DATA-ADAPTIVE, TIME-LOCAL METHODOLOGY FOR NUMERICAL MODELING OF NONLINEAR NONSTATIONARY DYNAMICAL SYSTEMS

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Goal: Develop a methodology and a computational framework for identification and quantification of nonlinear, nonstationary hydrodynamic phenomena frequently encountered in offshore engineering applications prone to Flow-Induced Vibrations (FIV). Our approach is based on data-adaptive, time-local, numerical modeling and nonparametric time-frequency analysis to reveal and quantify force components in engineering problems such as:

(a) Accurate reconstruction of loads critical to the design and analysis of structures (ocean platforms, risers, pipelines, transmission cables, antenna guy wires, fuel rods in nuclear reactors, suspension bridges, etc.)
(b) Capturing hydrodynamic patterns in data to characterize the nonlinearity and non-stationarity of fluid-structure interaction (FSI) dynamics.
(c) Assessment of FIV for suppression [1] or enhancement [2] of forces to mitigate vibrations transferred to instrument sensors or to harness efficiently in-stream marine hydrokinetic (MHK) energy.

Physics: Offshore engineering problems involving FSI are complex systems whose behavior is intrinsically challenging to model. They are often modeled approximately by differential equations as nonautonomous dynamical systems. The complexity is caused by the nonlinear and nonstationary nature of fluid-structure interactions, which prevents us from realistically modeling the system by decomposing it into meaningful subsystems pertinent to inherent flow-physics. The external input embedded in the nonhomogeneous part of the governing equations as well as the impact it may have on the system itself can provide insight into the driving phenomena (e.g. hydrodynamic loading on flexible risers in FIV or galloping) behind the system of interest.

Problem Definition: The assessment of nonlinear, nonstationary systems becomes even more challenging when the external input and the system mutually modify each other as in the case of time-varying FSI. Among the current practices used to address this challenge are:

(a) Direct measurement of quantities forming the external input can be costly or difficult to obtain due to scale (e.g. calibration of force-sensors for a wide range of flow-speeds and experiment parameters), nature (e.g. large amplitude-frequency modulations in galloping) and sensitivity (e.g. accurate determination of flow separation at high *Re* in Computational Fluid Dynamics simulations) of physical and computational experiments.
(b) Using time-averaged values of experimentally measured FIV data in simplified, closed-form solutions of a Morison's type equation with a linear combination of constant amplitude and frequency Fourier component approach is incapable of describing important coexisting amplitude and frequency modulations (AM-FM) [3, 4]. This process does not capture adequately the nonlinear and non-stationary nature of FIV due to memory effects embedded in vortex growth and shedding as well as interference of the wakes between multiple bodies [5, 6, 7].
(c) Semi-empirical programs (e.g. SHEAR7, VIVA, VIVANA, ViCoMo etc.) applied in the analysis of Vortex-Induced Vibrations (VIV) all operate in the frequency domain and use hydrodynamic coefficients that depend on dimensionless parameters determined from experiments in a limited *Re* range [8]. The linearization of the structure with the assumption of stationary flow conditions and structural response as utilized in these codes cannot explain the nonlinear, nonstationary excitation directly dependent on the response. They show considerable discrepancies between each other, concluding that at present no generally accepted program exists for calculation of VIV response [9].
(d) Numerical differentiation with conventional methods, found in most scientific computing software and libraries, utilizes two or three points for difference operator window-size, which leads to inaccurate and noisy reconstruction of nonlinear, nonstationary phenomena [10]. Explicit use of band-pass filters is not adequate for getting rid of low-frequency noise that may exist in the signal, and due to its averaging behavior, can cause loss of valuable amplitude-sensitive high-frequency information such as vortex-shedding forces.

Required breakthroughs: (i) Data-adaptive numerical modeling of time-dependent nonlinear forces from displacement time-series in large-scale experiments up to *Re* 140,000 (MRELab available data); (ii) followed by model-reduction to essential components (**Figure 1**). Our approach combines nonparametric time-frequency analysis and numerical differentiation with finite differences (FD) to obtain accurately the derivatives of the response needed in the reconstruction of the input to the differential equation [11]. The developed methodology finds and adapts to the instantaneous frequency of time-series data to automatically discover the correlation length necessary to characterize the frequency modulation properly in numerical differentiation. The required local polynomial model order and resulting order of accuracy of FD operator is automatically chosen by a statistical hypothesis testing algorithm based on evidence quantification using Bayesian model comparison with bias-variance tradeoff evaluation. Model reduction to essential components is achieved by denoising and trending decompositions of reconstructed forces with an automated model selection procedure based on statistical significance-test against characteristics of self-similar noise processes (**Figure 2**) [12]. This is needed in the analysis of the nonlinear and non-stationary hydrodynamic signal to identify the nature of dominant force components.

