
A. Nanomechanical Property Measurement Using SPM

SPM has become an enabling tool for nanoscale topography imaging and material properties measurement [11]. Specifically, the frequency-dependent mechanical properties of soft materials can be measured by exerting forces of different frequency components to the sample, and measuring the indentation in the material—the response of the material to the excitation force [1], [2] (see Fig. 1). The measurement becomes more efficient by using the force-modulation method [1], [5], [12]. The indentation in the soft sample is obtained from the difference of the cantilever deflection on the soft sample and that on a hard reference sample with the same driving input.

![Fig. 1](image)

The cantilever deflection signal is measured to quantify the excitation force and the indentation. The force applied is measured as [1]

\[ P(t) = K_e \times C_t \times D(t), \tag{1} \]

where \( K_e \) is the stiffness constant of the cantilever, \( C_t \) is the sensitivity constant of the vertical displacement of the probe vs. the deflection signal (both can be experimentally calibrated [13]), and \( D(t) \) denotes the cantilever deflection. Then, the indentation in the soft sample can be obtained as [1]

\[ h(t) = C_t \times [D_H(t) - D_S(t)] = C_t \times \Delta D(t), \tag{2} \]

where \( \Delta D(t) \) denotes the difference between the cantilever deflection on the hard material, \( D_H(t) \), and that on the soft material, \( D_S(t) \). Various contact mechanics models have been developed to obtain the mechanical properties of materials (e.g., the complex compliance) [14]. For example, when the probe-sample interaction can be modeled as the contact of a frictionless, rigid, spherical indenter with a homogeneous, linear, and isotropic viscoelastic substrate, the complex compliance of the material in uniaxial compression, \( J^*(j\omega) \), can be obtained from the following Hertz contact model in frequency-domain,

\[ J^*(j\omega) = \frac{h^2(\omega)}{\mathcal{C}_1 \times P(j\omega)}, \tag{3} \]

where \( P(\cdot) \) and \( h(\cdot) \) are defined in (1, 2), and the constant \( \mathcal{C}_1 \) is given by

\[ \mathcal{C}_1 = \frac{3(1 - v^2)}{4\sqrt{R}}, \tag{4} \]

where \( v \) is the poisson ratio of the sample, and \( R \) is the probe radius.

We assume, in the following, that the amplitude of the excitation force is relatively small, and a full probe-sample contact is maintained throughout the measurement [1], [11].

B. Dynamics convolution Effect on Indentation-based Nanomechanical Property Measurement

In indentation-based nanomechanical measurements, the excitation force \( P(t) \) should be applied accurately, so should the indentation \( h(t) \) be measured. Particularly, the applied force \( P(t) \), needs to follow the desired excitation profile, and the difference between the cantilever deflection on the soft material and that on the hard reference should accurately represent the indentation in the soft material. Challenge arises in maintaining accuracy in the force applied and the indentation measured. Specifically, the deflection signal measured on the soft sample can be represented in frequency domain as (see Fig. 2)

\[ D_S(j\omega) = G_{cs}(j\omega)G_{es}(j\omega)G_{pc}(j\omega)V(j\omega) \cong G_S(j\omega)V(j\omega), \tag{5} \]

where \( G_{cs}(j\omega) \) denotes the material dynamics of the soft sample, \( G_{es}(j\omega) \) denotes the interaction dynamics between the cantilever-probe and the soft sample, \( G_{pc}(j\omega) \) denotes the dynamics model from the piezoactuator to the cantilever along with the related mechanical fixture, and \( V(j\omega) \) denotes the Fourier transform of the input voltage applied to the piezoactuator. Similarly, the deflection on the hard reference sample is given by

\[ D_H(j\omega) = G_{hs}(j\omega)G_{ch}(j\omega)G_{pc}(j\omega)V(j\omega) \]

\[ = K_{hs}G_{ch}(j\omega)G_{pc}(j\omega)V(j\omega) \cong G_H(j\omega)V(j\omega), \tag{6} \]

where \( G_{hs}(j\omega) \) models the dynamic behavior of the hard material, \( G_{ch}(j\omega) \) models the interaction dynamics between the cantilever-probe and the hard sample, and \( G_{pc}(j\omega) \) and \( V(j\omega) \) are the same as defined in Eq. (5). Note that the mechanical behavior of the hard reference sample can be regarded as frequency-independent in the measured frequency range — \( G_{hs}(j\omega) \) can be replaced by a constant \( K_{hs} \). By Eqs. (2, 5, 6), the dynamics involved in the indentation measurement can be depicted by the block diagram in Fig. 3.

