Health status of ancient buildings:
interferometric radar NDT inspection

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Abstract

In this paper an innovative NDT methodology for the monitoring of the health condition of ancient building is presented. The methodology is based on the reconstruction of the dynamic behaviour of the structure using an interferometric radar, that is a non-contact sensor able to monitor in real time the displacement of several points belonging to the building. The monitoring of any modal parameters change into the years is of use for the structural integrity assessment.

Keywords: interferometric radar, structural integrity of buildings, vibration-based damage detection

1. Introduction

The knowledge of the health conditions of historical buildings is of great concern for the preservation and maintenance of the cultural and artistic inheritance from the past. In the most part of the Italian towns, we all can admire churches, palaces and monuments, also older than one thousand years. Churches, masonry towers and bell towers are among the structures subjected to the higher risk, due to their age, elevation and low base area on height ratio. The research of new techniques applied to the civil and structural fields is continuously aimed to the optimization of measures and methods. In particular, in the case of ancient structures, the non invasive non destructive techniques are of great interest.

The conventional monitoring tools of structural displacements of buildings are represented by a variety of techniques: networks of optical targets installed over the structure, strain gauges to detect deformations, collimation nets to detect displacements, inclinometers to measure rotations[1]. Such sensors, accurate and reliable, require to be in contact with the structure to be surveyed, and information is localized to the specific point where the sensor is positioned. Settling the optimal sensor placement is a common problem encountered in many engineering applications and is a critical issue in the implementation of effective structural health monitoring[2,3]. Furthermore, the monitoring of large structures can give rise to accessibility problems, often requiring the use of costly and cumbersome scaffolding. In a number of situations, the placing of contact sensors may be not possible; this is the case, for example, in buildings with symptoms of impending collapse after a seismic shock or a blast. The capability of performing in-service monitoring is a key requirement for planning survey campaigns aimed at the early identification of structural problems in order to enable low-cost maintenance remedial actions to be taken.

In particular, the monitoring of the dynamic characteristics of a structure is one of the possible keys of interpreting its health status. Each body has its own shapes, frequencies of vibration and dumping properties - the modal parameters - that are a function of its mechanical characteristics: a damaged structure shows a frequency autospectrum which differs from that of the integral one. The use of natural frequency as a diagnostic parameter in structural assessment procedures using vibration monitoring is not new in the technical literature[4-8]. The approach is based on the fact that natural frequencies are sensitive indicators of structural integrity. Thus, an analysis of periodical frequency measurements can be used to monitor structural condition. Since frequency measurements can be cheaply acquired, the approach could provide an inexpensive structural assessment technique[8, 9].

In this paper the authors present a non-destructive, non-invasive and non-contact technique applied to the monitoring of the structural integrity of historical buildings. In particular, the work is devoted to the detection of the dynamic characteristics of buildings to identify and recorder the dynamical behaviour of the structure. The modal parameters of the San Sepolcro bell-tower in Parma – Italy - are presented, and a methodology of damage detection discussed.

2. The Interferometric Radar

The microwave interferometer, showed in Figure 1, is a radar sensor able to simultaneously monitor the response of several points belonging to the structure, providing for each point the displacement response[3].

