Using Self-Sensing Techniques to Produce a Small, Robust, Inexpensive Rheometer

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Abstract:
Self-sensing is the technique of using a transducer to both actuate and sense concurrently, therefore eliminating the need for separate sensors. A sensorless rheometer could be much smaller, simpler and more robust than traditional designs. One application where such a rheometer would be desired is the in-situ measurement of curing bone cement in orthopaedic surgery. A set of equations was developed that models the relationship between force, motion and back-e.m.f. generation for a class of electromagnetic actuators. This enables velocity, displacement and force to be self-sensed from voltage measurements only. This self-sensing was validated on a conventional linear electromagnetic actuator, and a small rotary moving magnet device, which was designed to be a small self-sensing rheometer. The accuracy of the estimation was assessed and shown to compare favourably with measured data. The actuators were then used to construct simple rheometers to measure bone cement. Rheological models were used to calculate storage and loss moduli and dynamic viscosity from the self-sensed values of displacement, velocity and torque. The accuracy of these self-sensing rheometers was verified against a traditional rheometer using a silicone fluid and a polyethylene oxide solution. The self-sensing rheometers were used to characterise acrylic bone cements during curing, reinforcing and extending upon previous results. The elimination of sensors meant that it was possible to produce a small, inexpensive rheometer with a very simple structure. This indicates there is potential to develop small rheo-transducers for certain applications.

Zusammenfassung:
Selbst-Abfragung ("self-sensing") beinhaltet die Verwendens eines Signalumformers, der sich gleichzeitig selbst anregt und dabei misst, und somit die Notwendigkeit unterschiedlicher Sensoren vermeidet. Ein sensorloses Rheometer kann daher viel kleiner, einfacher und robuster als traditionelle Rheometer sein. Eine Anwendung, in der ein solches Gerät gewünscht wird, ist das in-situ-Messen des Ausheilens von Knochenkleber in der orthopädischen Chirurgie. Ein Gleichungensatz wurde aufgestellt, um das Verhältnis zwischen Kraft, Bewegung und Rückkopplung an das e.m.f. für den elektromagnetischen Erreger zu beschreiben. Dieser Satz ermöglicht die Selbst-Abfrage von Geschwindigkeit, Deformation und Kraft auf der Basis von Spannungsmessungen. Die Methode wurde erfolgreich für konventionelle lineare elektromagnetische Erreger und sich drehende Magnete bestätigt, mit dem Ziel kleine selbst-abfragende Rheometer zu entwickeln. Die Genauigkeit der Methode wurde anhand vorhandener rheologischer Daten erfolgreich untersucht. Die Erreger wurden dann benützt, um einfache Rheometer zu konstruieren, die Knochenkleber messen. Rheologische Modelle wurden benutzt, um Speicher- und Verlustmoduln und dynamische Viskositäten von den selbst-abgefragten Werten der Versetzung, der Geschwindigkeit und der Drehkraft zu errechnen. Die Genauigkeit dieser Technik wurde weiter gegen ein traditionelles Rheometer validiert, unter Verwendung einer Silikonflüssigkeit und einer Polyäthylenoxidlösung. Das selbst-abfragende Rheometer wurde eingesetzt, um Acrylknochenkleber während des Kurierens, der Verstärkung und des Verlängerns zu kennzeichnen. Die Beseitigung der Sensoren bedeutete, dass es möglich war, ein kleines, billiges Rheometer mit einer sehr einfachen Struktur zu produzieren. Dieses Beispiel zeigt, dass es möglich ist, kleine Rheosignalumformer für bestimmte Anwendungen zu entwickeln.

Résumé:
"L'auto-détection" est la technique qui consiste à utiliser un transducteur pour mesurer et appliquer un deplacement simultanément, éliminant donc le besoin d'utiliser des détecteurs séparement. Un rhéomètre sans détecteur pourrait être bien plus petit, plus simple et plus robuste que les équipements traditionels. Une application où un tel rhéomètre serait souhaitable est la mesure in-situ de la cuisson d'un ciment osseux dans le domaine de la chirurgie orthopédique. Un ensemble d'équations a été développé qui modélise la relation entre la force, le mouvement et la génération de « back-e.m.f. », pour une classe de transducteurs électromagnétiques. Ceci permet de auto-détecter la vitesse, le déplacement et la force à partir de mesures de voltages uniquement. Cette auto-détection a été validée avec un transducteur électromagnétique linéaire conventionel, et un appareil constitué d'un petit aimant à mouvement rotatif, qui a été mis au point afin de construire un petit rhéomètre auto-detecteur. L'estimation de la précision a été établie et il a été montré que celle ci se compare de manière favorable avec les données mesurées expérimentalement. Les transducteurs ont alors été utilisés pour construire de simples rhéomètres afin de mesurer du ciment osseux. Des modèles rhéologiques ont été utilisés pour calculer les modules de perte et d'élasticité ainsi que la viscosité dynamique à partir des valeurs auto-détectées du déplacement, de la vitesse et du couple. La précision de ces rhéomètres auto-détecteurs a été vérifiée en comparant avec un rhéomètre conventionel les résultats obtenus sur un fluide siliconé et une solution d'oxyde de polyéthylène. Les rhéomètres auto-détecteurs ont été utilisés pour caractériser des ciments osseux acryliques durant la cuisson, ce qui a permis de confirmer et compléter les résultats précédents. L'élimination de détecteurs a établi qu'il était possible de produire un rhéomètre petit, peu cher avec une structure très simple. Ceci indique qu'il existe un potentiel pour développer de petits rhéo-transducteurs pour certaines applications.