Benefits: This data-adaptive modeling and time-series analysis framework can: (a) Automatically reconstruct the multicomponent hydrodynamic force accurately (up to arbitrary order) from body displacement time-history while sustaining high signal-to-noise ratio; (b) Capture nonlinear contributions from multiple frequency components missed by conventional methods like DFT and average zero-crossings without an *a-priori* assumption of the analyzed spectra; and (c) Allow time-local identification and quantification of nonlinear, nonstationary hydrodynamic phenomena (**Figure 3**) in FIV of multiple bodies as a result of AM-FM within the statistically significant force components.

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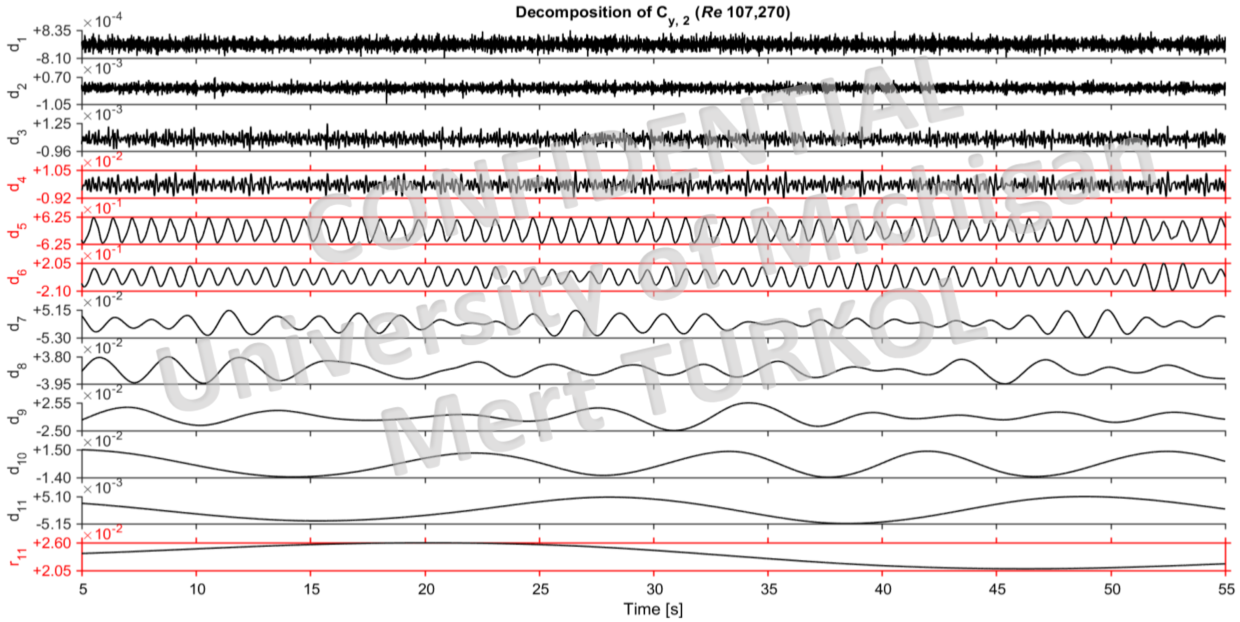

Figure 1. Decomposition of the multicomponent transverse hydrodynamic force in amplitude-frequency modulated contributions

