A Microwave Radar Technique for Dynamic Testing of Large Structures

Massimiliano Pieraccini, *Associate Member, IEEE*, Guido Luzi, Daniele Mecatti, *Student Member, IEEE*, Linhsia Noferini, and Carlo Atzeni

***Abstract*—In this paper, the authors propose an innovative survey radar technique based on microwave holographic images for dynamic testing of large structures providing both vibration amplitude pattern and frequency. Theoretical background is provided and experimental results obtained during a dynamic test on a concrete and masonry building are reported.**

***Index Terms*—Large structure, microwave, nondestructive testing, radar, remote monitoring.**

I. INTRODUCTION

THE interest in damage identification and health monitoring of civil mechanical and aerospace structures at the earliest possible stage is pervasive throughout engineering communities. In recent years, great research effort has been devoted to development of monitoring techniques based on measured changes in dynamic properties of the structures under test [1]. Dynamic testing methods for damage detection are based on measured shift in natural frequencies and on modal changes of the structure under test [2], [3]. With respect to other methods, these techniques do not require that the vicinity of the damage is known *a priori* and that the portion of the structure being inspected is readily accessible.

The most popular types of sensors used for vibration testing are piezoelectric accelerometers [4] that are accurate, reliable, and relatively inexpensive. However, they must be mounted at appropriate locations that are representative of the structure motion, and access may be a problem. Mounting and wiring of accelerometers are typically the most difficult and most time-consuming task associated with the test. Furthermore, accelerometers give punctual information while a global knowledge of the deformation pattern is often desirable.

In 1999, Farrar *et al.* [5] proposed a microwave interferometer for noncontact measurements of vibration frequency in dynamic testing of structures. They were able to measure punctual vibration frequency with satisfactory performance, but without imaging capability.

A ground-based synthetic aperture radar (GB-SAR) technique has been recently proposed to image deformation maps of static displacements of a variety of structures, including concrete girders in a controlled environment [6], building models [7], dams [8], and bridges [9]. The fundamentals of this technique derive from synthetic aperture radar (SAR) interferometry for airborne or spaceborne remote-sensing applications [10]. In a ground-based arrangement, synthetic aperture can be obtained by scanning the antenna on a linear mechanical guide. The scan along the rail provides image spatial resolution in scan direction, range resolution is provided by range synthesis of the radar signal, and it depends on radar bandwidth.

In this paper, the authors propose an innovative survey radar technique, which exploit the GB-SAR to provide accurate measurement of both vibration amplitude pattern and frequency value during the dynamic test of a large structure. The physical principle of this technique is related to radar response of oscillating targets: if the acquisition time is longer than the vibration period, then the radar cross section of an oscillating target is affected by a reduction. Therefore, the amplitude vibration pattern of a scenario imaged by radar can be obtained by measuring the reduction in amplitude pixel by pixel in a radar image with respect to a reference image taken from the same point of sight in static conditions. This principle has been verified in a field test on a masonry structure subject to a steady-state vibration that has been produced by using a vibrodyne on the top of the structure.

II. RADAR IMAGE SYNTHESIS

This technique is based on a portable ground-based radar system that realizes a synthetic aperture moving an antenna along a linear mechanical guide [9], [11]. With reference to Fig. 1, the radar transmits continuous-wave step-frequency (CW-SF) waveform scanning a bandwidth $B = f_2 - f_1$ at increasing discrete values in a sweep time $t_{\rm sweep}$. At each frequency f_i, the instrumentation measures the in-phase (I) and quadrature (Q) components of the received signal; thus, a single measurement consists of a complex matrix $E_{i,n} = I_{i,n} + jQ_{i,n}$ of $N_f \times N_p$ values, with N_f number of frequencies and N_p number of positions along the scan length.

A synthetic radar image can be obtained from measurement matrix $E_{i,k}$ by coherently adding all signal contributions taken at a different frequency and position, taking in account their phase history [9], [11]. With this aim, a set of image points $\{\underline{R}_l\}$ with an R_l distance of the l-point from the central point of the linear scan has to be defined. These points could build a grid, as shown in Fig. 1, or could constitute a sparse set. In the latter

Manuscript received September 18, 2002; revised November 4, 2002. This work was supported under the Patrimonio Artistico: Ricerca e Nuove tecnologie Applicate allo Sviluppo Occupazionale Monitoraggio Architettonico e Ambientale mediante Tecnologie di Elaborazione Radar Project. This work was supported in part by the Italian Ministry of Scientific Research.

The authors are with the Department of Electronics and Telecommunications, University of Florence, 50139 Firenze, Italy (e-mail: pieraccini@det.unifi.it).