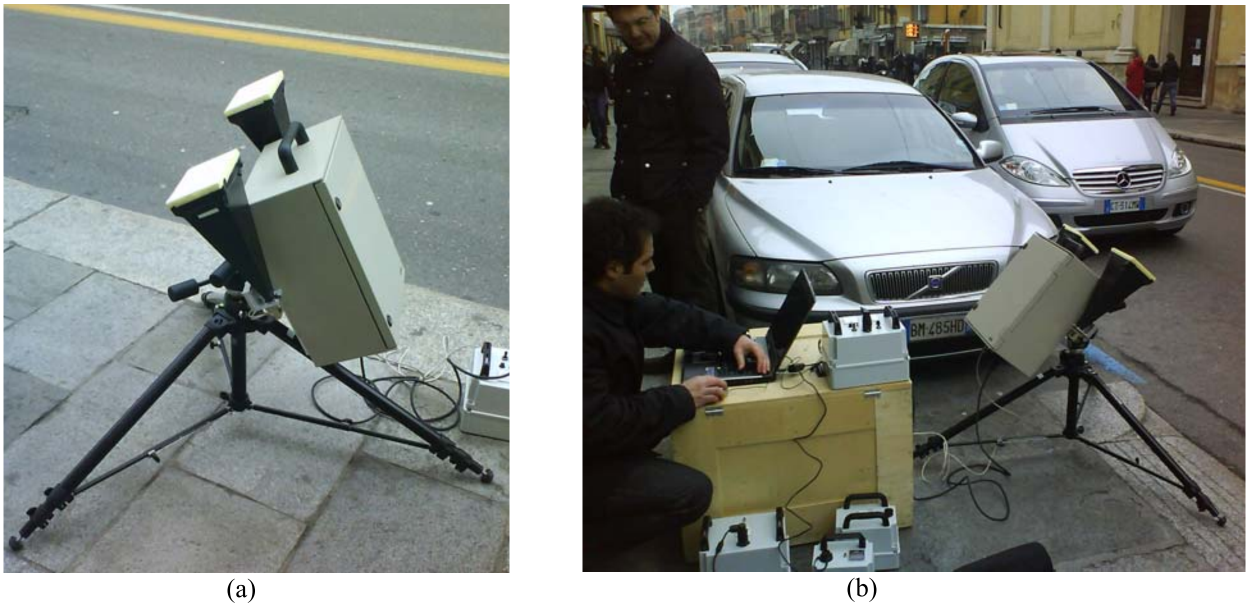
(a) (b)

Figure 1. (a) Interferometric radar apparatus; (b) example of in-situ measurement (San Sepolcro tower-bell, Parma).

The working principle of the sensor is based on two well-known radar techniques:

1. the Stepped-Frequency Continuous Wave (*SF-CW*) technique, allowing the system to resolve the scenario in the range direction, i.e. to detect the position of target surfaces placed at different distances from the sensor;

2. the Differential Interferometric technique, allowing the system to measure the displacements of the structure illuminated by the antenna beam by comparing the phase information of the back-scattered electromagnetic waves collected in different times.

Lets' have a brief overview of these two basics techniques. The *SF-CW* technique offers the capability to determine the range (i.e. distance) by measuring the time for the radar signal to propagate to the target and back is surely the most important characteristic of radar systems. Two or more targets, illuminated by the radar, are individually detectable if they produce different echoes. The *resolution* is a measure of the minimum distance between two targets at which they can still be detected individually. The *range resolution* refers to the minimum separation that can be detected along the radar's line of sight. The *SF-CW* technique is based on the synthesis and transmission of a burst of *N* monochromatic pulses equally and incrementally spaced in frequency. At each sampled time instant, both *I* (In-phase) and *Q* (Quadrature) components of the received signals are acquired so that the resulting data consist of a vector of *N* complex samples, representing the frequency response measured at *N* discrete frequencies. By taking the Inverse Discrete Fourier Transform (*IDFT*) the response is reconstructed in the time domain of the radar. In this sensor, the *SF-CW* technique has been implemented to obtain a range resolution of 0.50 m, independently from the maximum operative distance; in other words, the sensor is able to distinguish two different targets if their relative distance is greater than 0.50 m. The range resolution area is termed *range bin*. The concept of range profile is illustrated in Figure 4; peculiarly Figure 2 shows an ideal range profile obtained when the radar transmitting beam illuminates a series of targets at different distances and different angles from the system[1-3].

