Non-contact full field vibration measurement based on phase-shifting

Hiroyuki Kayaba
Hiroyuki.Kayaba@nikon.com
Nikon Corporation, Japan

Yuji Kokumai
Yuji.Kokumai@nikon.com

Objective
This paper presents a novel, non-contact full field joint measurement technique both of vibrations and shape based on phase-shifting.

Main Idea
The main idea is to take phase shifting based structured light systems and derive a relationship between vibration of an object and errors in the predicted phase shift value. To estimate the phase-shift error by iterating frame-to-frame optimization and pixel-to-pixel optimization.

Phase-shifting Algorithm
\( I_n \) is the intensity at point \((x,y)\). \( B(x,y) \) is the intensity modulation, \( A(x,y) \) is the average intensity and \( \phi(x,y) \) is the phase

\[ I_n(x,y) = B(x,y) + A(x,y) \cos(\phi(x,y) + \phi_n) \]

\[ = B(x,y) + A(x,y) \cos(\phi_n) \cos \phi_n \]

\[ - A(x,y) \sin(\phi_n) \sin \phi_n. \]

(1)

Eq.(1) can also be rewritten as follows:

\[ I_n(x,y) = p(x,y) + q(x,y) s_n + r(x,y)t_n \]

(2)

Solving eq.(2) using the least-squares algorithm, we obtain \( \phi(x,y) \) as follows:

\[ \phi(x,y) = \tan^{-1} \left( \frac{\sum_{n=1}^{N} I_n \sin(\phi_n)}{\sum_{n=1}^{N} I_n \cos(\phi_n)} \right) \]

\[ \phi_n = \frac{2\pi n}{N} \]

where \( \phi_n \) is a phase-shifting offset. The phase residual is then defined as:

\[ \Delta \phi_n(x,y) = \phi_n(x,y) - \phi_n \]

Experiment Setup
- Pattern rate: 100 Hz (8 bit)
- System size: 30 x 15 x 10 cm
- DLP projector (1140 x 912)
- 150 lumen
- CMOS camera (1328 x 1048)

Non-linear Correction of Phase Error
Phase-shift errors caused by object or projector movement during measurement. Problem: These errors are usually non-linear.

Iterative optimization performed frame-to-frame in the ROI image and optimization pixel-to-pixel in images.

\[ I(x,y) = p(x,y) + q(x,y) s_n + r(x,y)t_n \]

Pixel-to-pixel optimization
The optimization of common variables at each pixel.

Frame-to-frame optimization
The optimization of common variables in an images.

Conclusion
The proposed system can perform high accuracy vibration(0-10 Hz) measurement and reconstruct a 3D shape. This paper presents an active-lighting approach to measuring a 2D frequency map of vibrating surface. Our system is the same as that used for measuring a 3D shape using phase-shifting.