Digital Object Identifier 10.1109/TMTT.2003.810145

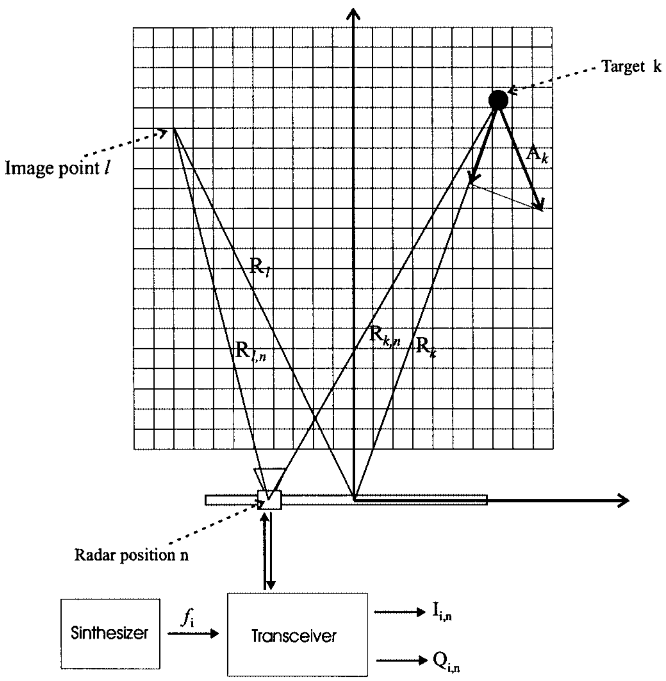

Fig. 1. Working principle.

case, they should be projected and interpolated on a planar grid in order to obtain a readable map. Therefore, the value of the complex radar image at point l (M_l) of the set $\{\underline{R}_l\}$ is

$$M_l = \frac{1}{N_f N_p} \sum_{n}^{N_p} R_{l,n}^2 F_{l,n} \tag{1}$$

$$F_{l,n} = \sum_{i}^{N_f} E_{i,n} \exp\left(j2k_i\left(R_{l,n} - R_{\text{inst}}\right)\right) \tag{2}$$

where $R_{l,n}$ is the distance between the image point l and the nth position on the rail. k_i is the wavenumber relative to the frequency f_i ($k_i = 2\pi f_i/c$ with c speed of light). In order to evaluate the constant R_{inst} (dimensionally a distance) that takes into account the RF system internal delay introduced by components and cables, it has to be noted that in a quasi-monostatic radar arrangement, $2R_0/c$ (dimensionally a time) is approximately the antenna coupling delay, which can be estimated directly from measured data. This delay is identified by a well-evident peak appearing in the inverse Fourier transform of a frequency sweep.

As the radar image is obtained through synthesis and sampling techniques, its characteristics are constrained by the radar measuring parameters: 1) bandwidth; 2) frequency step; 3) scan length; and 4) scan step.

In particular, the bandwidth B is related to range resolution Δr by

$$B = \frac{c}{2\Delta r} \tag{3}$$

with c being speed of light. In practice, 500 MHz of bandwidth could be used for achieving a range resolution of 0.3 m, which is widely satisfactory in engineering. Furthermore, the observed scenario can be correctly represented only within an unambiguous range R_U related to the frequency step $\Delta f = B/N_f$ by

$$\Delta f = \frac{c}{2R_U}. \tag{4}$$

A reasonable practical rule is to take Δf as to obtain an unambiguous range R_U twice the distance of the farthest target the radar can detect.

The expected angular resolution $\Delta\vartheta$ is related by scan length L so the latter can be set by using the following approximate relationship [12]:

$$L \geq \frac{c}{2f_c \Delta\vartheta} \tag{5}$$

where $f_c = (f_1 + f_2)/2$ is the central frequency. Finally, the scan step (Δx) must be small enough to not produce angular ambiguity in the radar image [12]:

$$\Delta x \leq \frac{c}{2f_c \sin(\vartheta_A)} \tag{6}$$

where ϑ_A is the half-aperture of antenna radiation lobe. A prudential rule is to take $\vartheta_A = \pi/2$. For example, to obtain 0.5 m of cross-range resolution at 10-m distance, using a radar system working at 5.75 GHz, it is necessary to scan an aperture of at least 0.5 m, with steps not exceeding 26 mm.