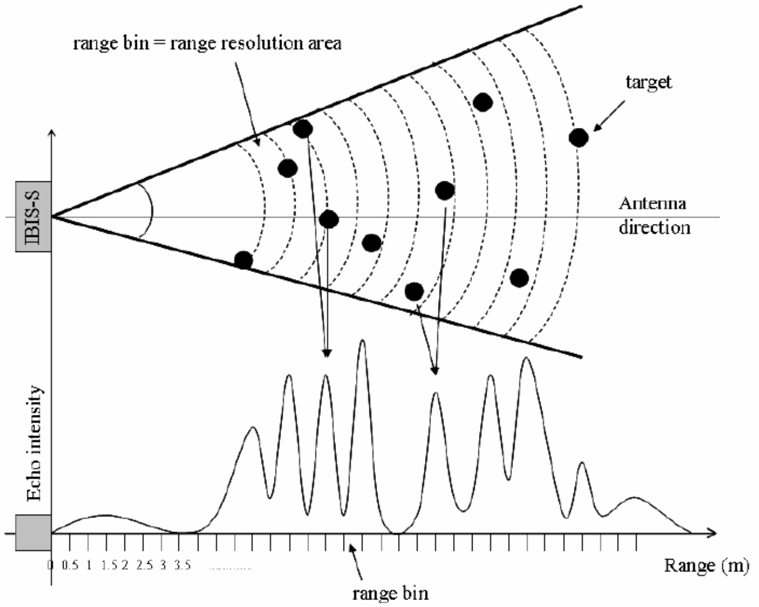

Figure 2. Range resolution concept.

Once the range profile of a structure has been determined at uniform sampling intervals, the displacement response of each range bin is evaluated by using the Differential Interferometry technique. Interferometry is a powerful technique that allows the displacement of a scattering object to be evaluated by comparing the phase information of the electromagnetic waves reflected by the object in different time instants. Generally speaking, when of a target surface moves with respect to the sensor a phase shift arises between the signals reflected by the target surface. Hence, the displacement of the investigated object can be determined from the phase shift measured by the radar sensor. The radial displacement d_p (i.e. the displacement along the direction of wave propagation) and the phase shift $\Delta\varphi$ are linked by the following eq. (1)[3]:

$$d_p = \frac{\lambda}{4\pi}\Delta\varphi \tag{1}$$

where λ is the wavelength of the electromagnetic signal.

3. Experimental procedure: the tower-bell of San Sepolcro in Parma

When a tower is subjected to a mechanical excitation, being constrained at its foundations, it tends to oscillate essentially with displacements orthogonal to the vertical axis. These displacements get higher with the height of the tower. The interferometric radar is able to measure the displacements d_r occurring along the radial direction r that connect the antenna with the point of measure on the surface, as illustrated in the scheme of Figure 3. The displacement orthogonal to the vertical axis is simply:

$$d_r = d \cdot sen\left(\alpha\right) \qquad (2).$$

Hence, for the equivalence $h = r \cdot sen\left(\alpha\right)$, it holds:

$$d = d_r \cdot \frac{r}{h} \qquad (3).$$

Now, measuring in advance the distance h and knowing the distance r of each point of interest along the tower, it is possible to automatically obtain the displacement of each the measure points.

The object of the present measurement is the San Sepolcro tower-bell in Parma, Italy. It is a 4 distinct levels tower of different dimensions: the first three levels from the basis of the tower has a squared section; the highest level, where the bell cell is located, has an octagonal cross section. The tower is consistent with the adjacent church masonry structure up to the height of 15 meters. The tower, erected in 1616 and many times subjected to restoration and modified during the centuries, in the last few decades has shown a worthy inclinations of the tip toward the south side.

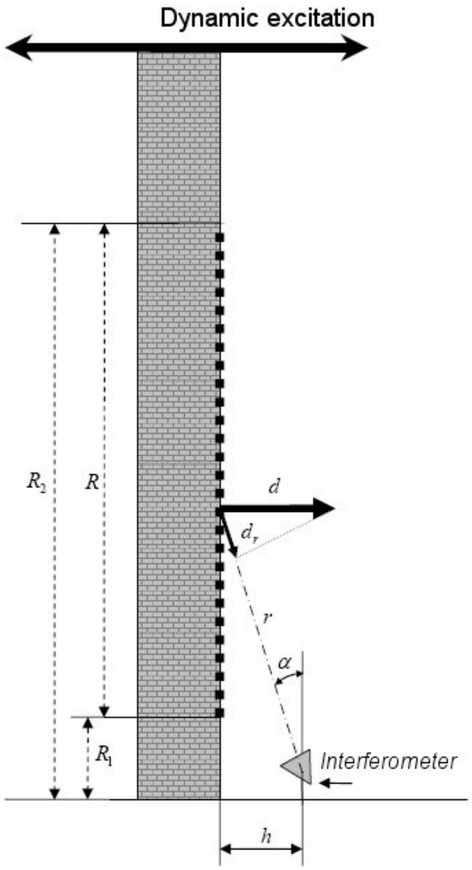

Figure 3. Scheme of displacement detection of several points of a tower by the interferometric radar technique.