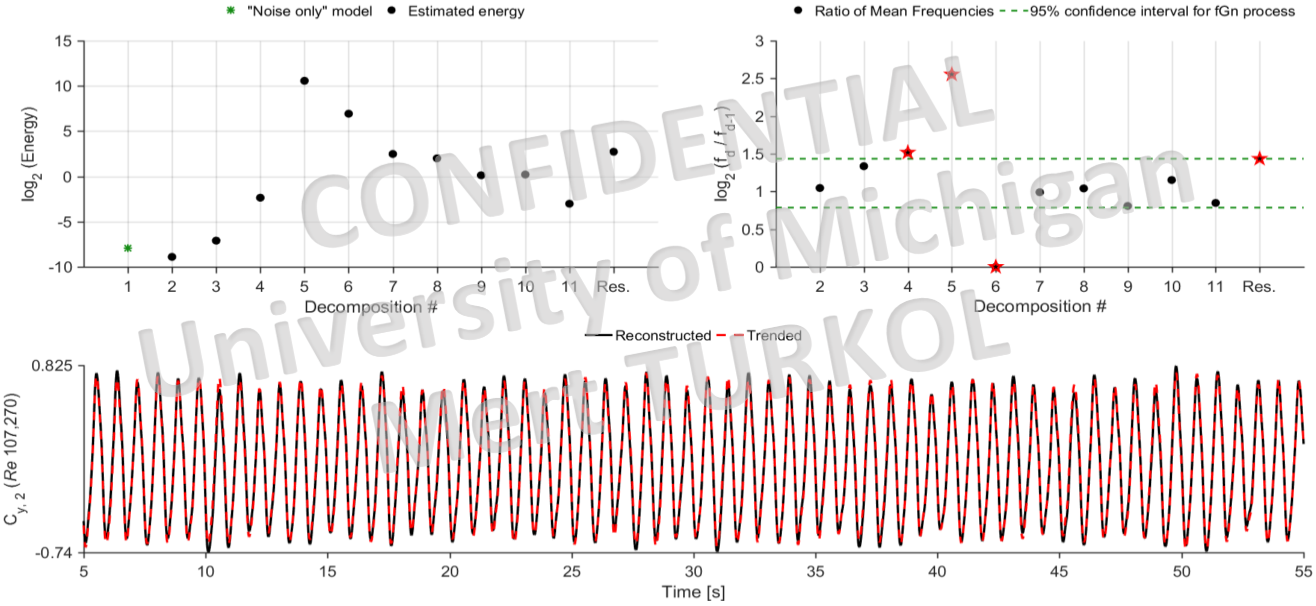

Figure 2. Model selection and trend capturing in reconstructed force time-history based on a statistical significance test

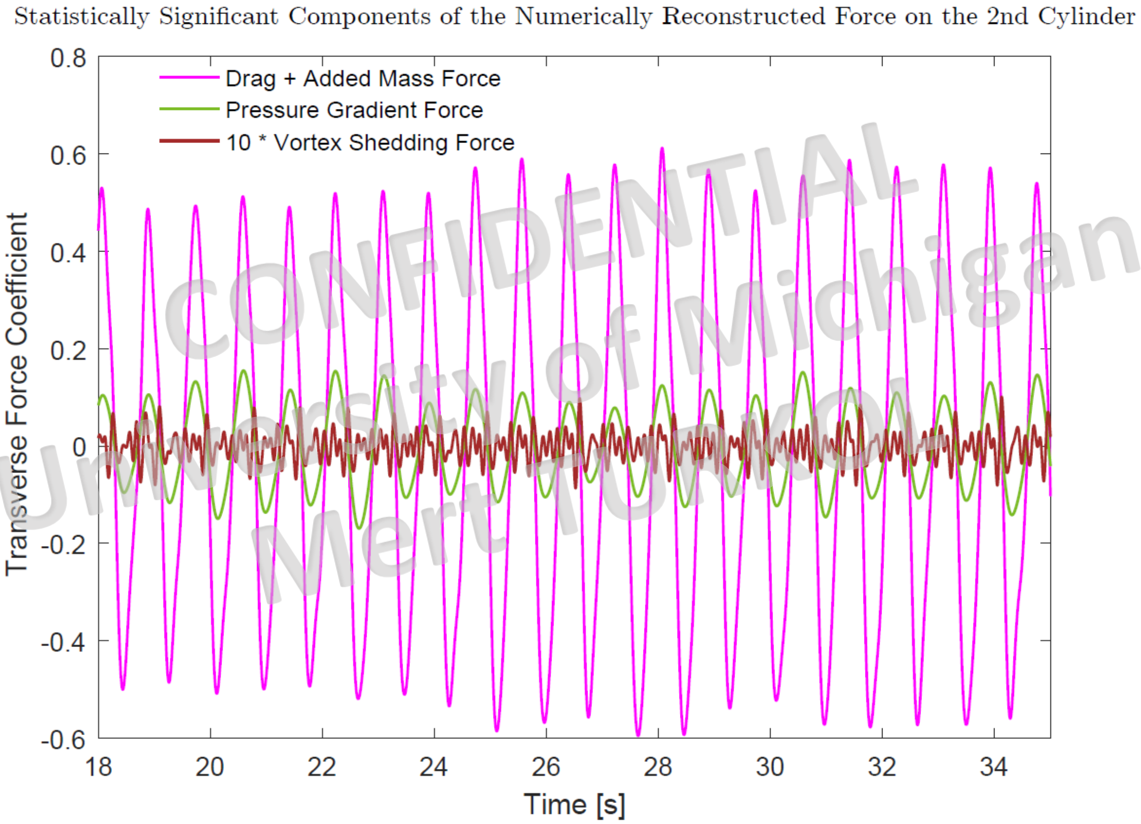

Figure 3. Identification and quantification of fluid-structure interaction phenomena