III. Theory and Processing Methods

Let a set of targets be vibrating at frequency $f^{(v)}$. In general, each target k is vibrating with a different amplitude vector $\underline{A}_k$. The vibration phase is constituted by the sum of two terms: the first, i.e., ϕ_n, is a constant value for all targets in the radar scene, and depends on the initial instant of the frequency sweep at the nth radar position; the latter, i.e., ϕ_k, is different for each target and depends on mechanical constraints between the target points: e.g., in a rigid scenario $\phi_k = 0$ for all targets. The received measured signal at the ith frequency at the nth position is

$$\begin{aligned} E_{i,n}^{(v)} = C \sum_k S_k \cdot \exp\Bigg(-j2k_i \Bigg(R_{k,n} + \frac{\underline{A}_k \cdot \underline{R}_{k,n}}{R_{k,n}} \cdot \sin\left(\omega^{(v)} t_{\text{sweep}} \frac{f_i - f_1}{B} + \phi_n + \phi_k\right) + R_{\text{inst}}\Bigg)\Bigg) \end{aligned} \tag{7}$$

where C is an instrumentation constant, S_k is the complex reflection coefficient of the kth target, f_i is the ith radar frequency, $R_{k,n}$ is the distance from the kth target to the nth antenna position, $\omega^{(\nu)}$ is the vibration angular frequency, and R_{inst} is an additional path introduced by cables and instrumentation.

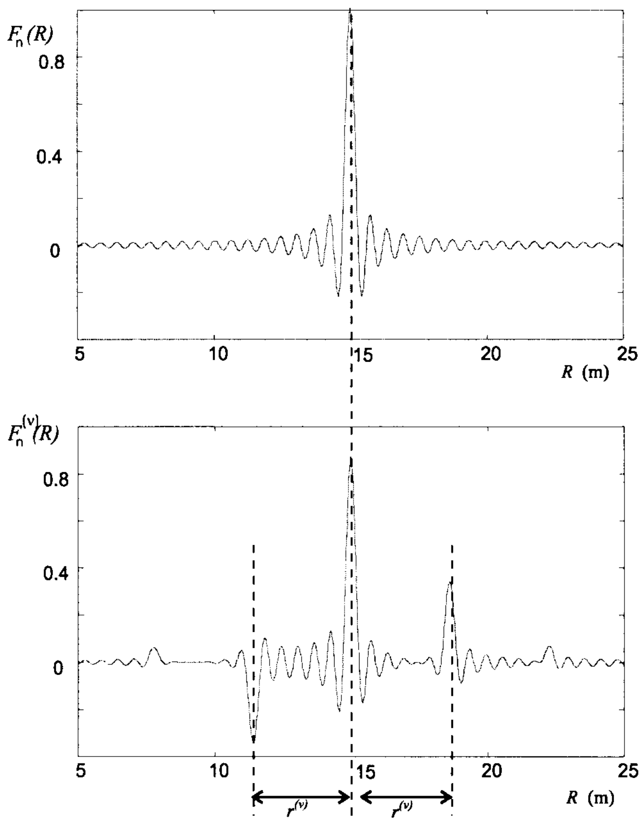

Fig. 2. Theoretical static and dynamic range response of a single target.

Equation (7) can be viewed as an FM of the microwave carrier caused by the vibration frequency $f^{(v)}$, thus, its Fourier transform can be written as

$$F_n^{(v)}(R) = C \sum_k \sum_{m=-\infty}^{m=\infty} S_k \cdot \exp\left(-j\left(2k_c R_{k,n} + m\left(\phi_n + \phi_k\right)\right)\right) J_m(\beta) \cdot \operatorname{sinc}\left(\frac{2B}{c}\left(R - R_{k,n} - mr^{(\nu)}\right)\right) \quad (8)$$

$$\beta = 2k_c \frac{\underline{A}_v \cdot \underline{R}_{k,n}}{R_{k,n}} \quad (9)$$

$$r^{(\nu)} = \frac{ct_{\text{sweep}} f^{(\nu)}}{2B} \quad (10)$$

where $J_m(\beta)$ is the Bessel function of mth order, k_c and ω_c are the central wavenumbers, and β is the modulation index.

For example, if we consider a scenario constituted by a single scattering center (the kth center) at a distance of 15 m from the radar ($R_{k,n} = 15$ m), the resulting Fourier transform $F_n(R)$ of the radar response relative to the static target and the Fourier transform $F_n^{(\nu)}(R)$ of the radar response of the vibrating target, both normalized with respect to $CS_1 \exp(-j2k_c R_{k,n})$, appear as shown in Fig. 2.

As an effect of vibration, the signal relative to the target decreases of a factor equal to the zeroth-order Bessel function of β. Furthermore, a symmetric set of secondary peaks appears at distances $R_k + mr^{(\nu)}$ with an m integer. The amplitudes of these secondary peaks are proportional to the mth-order Bessel function of β.