The radar measure has been made positioning the instrument in the street side, in two distinct places to monitor i) the front side and ii) the right side behavior of the structure. The radar has been collocated at a distance equal to 19 meters from the base of the tower. The configuration of the radar sensor has been made following the parameters reported in Table 1.

Table 1. Parameters of configuration of the radar sensor.

Used band	400 MHz
Number of frequency steps	1333
Non-ambiguous range	500 m
Resolution in distance	0.40 m
Sampling frequency	70.7 Hz
Duration of measure	1220 s

4. Results and damage detection methodology

Existence of structural damage in an engineering system leads to modification of the vibration modes. These modifications are manifested as changes in the modal parameters (natural frequencies, mode shapes and modal damping values) which can be obtained from results of dynamic vibration testing[10,11]. The detection of the dynamic behaviour of the San Sepolcro tower has been conducted from the elaboration of the displacement signal, in real-time. The excitation of the structure has been provided by a light breeze in conjunction with the traffic (especially of buses) in the front street.

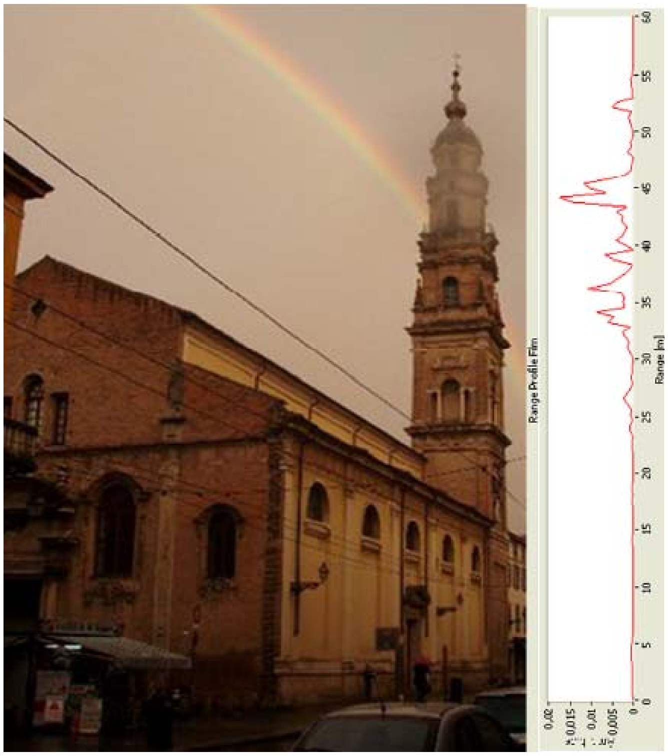

Figure 4. The San Sepolcro tower-bell and the peaks of displacement signal along its height.

The radar profile along the tower height is shown in Figure 4. The zero corresponds to the radar street level, the highest quota, at 52 meters, is the tower-bell tip (a round metallic ornament). Looking at Figure 4, it is possible to detect for each meaningful peak of the radar signal, a discontinuity in the structure profile, that can well reflect the radar microwaves.

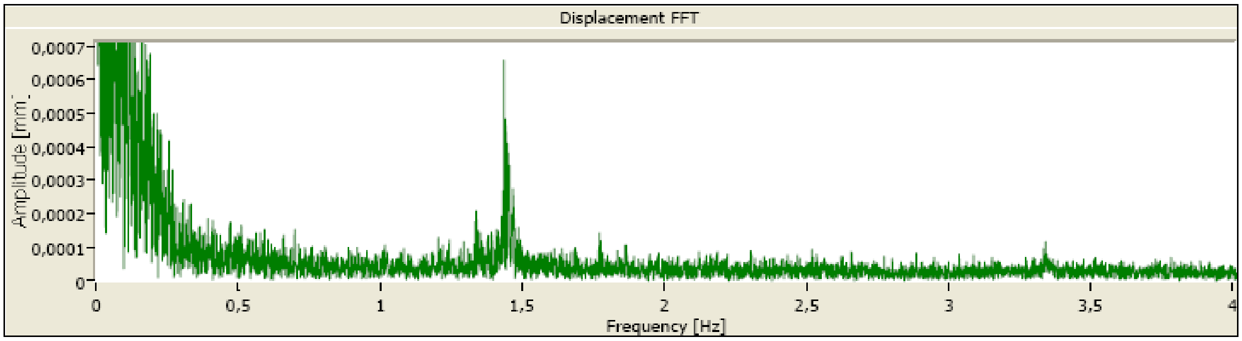

Figure 5. FFT of the displacement of the tower-bell tip at 44 m.