Equation (5) implies that the cantilever deflection \( D_S(j\omega) \) will follow the input voltage \( V(j\omega) \) if the total deflection dynamics on the soft sample, \( G_S(j\omega) \), can be adequately approximated as a constant. As the measurement frequency
increases, the desired excitation force cannot be tracked by the probe if the desired force profile (after scaling) is directly applied to drive the piezoactuator. Such a direct driving method is used in the multi-frequency method [8], [15], which limits the measurement frequency range of the multi-frequency method. On the contrary, this dynamics convolution effect can be compensated for by using control techniques [9].

The dynamics convolution effect becomes more pronounced in the indentation measurement. By Eqs. (5, 6), the difference of the cantilever deflections (see Eq. (2)) is given as

$$\Delta D(j\omega) = [K_{hs}G_{ch}(j\omega) - G_{ss}(j\omega)G_{cs}(j\omega)] \times G_{pc}(j\omega)V(j\omega).$$

(7)

When the measurement frequency range is relatively low, the difference between the interaction dynamics on the soft sample and that on the hard samples also tends to be small, i.e., $G_{cs}(j\omega) \approx G_{ch}(j\omega)$. Thus, the cantilever deflection difference becomes

$$\Delta D_{c}(j\omega) = [K_{hs} - G_{ss}(j\omega)]G_{cs}(j\omega)G_{pc}(j\omega)V(j\omega).$$

(8)

The above Eq. (8) shows that in this case, the cantilever deflection difference is solely generated by the mechanical behavior difference between the soft sample and the hard reference sample, $K_{hs} - G_{ss}(j\omega)$, thereby representing the "true" indentation in the soft sample. When the measurement frequency range becomes large, the deflection difference becomes

$$\Delta D(j\omega) = [K_{hs}G_{ch}(j\omega) - G_{ss}(j\omega)G_{cs}(j\omega)] \times G_{pc}(j\omega)V(j\omega)
= [K_{hs} - G_{ss}(j\omega)]G_{cs}(j\omega)G_{pc}(j\omega)V(j\omega)
+ [G_{ch}(j\omega) - G_{cs}(j\omega)]K_{hs}G_{pc}(j\omega)V(j\omega))
\triangleq \Delta D_{c}(j\omega) + \Delta D_{e}(j\omega).$$

(9)

As described by the second term of the summation in the above Eq. (9), $\Delta D_{e}(j\omega)$, the measurement error is induced into the indentation measurement due to the difference of the interaction dynamics, $G_{ch}(j\omega) - G_{cs}(j\omega)$, which is caused by issues such as the probe-sample contact area on the soft sample and that on the hard one are different, so is the damping effect on the cantilever deflections by the soft sample and that by the hard one.

C. Model-based Approach to Compensate for the Dynamics Convolution Effect on Nanomechanical Measurement

Next, we present a model-based approach to compensate for the dynamics effect on nanomechanical property measurements. We focus, in the following, on the compensation for the convolution effect on the indentation measurement.

We define the total convoluted dynamics ratio, $G_{cv}(j\omega)$, as the ratio of the total deflection dynamics on the hard reference sample, $G_{H}(j\omega)$, to that on the soft sample, $G_{S}(j\omega)$,

$$G_{cs}(j\omega) \triangleq \frac{G_{H}(j\omega)}{G_{S}(j\omega)} = \frac{K_{hs}G_{ch}(j\omega)G_{pc}(j\omega)}{G_{ss}(j\omega)G_{cs}(j\omega)G_{pc}(j\omega)}$$

(10)

$$= \frac{K_{hs}G_{ch}(j\omega)}{G_{ss}(j\omega)G_{cs}(j\omega)} \quad \text{(by Eqs. (5, 6))}$$

The first term on the right side of the above equation, $\Delta G_{hs}(j\omega)/G_{ss}(j\omega)$ is called the hard-soft material dynamics ratio thereinafter, and the second term, $\Delta G_{ch}(j\omega)$ is called the hard-soft interaction dynamics ratio thereinafter.

The total deflection dynamics, $G_{S}(j\omega)$ and $G_{H}(j\omega)$, can be obtained by applying an excitation input to the piezoactuator and measuring the cantilever deflection as the output in the usual “black box” identification approach (e.g., the sweep sine method). Note that full contact of the probe with the sample is maintained by augmenting a normal load to the excitation signal, and the measured dynamics is linear by keeping a small excitation amplitude.