For $\beta \ll 1$, the secondary peaks are negligible. For greater values of β, secondary peaks appear at fixed positions depending on the vibration frequency, swept bandwidth, and sweep time. However, as the amplitude of the main peak is again given by the zeroth-order Bessel function, if the main peaks are well distinguishable from the secondary peaks, then the technique is again applicable. Main and secondary peaks are well separated, for example, by setting t_{sweep} and B in such a way that $r^{(\nu)}$ is bigger than the range dimension of the large structure, thus, secondary peaks appear in a zone of the radar image where there are not any targets. As the main peak decreases of a factor equal to the zeroth-order Bessel function of β, the vibration amplitude of a target positioned at distance $R_{k,n}$ from the radar can be evaluated by the following relationship:

$$\left|\frac{\underline{A}_k \cdot \underline{R}_{k,n}}{R_{k,n}}\right| = \frac{1}{2k_c} J_0^{-1}\left(\left|\frac{F_n^{(v)}(R_{k,n})}{F_n(R_{k,n})}\right|\right). \quad (11)$$

It is of note that this radar technique is able to measure only the vibration amplitude component in the range direction. Theoretically, for measuring the effective amplitude and direction of the vibration, it is necessary to perform almost three measurements by different points-of-view, but, in most practical cases, simple static and geometrical considerations allow the measured vibration amplitude at each point in the structure to be related to the actual displacement.

Furthermore, as vibration frequency is obtained by a sampling technique, it should be noted that the frequency stepping in the radar setting has to obey the sampling theorem

$$\frac{N_f}{2t_{\text{sweep}}} > f^{(\nu)} \quad (12)$$

and the measurement resolution $\Delta f^{(\nu)}$ is given as the following:

$$\Delta f^{(\nu)} = \frac{1}{t_{\text{sweep}}}. \quad (13)$$

In order to evaluate the vibration amplitude of a structure under test, two radar images have to be synthesized by using (1) and (2): a reference image of the structure in static state $\{M_l\}$ and an image of the vibrating structure $\left\{M_l^{(\nu)}\right\}$. The amplitude is obtained by applying the following relationship to the pixel-by-pixel ratio between the two images:

$$\left|\frac{\underline{A}_l \cdot \underline{R}_l}{R_l}\right| = \frac{1}{2k_c} J_0^{-1}\left(\left|\frac{M_l^{(v)}}{M_l}\right|\right). \quad (14)$$

The vibration frequency of an excited structure is an important value to be measured during a dynamic test. This can be straightforwardly obtained by calculating the Fourier transform of the phase of the measured response in time normalized with respect

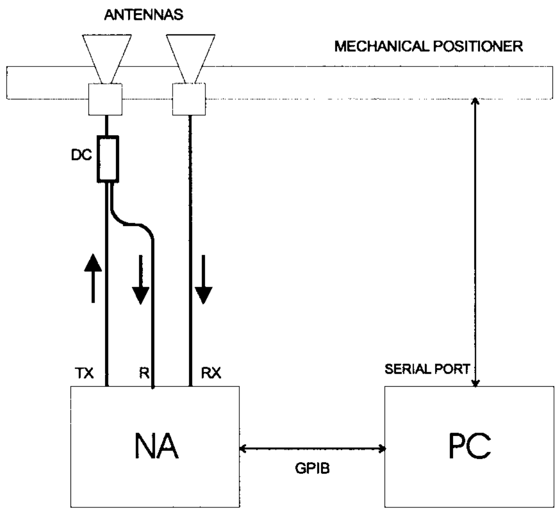

Fig. 3. Block scheme of the radar prototype. DC: directional coupler. NA: network analyzer. TX: transmitting channel. RX: receiving channel. R: reference channel. PC: personal computer.

TABLE I
MEASUREMENT PARAMETERS

Linear scan length (L)	2.00 m
Linear scan point number (N_p)	161
Number of frequencies (N_f)	1601
Central frequency (f_c)	5.75 GHz
Bandwidth (B)	500 MHz
Sweeping time (t_{sweep})	20 s
Polarization	VV
Half Power Beam Width (HPBW)	15°
Antenna gain	14 dB
Microwave power	20 dBm

to the instantaneous microwave frequency. The averaged spectral distribution can be calculated as

$$G(\omega) = \sum_{i,n} \left| \exp\left(-j\omega \frac{t_{\text{sweep}}}{N_f - 1} i\right) \frac{1}{2k_i} \arg\left(E_{i,n}^{(v)} \big/ E_{i,n}\right) \right|. \tag{15}$$

Since the vibration frequency is the same for all vibrating points in the scenario, $G(\omega)$ will exhibit a well evident peak at the vibration frequency $\omega^{(v)}$.

It should be noted that (15) does not require any hypothesis about the motion, in effect, it can also be applied for detecting the natural frequencies of a large structure excited by a large spectrum stimulus such as wind or a single pulse.

IV. Radar System and Experimental Results

A CW-SF radar according to the specifications can be designed using several architectures and different technologies [13], [14]. In this study, with the aim to verify the working principle, a laboratory prototype based on a network analyzer (HP 8753D), which operated as a coherent microwave transceiver, with a couple of horn antennas with 15° of half-power beamwidth (HPBW) mounted on a linear mechanical guide of 3-m length, was used.