In Figure 5 the FFT of the displacement signal in time is presented. It has been elaborated in real-time by the acquisition system connected to the radar sensor. By a comparison with the FFT related to other points of the structure at different height, not shown here, it is possible to detect the resonance frequency of the first vibration mode of the tower-bell, at 1.44 Hz.

Now, monitoring the dynamic behaviour of the tower-bell during some years at regular intervals, any change of the modal parameters can be recorded. Changes in the modal parameters may not be the same for each mode since the changes depend on the nature, location and severity of the damage. This effect offers the possibility of using data from dynamic testing to detect, locate and quantify damage. Results of tests conducted at different times, possibly coinciding with principal or other scheduled inspections, actually offer the opportunity of monitoring changes in structural condition with time.

Abnormal loss of stiffness is inferred when measured natural frequencies are substantially lower than expected. Frequencies higher than expected are indicative of supports stiffer than expected[5]. It would be necessary for a natural frequency to change by about 5% for damage to be detected with confidence. However, significant frequency changes alone do not automatically imply the existence of damage since frequency shifts (exceeding 5%) due to changes in ambient conditions have been measured for both concrete and steel bridges within a single day[12].

Detection of damage using frequency measurements might be unreliable when the damage is located at regions of low stresses. Thus, a shift in natural frequencies alone might not provide sufficient information for integrity monitoring, unless the damage is in an important load bearing member. A theoretical explanation of the relationship between the magnitude of frequency changes and the extent of damage is given below. The existence of a crack at a section of a beam is equivalent to a reduction (proportional to the crack's severity) in the second moment of area. This leads to a reduction in the local bending stiffness at that cross-section. The modified beam can be represented as two beams connected by a torsional spring (which models the section) with a stiffness dependent on the depth of the crack. The consequence of reduced local bending stiffness is a lowering of the values of the natural frequencies in bending. The natural frequency changes vary proportionally with the square root of the stiffness change, thus underlining the need for relatively large stiffness changes before significant frequency changes can be detected. The reduction (in frequency) becomes more important when the crack is at regions of high curvature for the modes under consideration.

The equation of motion for a multi-degree-of-freedom structural system can be written in a state-space form as[7,8]:

$$\mathbf{A}\dot{\mathbf{y}} + \mathbf{B}\mathbf{y} = \mathbf{f}\,'(t) \tag{4}$$

where:

$$\mathbf{A} = \begin{pmatrix} \mathbf{C} & \mathbf{M} \\ \mathbf{M} & 0 \end{pmatrix} \qquad \mathbf{B} = \begin{pmatrix} \mathbf{K} & 0 \\ 0 & \mathbf{-M} \end{pmatrix} \tag{5}$$

and $\mathbf{y} = \left\{ \mathbf{x}(t) \quad \dot{\mathbf{x}}(t) \right\}^T$, $\mathbf{f}\,'(t) = \left\{ \mathbf{f}(t) \quad \mathbf{0} \right\}^T$. The vector $\mathbf{x}(t)$, $\dot{\mathbf{x}}(t)$ and $\mathbf{f}(t)$ denote the displacement, velocity and applied force respectively. The matrix **A** and **B** are the system block matrix, which consist of mass [**M**], stiffness [**K**] and damping matrix [**C**]. The homogeneous solution of eq. (4) is obtained by solving the eigenvalue problem:

$$\mathbf{B}\boldsymbol{\Phi}_{\mathbf{u}} = -\mathbf{A}\boldsymbol{\Phi}_{\mathbf{u}}\boldsymbol{\Lambda}_{\mathbf{u}} \tag{6}$$

