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## A regime-switching cointegration approach for removing environmental and operational variations in structural health monitoring

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### ABSTRACT

Cointegration is now extensively used to model the long term common trends among economic variables in the field of econometrics. Recently, cointegration has been successfully implemented in the context of structural health monitoring (SHM), where it has been used to remove the confounding influences of environmental and operational variations (EOVs) that can often mask the signature of structural damage. However, restrained by its linear nature, the conventional cointegration approach has limited power in modelling systems where measurands are nonlinearly related; this occurs, for example, in the benchmark study of the Z24 Bridge, where nonlinear relationships between natural frequencies were induced during a period of very cold temperatures. To allow the removal of EOVs from SHM data with nonlinear relationships like this, this paper extends the well-established cointegration method to a nonlinear context, which is to allow a breakpoint in the cointegrating vector. In a novel approach, the augmented Dickey-Fuller (ADF) statistic is used to find which position is most appropriate for inserting a breakpoint, the Johansen procedure is then utilised for the estimation of cointegrating vectors. The proposed approach is examined with a simulated case and real SHM data from the Z24 Bridge, demonstrating that the EOVs can be neatly eliminated.

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## 1. Introduction

Due to the fact that many structural and mechanical systems are approaching or exceeding their original design life, structural health monitoring (SHM) has been continually developing over the past decades. However, one of the main obstacles that has kept SHM from practical implementation in industry is the effect of environmental and operational variations (EOVs). EOVs are variations induced by temperature, wind, humidity, traffic, etc. Because EOVs are influencing the systems constantly, any measurements of the system responses can be contaminated by EOVs, thus any potential damage information may be masked falsely [1]. For instance, when Farrar et al. considered different levels of damage on the I-40 Bridge in New Mexico, USA, it turned out that changes of the first modal frequency caused by damage were from 2% to 6% depending on different damage levels [2]; however, numerous investigations have suggested that variations induced by ambient temperature can range from 5% to 10% [3]. As such, it is crucial for *in situ* SHM to discriminate the changes in the features extracted from sensor readings which are caused by structural damage from those changes caused by benign EOVs, such

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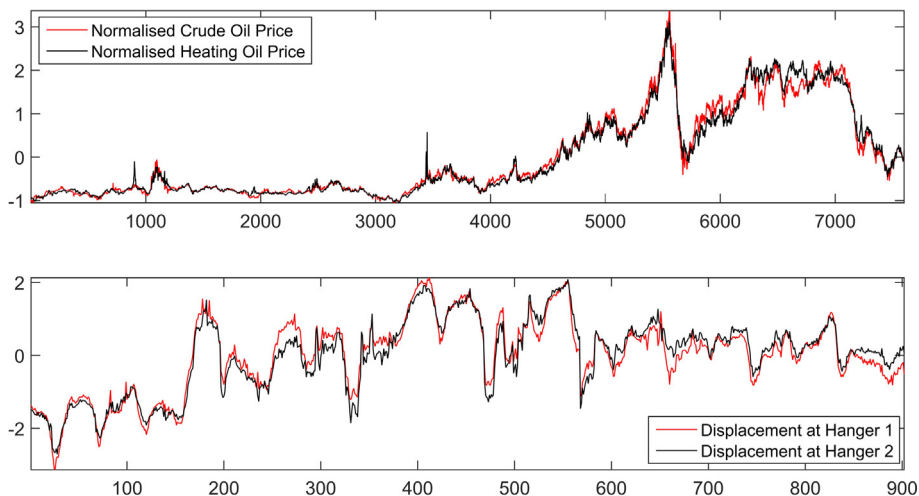
a process is termed as *data normalisation*. Many approaches have been developed to address data normalisation issues, including regression modelling, machine learning approaches, projection methods and so on [1]. When the measurements of the EOVs are available, regression models are common methods employed to explicitly model the dependency between the EOVs and system response or damage-sensitive features [4]. Alternatively, principal component analysis (PCA) is a projection method to find EOV-insensitive features which are damage-sensitive at the same time. The fact that EOVs are accountable for the most of the variance in the sensor readings, meaning that, by projecting the features onto the space spanned by the eigenvectors associated with the smallest eigenvalues, one can obtain features that are not influenced by EOVs but are potentially still sensitive to damage [5]. For further information on these methods, readers are suggested to refer to [6] as a comparatively recent review.

Recently, *cointegration* has been adopted successfully to address the challenge of EOVs in structural health monitoring [7]. As a routine method for dealing with nonstationary time series in econometric studies, cointegration is now widely used in statistical arbitrage, macroeconomic analysis, and fiscal policy research. However, what is the link between an econometric method and EOVs in SHM? The answer is the existence of stochastic common trends. Consider Fig. 1 for example; the upper panel shows two normalised price indices (heating oil and crude oil in the US) during a certain time period; the lower panel exhibits two time series of two hanger displacements of the Tamar Bridge measured during a certain time history [8]. By visual inspection of these two images, two common characteristics can be observed immediately: each pair of time series is nonstationary; each pair shares some long-term common trend. These characteristics are not hard to understand, that economic time series are simultaneously affected by markets, monetary policies, etc., while displacement of each bridge hanger is significantly influenced by temperature, traffic, etc., or in the terminology of this paper - EOVs. Nonstationary series are said to be *cointegrated* if there exists a linear combination of them that is stationary. Denote the two time series in the upper panel of Fig. 1 by  $x_t$  and  $y_t$ ; they can be found to be cointegrated if some linear combination of them:

$$\varepsilon_t = x_t + \alpha y_t \quad (1)$$

is stationary (confirmed by performing a stationarity hypothesis test). The residual series for the oil price series and the displacement series are plotted in Fig. 2, which shows that the residual series are purged of common trends and become largely stationary. Once the underlying equilibrium between the displacement series is built, the stationary residual series can serve as a damage indicator that is immune to EOVs. It is worth noting at this point that the cointegrated residual series of the oil series seems to behave differently before and after approximately point 5000. This interesting phenomenon can be seen as a regime change in the market, which will be elaborated more in the latter part of this paper.

Based on the concept of cointegration, several applications on the issue of EOVs in SHM have been attempted. Cross et al. [7] proposed the whole framework of the cointegration approach for SHM; the method was validated with a time-varying multi-degree-freedom lumped mass system, and also a real SHM problem, which was to perform damage detection of a composite plate subjected to cyclic temperature variations. An efficient maximum likelihood estimation method - the Johansen procedure (technical details of which will be covered shortly in Section 2) - was used to estimate the most stationary cointegrating relationship; environmental variability could be significantly suppressed in the stationary residual series and damage could be successfully detected. One major benefit of employing the cointegration method was that by building the inner relationship of the monitored variables, direct measurements of EOVs were not necessary. Furthermore, Cross et al. [5] compared the cointegration method with another two conventional methods: outlier analysis and principal component analysis (PCA), utilising the same experimental data from [7]. Although outlier analysis may produce an acceptably low number



**Fig. 1.** Upper panel: normalised price index of crude oil price and household heating oil price of US; Lower panel: normalised series of displacement measurements from the Tamar Bridge.

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