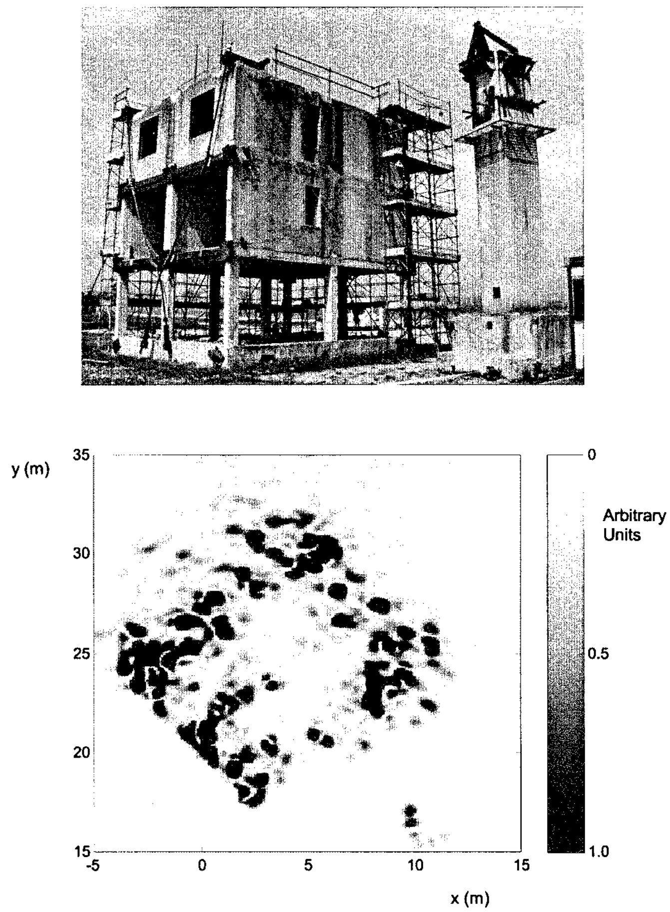

Fig. 4. Picture of the structure and radar image acquired through a horizontal scan.

Fig. 3 shows the block scheme of the radar instrumentation. A directional coupler before the transmitting antenna provided the reference signal to the network analyzer. A personal computer controlled both the network analyzer by a general-purpose interface bus (GPIB) link and the mechanical guide by the serial port.

The radar technique described above has been tested in the laboratories of the ENEL.HYDRO–ISMES Company, Bergamo, Italy. The test facility consisted of a three-storey masonry and concrete frame 10 m in height, 9 m in width, and 8 m in depth. A vibrodyne was positioned on the top floor in order to force a controlled horizontal vibration. The radar system was positioned at approximately 18-m distance. The mechanical guide was both horizontally and vertically oriented to obtain radar images with resolution in the horizontal and vertical planes, respectively. Eight accelerometers were located at the girder–column joints.

First, a radar acquisition of the static scenario was performed according to measurement parameters in Table I with the mechanical guide horizontally positioned.

Fig. 4 shows a picture and the radar image of the structure. The picture is taken from the point-of-view of the radar installation. In the radar image, several features are recognizable, i.e., the corner of the vertical metallic column, the four external

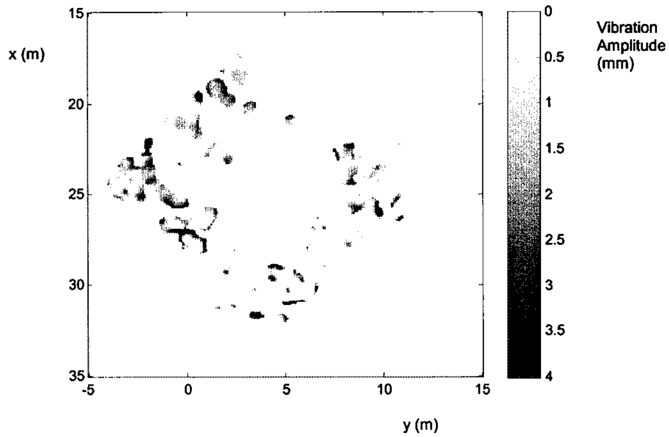

Fig. 5. Vibration amplitude map obtained through a horizontal antenna scan during the test at 2.85 Hz.

