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# TEMPORAL VIBRATION FORCE IDENTIFICATION USING HIGH-SPEED DIGITAL HOLOGRAPHY

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## ABSTRACT

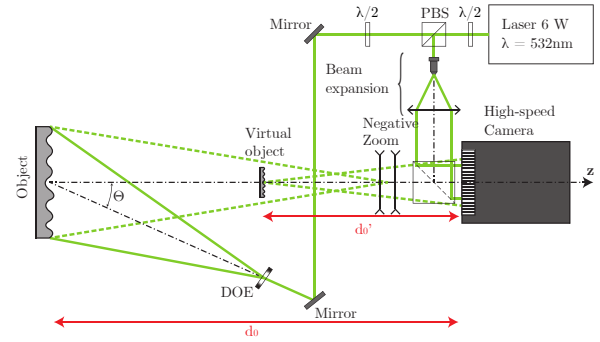
High-speed digital holography is a contactless optical method, which yields observation and measurement of vibration phenomena over a large field of view. By this technique, the displacement field of the studied structure is obtained with the measurement of the Doppler phase extracted in digital holograms that are recorded using a high-speed camera. Simultaneous measurements of about 50000 data points at the surface of the structure can be obtained at 100 kHz frame rate. Thanks to the full-field approach, the observation of stationary and transient vibrations can also be made at both their spatial and temporal scales. We propose to apply the digital holographic method to the force identification in mechanical structures when submitted to different excitation regimes. The dense mesh of data points can be advantageously used to solve the inverse problem of force identification. In this paper, the inverse problem is based on the Force Analysis Technique (FAT) where the displacement field from digital holography is used as input in the motion equation of the plate. Since the FAT requires regularization, it is here approached thanks to a low-pass-wavenumber filtering or Bayesian approach of the method.

## 1. INTRODUCTION

High-speed digital holography provides contact-less and full field measurement of vibration phenomena. The full-field observation permits measurement of stationary and transient vibrations [1]. Here we demonstrate that high-speed digital holography can be used to identify the force distribution applied to the structure by using an inverse problem called Force Analysis Technique (FAT) regularized by low-pass-wavenumber filtering and Bayesian approach on different excitation regimes.

## 2. DIGITAL HOLOGRAPHY

Digital Holography results in the interferences of two coherent waves. The first one is a reference wave which directly impact the camera sensor, the second one is the result of the diffraction of the beam illuminating the object as described in figure 1.



**Figure 1.** Experimental set-up of digital holography, (PBS: polarizing beam splitter, DOE: diffractive optical element, high-speed camera: Photron FastCam SAX2)

A high-speed camera then records the holograms expressed as [2]:

$$H = |A_R|^2 + |A_O|^2 + A_R^* A_O + A_R A_O^*, \quad (1)$$

where  $A_R$  is the reference wave and  $A_O$  is the wave coming from the object. We also record the reference signal  $|A_R|^2$ . To retrieve the complex field hologram of the object, we apply the Discrete Fresnel transform to data  $H - |A_R|^2$ . Data related to the vibration is obtained as follows: the phase difference is calculated from two consecutive reconstructed phases. With the time sequence obtained from the phase difference the amplitude and phase of the vibration can be retrieved [3].

## 3. FORCE ANALYSIS TECHNIQUE (FAT)

The force identification in the structure is performed by the FAT method [4] which can retrieve both the spatial localization and amplitude of the force. This method is based on the movement equation of the plate, for example in harmonic regime:

$$D \nabla^4 W(x, y, \omega) + j \omega 2 \zeta D \nabla^4 W(x, y, \omega) - \omega^2 \rho h W(x, y, \omega) = F(x, y, \omega), \quad (2)$$

with  $h$  the stiffness and  $D$  the rigidity of the structure. Spatial derivatives are approximated by finite differences. Af-

ter discretisation, the equation can be rewritten under matrix formulation as:

$$\begin{aligned}\hat{\mathbf{F}}(\omega) &= (D_r + D_c - D_m)\hat{\mathbf{W}}(\omega) \\ &= D_{global}\hat{\mathbf{W}}(\omega),\end{aligned}\quad (3)$$