where $\boldsymbol{\Phi}_{\mathbf{u}}$ and $\boldsymbol{\Lambda}\mathbf{u}$ are eigenvector and eigenvalue matrix respectively. Here, the subscript **u** denotes the undamaged state of the system. Structural damages are modelled as deviations or changes of mass, stiffness and damping coefficient. The changes will be defined as $\delta\mathbf{M}$, $\delta\mathbf{K}$, and $\delta\mathbf{C} \in \mathbb{R}^{N \times N}$, respectively. In these matrices, system connectivity should be maintained so that the solution is physically meaningful. Following the definition in eq. (5), the system matrices after damage become $\mathbf{A} + \delta\mathbf{A}$ and $\mathbf{B} + \delta\mathbf{B}$, where $\delta\mathbf{A}$ and $\delta\mathbf{B}$ denote the deviations of matrix **A** and **B** respectively, and are defined as:

$$\mathbf{A} = \begin{pmatrix} \delta\mathbf{C} & \delta\mathbf{M} \\ \delta\mathbf{M} & 0 \end{pmatrix} \qquad \mathbf{B} = \begin{pmatrix} \delta\mathbf{K} & 0 \\ 0 & \mathbf{-}\delta\mathbf{M} \end{pmatrix} \tag{7}$$

These two matrices are sparse matrices where the non-zero elements appear only at degrees-of-freedom that are associated with damage. Following eq. (6), the homogeneous solution at after-damage becomes:

$$(\mathbf{B} + \delta\mathbf{B})\boldsymbol{\Phi}_{\mathbf{d}} = -(\mathbf{A} + \delta\mathbf{A})\boldsymbol{\Phi}_{\mathbf{d}}\boldsymbol{\Lambda}_{\mathbf{d}} \tag{8}$$

where the subscript **d** denotes the after damage state. Equations (6) and (8) are both exact regardless of the number of measured modes, even when the number of measured modes (N_e) is less than the total number of DOFs, (N). Transposing Eq. (6) and post-multiplying the result by $\boldsymbol{\Phi}_{\mathbf{d}}$ afterwards yields:

$$\boldsymbol{\Phi}_{\mathbf{u}}^{\mathbf{T}}\mathbf{B}\,\boldsymbol{\Phi}_{\mathbf{d}} = \boldsymbol{\Lambda}_{\mathbf{u}}\boldsymbol{\Phi}_{\mathbf{u}}^{\mathbf{T}}(\mathbf{-A})\boldsymbol{\Phi}_{\mathbf{d}} \tag{9}$$

Now, pre-multiplying Eq. (8) by $\boldsymbol{\Phi}_{\mathbf{u}}^{\mathbf{T}}$ and subtracting from Eq. (6) leads to:

$$\boldsymbol{\Phi}_{\mathbf{u}}^{\mathbf{T}}\delta\mathbf{A}\boldsymbol{\Phi}_{\mathbf{d}}\boldsymbol{\Lambda}_{\mathbf{d}} + \boldsymbol{\Phi}_{\mathbf{u}}^{\mathbf{T}}\delta\mathbf{B}\boldsymbol{\Phi}_{\mathbf{d}} = \boldsymbol{\Lambda}_{\mathbf{u}}\boldsymbol{\Phi}_{\mathbf{u}}^{\mathbf{T}}\mathbf{A}\boldsymbol{\Phi}_{\mathbf{d}} - \boldsymbol{\Phi}_{\mathbf{u}}^{\mathbf{T}}\mathbf{A}\boldsymbol{\Phi}_{\mathbf{d}}\boldsymbol{\Lambda}_{\mathbf{d}} \tag{10}$$

One can see from Eq. (10), that there are two unknown matrices on the left hand side of the equation, $\delta\mathbf{A}$ and $\delta\mathbf{B}$. However, it can also be solved non-iteratively by employing some matrix algebra manipulations in such a way that the unknown matrix is transformed into a vector space so that the vector addition can be performed. Moreover, the mode shapes matrices $\boldsymbol{\Phi}_{\mathbf{u}}$ and $\boldsymbol{\Phi}_{\mathbf{d}}$ can take the form of rectangular matrices and therefore allows the technique to be applied to data from measurement with incomplete modal information.

5. Conclusions

1. Dynamic testing of large structures using interferometric radar appears a very attractive and promising tool for a number of reasons: it performs a remote NDT measurement, not requiring contact with the structure; the measuring technique is rapid and simple; the same portable instrument performs both static and dynamic tests, it can operate on in-service structures;
2. the monitoring of the dynamic behavior of a structure during some years, in conjunction with a methodology of damage assessment, is a powerful tool for the detection of the health status of ancient buildings.

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