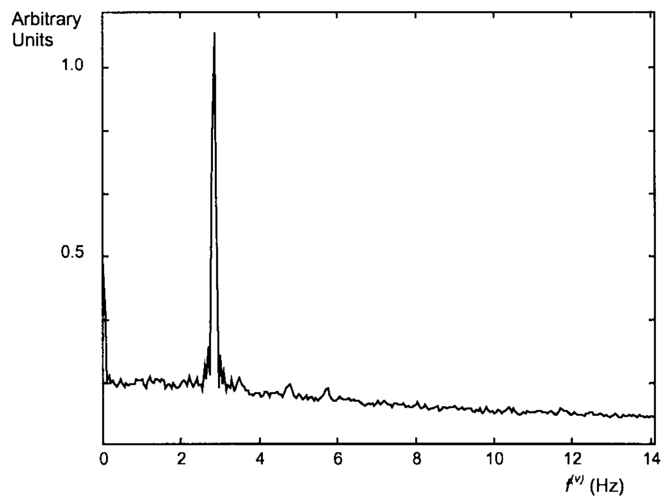

Fig. 6. Measured vibration frequency spectrum for the test at 2.85 Hz.

walls, and an internal wall. The coordinate system has its origin in the center of the mechanical guide. The amplitudes in the radar image are linear grayscale coded. It should be noted that, as this radar image is obtained through a horizontal scan, it has no synthetic resolution in the z-direction and each pixel in the image is relative to the entire aperture in the z-direction of the antenna lobe (15° of HPBW) that pointed the half-height of the structure.

Afterwards, the structure was excited at 2.85-Hz vibration frequency by the vibrodyne, and a radar acquisition of the scenario in dynamic steady state was carried out. From the pixel-by-pixel ratio between the static and dynamic images, the amplitude pattern image shown in Fig. 5 was obtained.

The mean amplitude was 1.33 mm to be compared with 1.15-mm vibration amplitude measured by the accelerometers installed at the height of the first floor. The vibration frequency has been measured using (15). From the spectral plot in Fig. 6, the peak at 2.85 Hz is well evident; this value is exactly the same as measured by the accelerometers installed on the structure.

A further test has been performed by vertically positioning the radar mechanical guide. Fig. 7 shows the radar image and a picture of the structure.

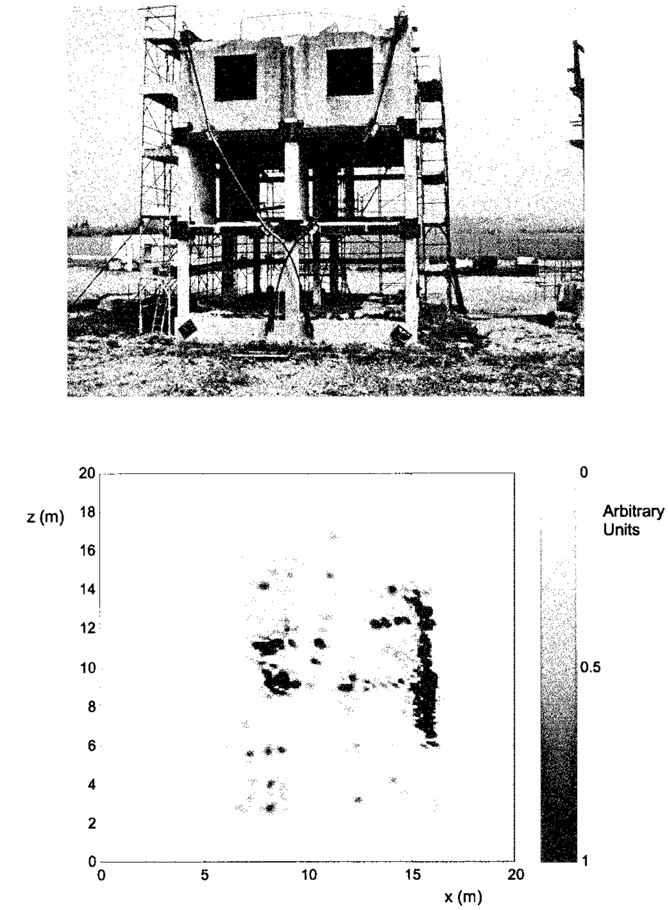

Fig. 7. Picture of the structure and radar image acquired through a vertical scan.

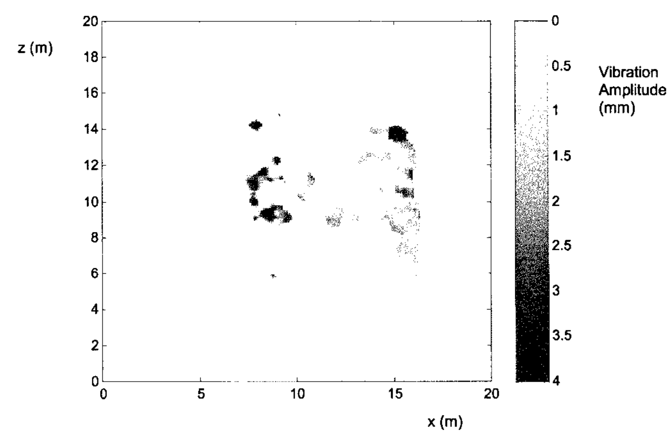

Fig. 8. Vibration amplitude map obtained through a vertical antenna scan during the test at 2.45 Hz.