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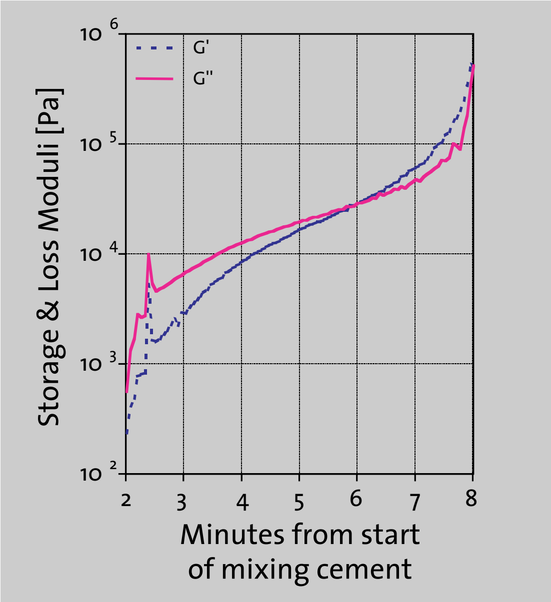

Figure 10: Self-sensed storage and loss moduli of CMW3 bone cement.

Lewis and Carroll [15] only published results of complex viscosity, η^*, however these were at least an order of magnitude higher than this study, and previous studies of absolute viscosity [10 - 13]. A possible reason for the difference is that Lewis and Carroll applied a very small deformation of ± 10 μm, which is less than the mean particle size of the cement mixture.

6 DISCUSSION AND CONCLUSIONS

Self-sensing can provide accurate estimates of displacement, velocity and force when used with electromagnetic actuators, under the condition that the actuators can be described by a linear model. Where errors appear in self-sensed values, this can be attributed to mis-match between the model of the actuator and its actual behaviour. For example, electrical heating of the coils causes Z_C and Z_M to vary from their previously-recorded values. Additionally the model is purely linear, whereas the actuator will be affected by non-linear effects such as bearing stiction. A total harmonic distortion analysis of the recorded sine waves is useful to identify any distortion caused by non-linear effects. With careful design, and/or a more detailed actuator model, these effects can be minimised.

An important limitation to this method of displacement estimation is that it depends on there being a measurable back-e.m.f. signal – this is proportional to velocity and to the electromagnetic constant K_C. Regarding force or torque self-sensing, in order to be detectable, an external force must cause a recordable change in actuator velocity. Therefore in designing or selecting an actuator for a self-sensing application, consideration must be given to the expected working conditions. For example, if low velocities are required, a high K_C will produce a larger, more measurable back-e.m.f. Additionally, the rheometer geometry must be chosen so that the test material causes a measurable restriction to the actuator motion. Whether or not a change in actuator behaviour is "measurable" depends on the quality of analogue measuring equipment. Although the accuracy of the results presented here is not equivalent to reference standard rheometers, it is certainly sufficient to provide an indication of rheological properties for some applications.

There is great potential to produce an inexpensive rheometer using self-sensing techniques – the rotary actuator used for this research was constructed for a parts cost of less than EUR 10. While the control technique described herein used a PC, the algorithms could equally be implemented on a microcontroller chip, which would reduce the cost of the overall system.

Although this self-sensing study has been limited to the case of oscillatory (sinusoidal) motion, encouraging results have also been achieved for arbitrary motion cases. This theoretically enables self-sensing control of stress-relaxation and creep tests. The self-sensing of displacement and force for arbitrary motion, using a range of electromagnetic devices will be the subject of future research.

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NOMENCLATURE

$V_s^*(t, \omega)$	Supply voltage	[V]
$V_s^*(t, \omega)$	Voltage across coil	[V]
R	Current-measuring resistance	[Ω]
$I_C^*(t, \omega)$	Current through coil ($I = (V_S - V_C)/R$)	[A]
$Z_C^*(\omega)$	Impedance of clamped coil	[W]
$Z_M^*(\omega)$	Impedance of free-to-move coil	[W]
$E^*(t, \omega)$	Back-e.m.f.	[V]
$E_d^*(t, \omega)$	Back-e.m.f. created by torque T_d	[V]
K_C	Electromagnetic constant	[N Amp^{-1}] or [V m^{-1} s]
$\theta^*(t, \omega)$	Angular displacement	[rad]
$T_d^*(t, \omega)$	Torque applied by/to actuator	[Nm]
J	Added inertia load	[kg m^2]
δ	Angle between torque and displacement	[rad]
r_2	Internal radius of container	[m]
R_1	Radius of spindle	[m]
i	Imaginary component	√-1

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For clarity, the suffixes (t, ω) have been removed from the equations herein while * denotes complex values.

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