with  $\hat{\mathbf{F}}(\omega)$  the vector formulation of the variable  $F(x, y, \omega)$  and  $\hat{\mathbf{W}}(\omega)$  of the variable  $W(x, y, \omega)$ .  $D_r$  is the matrix formulation of the term  $D\nabla^4$ ,  $D_m$  the term  $\omega^2\rho h$  and  $D_c$  the term  $j\omega 2\zeta D$  the term  $-\omega^2\rho h$  after discretization. With presence of noise, the simple inverse resolution is not yet possible because of the amplification of the noise induced by  $\nabla^4$  coefficient included in  $D_r$  and  $D_c$  operators, a regularization of the method is so needed.

### 3.1 Bayesian regularization

The Bayesian regularization of the FAT method was developed at LAUM and is based on the Bayes theorem which links the probability between events. The Bayesian regularization is also developed for a Gaussian noise and the estimated force resulting from the algorithm is expressed by [5]:

$$\hat{\mathbf{F}}^{MAP}(\omega) = M \left[ \frac{s_i}{s_i^2\eta^2 + 1} \right] V^H \hat{\mathbf{U}}_z^n(\omega). \quad (4)$$

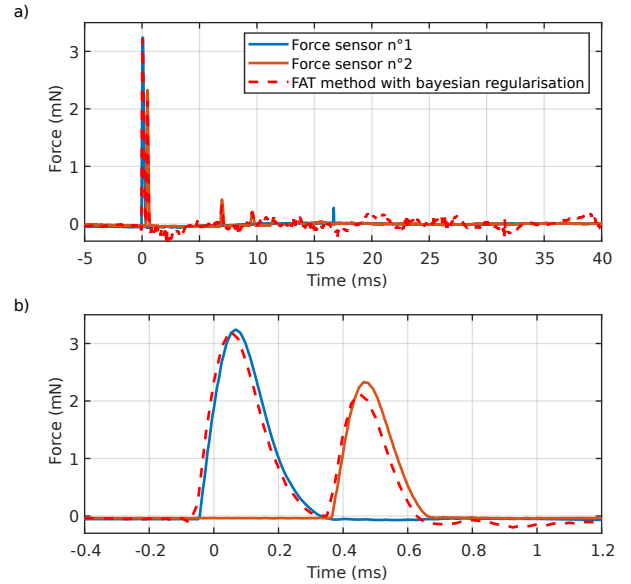
$F_{p,q}^{MAP}(\omega)$  can be retrieve by reshaping the force under a matrix formulation. In Eq. 4,  $M$  and  $V$  are the singular vector and  $s_i$  the singular values resulting from the singular value decomposition of matrix  $D_{global}$  and  $\eta^2$  is the regularization parameter to be determinated. This operation can be made by minimizing a cost function obtain by mMAP estimator [5]. The application of the method can then be performed by applying Fourier transform on time data provided by digital holography and by applying FAT method at each frequency provided by Fourier transform. Then an inverse Fourier transform on resolved data will give the temporal signal of the force.

## 4. RECONSTRUCTION IN TEMPORAL DOMAIN

Holographic measurement were performed in temporal regime with a resolution of 456x456 pixels. Two impacts hammer excites a steel plate on an area of 15 cm and is located in the measured field of view. The force profile reconstructed by the FAT method as well as the comparison with data coming from the force sensors positioned in the head of the impacts hammer is visible in figure 2. The force profile is well identified.

## 5. CONCLUSION

Ultra-fast numerical holography provides full field measurement with high resolution in space and time with the use of ultra-fast camera. We show that the FAT method regularized by Bayesian approach can be used with holographic measurements and permits to retrieve temporal force profile injected to the structure. Noise in the measurement requires to be taken into account for the convergence of the algorithm. We highlight new opportunities



**Figure 2.** Temporal force profiles, a) Comparison of the force temporal variation over 45ms duration, dashed red: from force identification with the FAT method with Bayesian regularization, blue: from the force sensor 1, orange: from the force sensor 2, b) zoom of a) around  $t = 0$ ms.

for studying complex physical phenomena that can only be investigated with our proposed approach: the observation and measurement of non-stationary waves in transient regime like rolling ball, friction and/or vibration induced by flow.

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