The radar was positioned in front of the right-hand-side wall in the picture. The radar pointed the half-height of the structure. There is a close correlation between the features in the radar image and the features in the picture. It has to be particularly noted that internal floors and the wall on the opposite side with respect to the radar installation are clearly detected.

After a radar acquisition of the structure excited at 2.45 Hz, the amplitude pattern image showed in Fig. 8 is obtained. The mean vibration amplitude resulted of 1.83 mm to be compared

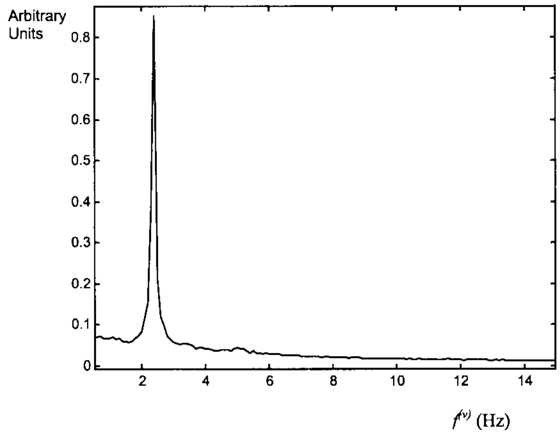

Fig. 9. Measured vibration frequency spectrum for the test at 2.45 Hz.

with 1.79-mm vibration amplitude measured by the accelerometers positioned on the girder at the height of the first floor.

Finally, the spectral plot shown in Fig. 9 relative to the latter acquisition exhibits a sharp peak at 2.45 Hz, which is exactly the same measured by the accelerometers installed on the structure

V. Conclusion

Microwave radar holography appears to be an effective technique for dynamic testing of engineering structures. This remote-sensing technique provides effective mapping of the dynamic response of large structures. Furthermore, intra-wall penetrating capability of microwaves allows vibrations of parts not directly visible from the radar equipment position to be detected as well. Even though at the state-of-the-art this instrument does not achieve the accuracy and reliability of the conventional contact sensors, it can monitor inaccessible structures and can also be rapidly installed in emergency situations.

Acknowledgment

The authors gratefully acknowledge the valuable technical support of Dr. G. Franchioni and Dr. L. Carissimi, both of the ENEL.HYDRO–ISMES Company, Bergamo, Italy.

References

[1] S. W. Doebling, C. R. Farrar, M. B. Prime, and D. W. Shevitz. (1996) Damage identification and health monitoring of structural and mechanical systems from change in their vibration characteristics: A literature review. Los Alamos Nat. Lab., Los Alamos, NM. [Online]. Available: Report LA-13070-MS. [Online]. Available: http://lib-www.lanl.gov/.

[2] J. M. Lifshitz and A. Rotem, “Determination of reinforcement unbonding of composites by a vibration technique,” *J. Composite Mater.*, vol. 3, pp. 412–423, 1969.

[3] G. Hearn and R. B. Testa, “Modal analysis for damage detection in structures,” *J. Struct. Eng.*, vol. 117, no. 10, pp. 3042–3063, 1991.

[4] J. Dunnicliff, *Geotechnical Instrumentation for Monitoring Field Performance*. New York: Wiley, 1988.

[5] C. R. Farrar, T. W. Darling, A. Migliorini, and W. E. Baker, “Microwave interferometer for noncontact vibration measurements on large structures,” *Mech. Syst. Signal Processing*, vol. 13, no. 2, pp. 241–253, 1999.

[6] D. Tarchi, E. Ohlmer, and A. Sieber, “Monitoring of structural changes by radar interferometry,” *Res. Nondestructive Evaluation*, no. 9, pp. 213–225, 1997.

[7] D. Tarchi, H. Rudolf, M. Pieraccini, and C. Atzeni, “Remote monitoring of buildings using a ground-based SAR: Application to cultural heritage survey,” *Int. J. Remote Sensing*, vol. 21, no. 18, pp. 3545–3551, 2000.

[8] D. Tarchi, H. Rudolf, G. Luzi, L. Chiarantini, P. Coppo, and A. J. Sieber, “SAR interferometry for structural changes detection: A demonstration test on a dam,” in *Int. Geoscience and Remote Sensing Symp.*, vol. 3, 1999, pp. 1522–1524.

[9] M. Pieraccini, D. Tarchi, H. Rudolf, D. Leva, G. Luzi, G. Bartoli, and C. Atzeni, “Structural static testing by interferometric synthetic radar,” *NDT&E Int.*, vol. 33, no. 8, pp. 565–570, 2000.