Combining Eq. (9) with (10), the coupling caused error in the deflection difference, $\Delta D_{c}(j\omega)$, can be rewritten as

$$\Delta D_{c}(j\omega) = [G_{ch}(j\omega) - G_{cs}(j\omega)]K_{hs}G_{pc}(j\omega)V(j\omega)
= [\Delta G_{ch}(j\omega)]\frac{K_{hs}G_{ch}(j\omega)G_{cs}(j\omega)G_{pc}(j\omega)V(j\omega)}{G_{ss}(j\omega)G_{cs}(j\omega)G_{pc}(j\omega)}
= [\Delta G_{hs}(j\omega)\Delta G_{ch}(j\omega)]D_{S}(j\omega)
= [G_{cv}(j\omega) - \Delta G_{hs}(j\omega)]D_{S}(j\omega),$$

(11)

Thus, the above Eq. (11) reveals that the coupling-caused deflection difference error, $\Delta D_{c}(j\omega)$, is due to the difference between the total convoluted dynamics ratio, $G_{cv}(j\omega)$, and the hard-soft material dynamics ratio, $\Delta G_{hs}(j\omega)$. We proceed by considering the fundamental difference between the hard-soft interaction dynamics ratio, $\Delta G_{ch}(j\omega)$, and the hard-soft material dynamics ratio, $\Delta G_{hs}(j\omega)$. Note that the hard-soft material dynamics ratio $\Delta G_{hs}(j\omega)$ essentially represents the complex compliance of the soft material (see Eq. (3)). Moreover the complex compliance of soft materials like polymers can be well described by a linear compliance model, for example, a truncated Prony series, i.e., the complex compliance of the soft sample is modeled as [10]

$$J^{*}(j\omega) = J_{0} + \sum_{i=1}^{n} \frac{J_{i}}{j\omega + 1/\tau_{i}},$$

(12)

where $\tau_{i}s > 0$ are the retardation time constants of the soft material at different time scales, $J_{0}$ is the fully relaxed compliance, and $J_{i}s$ are the compliance coefficients [16].
Thus, the hard-soft material dynamics ratio, $\Delta G_{hs}(j\omega)$, is overdamped in nature \[10\]. On the contrary, the interaction dynamics difference, $\Delta G_c(j\omega)$, tends to be lightly-damped, i.e., $\Delta G_c(j\omega)$ can be represented as

$$
\Delta G_c(j\omega) = \prod_{i=1}^{N} \frac{-\omega_n^2}{s^2 + 2\zeta_i\omega_n s + \omega_n^2}, 
$$

(13)

where $\omega_n$ is the undamped natural frequency and $\zeta_i$ for $0 < \zeta_i < 1$ is the corresponding damping ratio. The damping effect of the hard reference is rate-independent (in the measurement frequency range) whereas frequency-dependent for the soft sample (see Eq. (5)). And, the probe-sample contact area on the soft sample tends to be larger than that on the hard sample. As a result, these effects become much more pronounced around the lightly-damped poles and zeros of the piezo-cantilever dynamics. Thus, the material dynamic behavior and the difference of the interaction dynamics are distinct from each other, and numerical algorithms can be sought to decouple them. In this paper, the hard-soft interaction dynamics ratio $\Delta G_{hs}(j\omega)$ is removed from the total convoluted dynamics ratio $G_{cv}(j\omega)$ by fitting the latter into a Prony series like model (i.e., an overdamped linear dynamics model). Then the dynamics convolution-caused error $\Delta D_c(j\omega)$ is obtained by multiplying the fitting result with the deflection measured on the soft sample (see Eq. (11)), and the compensated indentation is obtained according to Eqs. (2, 9).

III. IMPLEMENTATION EXAMPLE

The proposed approach is illustrated by implementing it to the nanomechanical property data experimentally measured on a PDMS sample.