[10] P. A. Rosen, “Synthetic aperture radar interferometry,” *Proc. IEEE*, vol. 88, pp. 333–382, Mar. 2000.

[11] M. Pieraccini, G. Luzi, and C. Atzeni, “Terrain mapping by ground-based interferometric radar,” *IEEE Trans. Geosci. Remote Sensing*, vol. 39, pp. 2176–2181, Oct. 2001.

[12] D. L. Mensa, *High Resolution Radar Cross Section Imaging*. Norwood, MA: Artech House, 1991.

[13] M. Pieraccini, G. Luzi, D. Mecatti, L. Noferini, and C. Atzeni, “A high frequency penetrating radar for masonry investigation,” presented at the 9th Int. Ground Penetrating Radar Conf., Santa Barbara, CA, Apr. 29–May 2, 2002.

[14] S. K. Koppenjan, C. M. Allen, D. Gardner, H. R. Wong, H. Lee, and S. J. Lockwood, “Multi-frequency synthetic-aperture imaging with a lightweight ground penetrating radar system,” *J. Appl. Geophys.*, vol. 43, pp. 251–258, 2000.

Massimiliano Pieraccini (A’01) received the degree in physics and the Ph.D. degree in nondestructive testing from the University of Florence, Firenze, Italy, in 1994 and 1998, respectively.

In 1995, he joined the Department of Electronics and Telecommunications, University of Florence, where, since 1997, he has been a Researcher. He has taught “Electronics I” and “Electronics for Telecommunications” with the Engineering Faculty, University of Florence. He has been Research Manager for a number of research projects in the field of radar applications founded by the Ministry of Research and the National Research Council. He has authored several papers published in international journals. He holds three patents. His research interests include opto-electronic sensors, ultrasound transducers, SAR, and ground penetrating radar (GPR).

Dr. Pieraccini was the recipient of the Nello Carrara Degree Prize.

Guido Luzi received the degree in applied physics from the University of Florence, Firenze, Italy, in 1986.

He is currently with the Department of Electronics and Telecommunications, University of Florence, where he is involved in the design and experimentation of radar-based sensing techniques for cultural heritage and environmental monitoring. He has dedicated his research activity to the development and experimentation of electromagnetic sensing techniques. He has taken part in numerous international remote sensing campaigns (e.g., AGRISCATT, AGRISAR, MACEUROPE) concerning active and passive microwave sensors. He has investigated innovative applications of microwave radiometry within European Programs (e.g., EPOC, MEDALUS, ENVIRONMENT) and has focused his interest toward geophysical and civil applications. He has authored or coauthored several papers concerning the above investigated topics.

Daniele Mecatti (S’01) was born in Florence, Italy, in 1974. He received the degree in electronic engineering from the University of Florence, Firenze, Italy, in 2001, and is currently working toward the Ph.D. degree at the University of Florence.

He is currently working under the framework of the Patrimonio Artistico: Ricerca e Nuove tecnologie Applicate allo Sviluppo Occupazionale Monitoraggio Architettonico e Ambientale mediante Tecnologie di Elaborazione Radar (PARNASO-MATER) Project. He is involved with SAR, interferometric radar techniques, and on GPR prototypes development.

Mr. Mecatti is a member of the IEEE Geoscience and Remote Sensing Society.

Linhsia Noferini was born in Florence, Italy, in 1973. She received the degree in physics from the University of Florence, Firenze, Italy, in 1999, and is currently working toward the Ph.D. degree in electronic engineering.

Her research activity is mainly concerned with applications of interferometric SAR and GPR with an emphasis on the processing of acquired data.

Carlo Atzeni has been a Full Professor of microelectronics with the University of Florence, Firenze, Italy, since 1980. Prior to this, his experience included 15 years of activity with the Istituto di Ricerca sulle Onde Elettromagnetiche (IROE), The National Research Council, Florence, Italy. In 1980, he was awarded a full university professorship in both telecommunications and electronics, for which he opted for the latter chair. From 1993 to 1999, he was Director of the Department of Electronics and Telecommunications, University of Florence. His scientific activity has been mainly concerned with signal-processing techniques and devices, with emphasis on imaging systems, particularly based on microwave and ultrasound, with application to radar and medical diagnostics. He has recently organized an important research project in the frame of the Ministero dell'Università e della Ricerca Scientifica e Tecnologica Patrimonio Artistico: Ricerca e Nuove tecnologie Applicate allo Sviluppo Occupazionale (MURST PARNASO) Program for application to cultural heritage concerning remote monitoring and control of architectural heritage by means of microwave interferometry techniques. He established the Laboratory of Technology for Cultural Heritage, Florence, Italy, where he has developed pilot projects of high-quality digital tridimensional acquisition of famous masterpieces such as the "Maddalena" by Donatello and the "Adorazione dei Magi" by Leonardo Da Vinci.