A. Dynamics Convolution Effect On Broadband Nanomechanical Property Measurement

The experimental data obtained in a broadband viscoelasticity measurement of a PDMS sample were processed in this example. Specifically, two different approaches to broadband nanomechanical measurement were applied. The desired force profile was chosen to have a power spectrum similar to a band-limited white noise. Specifically, the cut-off frequency and the duration of the desired force were chosen at 4.5 KHz and 6 seconds, respectively (The dominant resonant frequency of the total deflection dynamics occurred at ∼2.85 KHz, as shown later in Fig. 5). First, the multi-frequency method \[8\], \[15\] was implemented, where the input voltage was generated by scaling the desired force profile with the DC gain of the total deflection dynamics. Secondly, the model-less inversion-based iterative learning control (MIIC)-based method was implemented \[9\], where the input obtained by using the MIIC technique was applied to the piezoactuator so that the cantilever deflection on the PDMS sample tracked the desired force profile (see \[9\] for details). The use of the MIIC technique was to demonstrate the use of control technique to compensate for the dynamics convolution effect on the excitation force (see Sec. II-B). In both cases, the indentation in the PDMS sample was measured by applying the same control input to the hard reference sample (a sapphire sample) whose Young’s modulus is 6 orders higher than that of PDMS. The obtained deflection signals were used to compute the force and the indentation (see Eqs. (1, 2)), where the sensitivity constant of the cantilever at 65 nm/V was experimentally measured by following the method outlined in the literature \[13\], and the cantilever spring constant of 0.53 N/m was calibrated by using the thermal noise method \[13\]. The probe radius of 95 nm was experimentally characterized by imaging a standard probe calibration sample (porous aluminum PA01) \[13\]. The force spectrum and the indentation spectrum obtained by using the multi-frequency method are compared with those obtained by using the MIIC-based method in Fig. 4 (a1) and (a2), and (b1) and (b2), respectively. The obtained force and indentation were used to obtain the complex compliance based on the Hertz model (see Eq. (3)), and the corresponding amplitudes of the complex compliance obtained by using these two methods are also compared in Fig. 4 (c1) and (c2), respectively.

The force-indentation data measured in the experiments showed that the dynamics convolution effect on both the applied force and the measured indentation was pronounced. When the multi-frequency method was used, the force applied to the PDMS sample was severely distorted from the desired force spectrum (compare Fig. 4 (a1) with the desired force profile shown in Fig. 4 (a2)). The largely uneven distribution of the excitation force spectrum can result in poor signal to noise ratio at some frequencies as well as signal saturation at others. On the contrary, evenly distributed excitation force spectrum was achieved by using the MIIC excitation method (see Fig. 4 (a2)). Therefore, the experimental results demonstrated the efficacy of the MIIC technique in compensating for the dynamics convolution effect on excitation force.

The experimental results also illustrated that the dynamics convolution effect on the indentation measurement was pronounced in both methods (see Fig. 4 (b1) and (b2)).
Comparing the indentation results measured in both methods, we note that by using the MIIC technique, the dominant peak of the indentation spectrum (at 2.85 KHz) obtained by using the multi-frequency method was eliminated (compare Fig. 4 (b1) with (b2)). However, other convolution-caused peaks became pronounced and distorted the indentation plot. As a result, the complex compliance data obtained were substantially distorted. The change of the complex compliance with the increase of frequency was severely distorted from the frequency-dependent complex compliance of PDMS (see Fig. 4 (c2)) [9]. Therefore, it was evident from the experiment results that the dynamics convolution effect needed to be compensated for in nanomechanical property measurement.

B. Compensation for the Convolved Dynamics Effect

The proposed method was applied to compensate for the dynamics convolution effect in both the multi-frequency and the MIIC-based methods. First, the total deflection dynamics on the PDMS sample $G_S(j\omega)$ (see Eq. (5)) was measured as described in Sec. II-C, and compared with that on the sapphire sample $G_H(j\omega)$ (see Eq. (6)), both are shown in Fig. 5. Then, the total convoluted dynamics ratio $G_{cv}(j\omega)$ was obtained as the ratio of these two deflection dynamics (see Eq. (10)), shown in Fig. 5 also. To take into account possible variations caused by different contact locations on sapphire, we measured the total deflection dynamics on the sapphire sample at five different locations. As shown in Fig. 6, the obtained total deflection dynamics on the sapphire sample at different points almost overlapped with each other. Thus, this experiment result also demonstrated that the proposed approach is robust with respect to the use of hard reference sample, i.e., the effect due to different contact locations of the reference sample can be ignored, and one can measure the total deflection dynamics on the reference sample only once and use it to measure a variety of different soft samples. In addition, we compared the total convoluted dynamics ratio with the uncompensated indentation (obtained by using the MIIC-based method) in Fig. 7.

Next, to eliminate the coupling caused deflection error $\Delta D_c(j\omega)$ (see Eq. (9)), the hard-soft material dynamics ratio was modeled by a linear $3^{rd}$-order Prony series, and the hard-soft material dynamics ratio $\Delta G_{hs}(j\omega)$ (see Eq. (10)) was decoupled from the total convoluted dynamics ratio $G_{cv}(j\omega)$ by using numerical fitting in Matlab (Matlab command "nlinfit"), based on Eq. (11). Specifically, the relative size of the real part of the hard-soft material dynamics ratio and that of the imaginary part were used as the weights to scale the parameters obtained from the real part fitting and those obtained from the imaginary part fitting. The fitting result is shown in Fig. 8. Then, the obtained parameters were used to estimate the hard-soft material dynamics ratio and therefore, the coupling caused deflection error $\Delta D_c(j\omega)$. The compensated indentation results are compared with the uncompensated (raw) one in Fig. 9 (a), and Fig. 10 (a) for the multi-frequency method and the MIIC-based method, respectively. Finally, the compensated indentation data were used to compute the compensated complex compliance. The uncompensated (raw) complex compliance was compared with the compensated one in Fig. 9 (b), (c), and Fig. 10 (b), (c) for the multi-frequency method and the MIIC-based approach, respectively.

The experimental results showed that the dynamics convolution effect on the indentation measurement was caused by the total convoluted dynamics ratio $G_{cv}(j\omega)$. As shown in Fig. 7, the “peaks” in the uncompensated indentation coincided with those in the total convoluted dynamics ratio. By using the proposed technique, such a dynamics convolution effect was substantially reduced (compare Fig. 9 (a) with Fig. 4 (a1) and (b1), particularly around frequencies near 2 KHz to 2.5 KHz, and around 3 KHz). As a result, the compensated indentation results are compared with the uncompensated (raw) one in Fig. 9 (a), and Fig. 10 (a) for the multi-frequency method and the MIIC-based method, respectively. Finally, the compensated indentation data were used to compute the compensated complex compliance. The uncompensated (raw) complex compliance was compared with the compensated one in Fig. 9 (b), (c), and Fig. 10 (b), (c) for the multi-frequency method and the MIIC-based approach, respectively.

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Compensated complex compliance obtained by using the multi-frequency method monotonically decreased as the frequency increased, which agreed with the viscoelastic behavior of PDMS. However, when using the multi-frequency method, such a viscoelastic behavior of PDMS cannot be seen from the compensated indentation result (compare Fig. 4 (b1) with Fig. 9 (a)). On the contrary, by applying the proposed technique to the indentation data obtained by using the MIIC-based method, the compensated indentation monotonically decreased as the frequency increased (see Fig. 10), and the convoluted dynamics effect was removed from the compensated complex compliance result. As shown in Fig. 10, the PDMS was above its glass temperature and displayed a clear viscoelastic solid response at room temperature. Therefore, the proposed approach can be used to effectively eliminate the effect of convoluted instrument dynamics on indentation measurement, thereby improving the bandwidth and/or the accuracy of broadband measurement of nanomechanical properties of soft materials.

Fig. 8. The curve fitting result of (a) the real part and (b) the imaginary part of the total convoluted dynamics ratio $G_{cv}(j\omega)$ by a 3rd-order Prony series like model.

Fig. 9. (a) The compensated indentation data obtained by using the multi-frequency excitation, and (b) the comparison of the uncompensated compliance of the PDMS sample (blue solid line) with the compensated compliance of the PDMS sample (red dashed line).

Fig. 10. (a) The compensated indentation result obtained by using the MIIC-based method, and (b) the comparison of the uncompensated compliance (blue solid line) of the PDMS sample with the compensated compliance of the PDMS sample (red dashed line).

**IV. CONCLUSION**

In this paper, a model-based approach to compensate for the dynamics convolution effect on nanomechanical property measurement of soft materials is proposed. The dynamics involved in indentation-based nanomechanical property measurement was analyzed to reveal that the convoluted dynamics effect can be described as the difference between the lightly-damped probe-sample interaction dynamics and the overdamped nanomechanical behavior of soft materials. Then, these two different dynamics effects were decoupled via numerical fitting based on a linear viscoelasticity model of the soft material. The proposed approach was illustrated by implementing it to compensate for the dynamics convolution effect on the experiment data of a broadband viscoelasticity measurement of PDMS using SPM. The experimental results showed that the dynamics convolution effect can be effectively compensated for by using the proposed approach.

**REFERENCES**


