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***Abstract*—To facilitate Guided Waves (GWs) communication in terms of hardware simplification and cost reductions, shaped transducers with inherent directional properties can be used. A promising example of such devices is provided by Frequency Steerable Acoustic Transducers (FSATs), where the propagation direction of waves is controlled by the frequency content of the transmitted/acquired signals, thanks to the spatial filtering effect. These peculiar characteristics make the FSAT devices particularly suited for implementation of frequency-based modulation protocols, in which the signal content assigned to each user is uniquely encoded by a corresponding carrier tone. In this work, the special directivity of FSATs is paired with a novel encoding strategy, which is based on a combination of Chirp Spread Spectrum (CSS) and Frequency Hopping (FH) multiplexing, similar to the LoRaWan solution adopted in radio-frequency environments. The devised strategy is aimed at suppressing the inherent destructive interference due to GWs dispersion and multi-path fading.**

***Index Terms*—Acoustic Data Communications, Chirp Spread Spectrum, Frequency Hopping, Frequency Steerable Acoustic Transducers**

I. Introduction

Ultrasonic testing based on Guided Waves (GWs) offers the opportunity to perform a punctual inspection of wide areas by leveraging their peculiar capability to be scattered by (internal and external) damages [1], while being confined by the boundaries of the mechanical medium in which they propagate [2]. Conventional GW–based structural health monitoring systems commonly comprise a distributed array of transducers installed on the inspected structure and used either for actively generating or passively sensing he elastic waves. However, the dimensions, costs, and weight of the commercial electronic equipments used for this purpose are typically not compliant with long–term functionalities and permanent installation. To address these issues, the design of a new generation of devices suitable for near—sensor and in-hardware GW signal processing has recently been fostered, which are equipped with custom actuation capabilities. The same devices are also capable of exchanging data without the need of additional cables, radio–frequency modules and/or external bulky instrumentation because the mechanical waveguide itself acts as the communication channel, while GWs are exploited as information carriers. In this perspective, the transmitted signals allow for the pursuit of a twofold purpose: (i) probing the inspected structures and, after local elaboration executed directly by the sensor board, (ii) communicating the results of the inspection itself. This feature is particularly desirable in harsh environments, where light propagation is very poor or sometimes impossible and, thus, standard electromagnetic waves cannot propagate.

According with this joint communication–monitoring perspective, the spatial multiplexing capability of Frequency Steerable Acoustic Transducers (FSATs) is exploited in this work and combined with a novel communication protocol based on spread spectrum techniques to counteract the complexities hidden in GWs propagation and those associated with multi–path fading. Noteworthy, the proposed encoding technique represents a total novelty in acoustic data communication and only a very few attempts can be found in the literature in which wideband modulation strategies are applied for the same purposes. This is the case of [2], which proves the feasibility of direct spread spectrum encoding mechanisms by transmitting data over a slender aluminum beam. Similarly, frequency hopping–based solutions are accounted in [3] to improve reliability of underwater communication systems.

The paper is organized as follows. In Section II, the underpinning principles behind FSATs are introduced, while a description of the proposed encoding mechanism is outlined in Section III. A numerical case study focused on GW–driven data communication across a metallic plate is presented in Section IV. Conclusions are finally drawn.

II. Frequency Steerable Acoustic Transducers

In previous works [4], [5], it has been shown that the voltage generated by an arbitrary shape patch in which the

GW propagates at angle θ can be calculated as follows:

$$V_p(\omega) = jU(\omega)K_0(\omega)H(\theta)D_p(\omega,\theta) \quad (1)$$

Among these quantities, θ indicates the direction of arrival of the incident wave mode, $U(\omega)$ denotes the amplitude of the wave mode at the angular frequency ω, H stands for the material properties of the piezostructure system, K_0 represents the wavenumber that describes the propagation, and D is the directivity function, which can be calculated as:

$$D_p(\omega,\theta) = \int_{\Omega_P} f(x)e^{-jk_0(\omega).x}d\Omega \quad (2)$$

with $f(x)$ being the load distribution function that represents the shape and polarization of the transducer. Eq. (2) expresses the 2-D Fourier Transform (FT) of the function $f(x)$ that allows the estimation of FT pairs and the calculation of the directivity patterns for different transducer shapes. Therefore, it is advantageous to determine first the desired directivity function in D and then employ the FT to generate a corresponding transducer geometry that achieves this directional behavior. By solving the elasto-dynamic equations of motion for harmonic wave propagation, it has been also proved in [6] that the maximum displacement output can be reached at wavenumber k^* where the load distribution intersects the medium's dispersion relation, and this determines the direction in which the wave propagates.

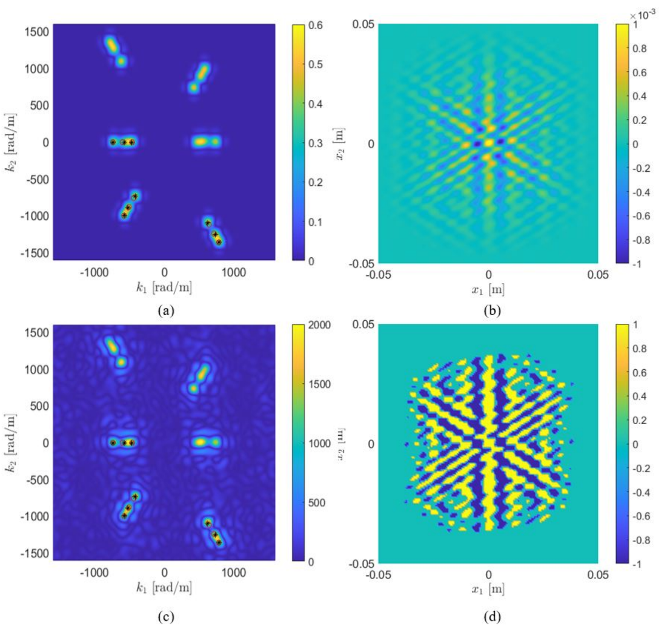

Fig. 1: FSAT design procedure: a) the load distribution in the wavenumber domain b) associated spatial distribution c) and d) effect of the quantization procedure on distributions (a) and (b)

A discrete directivity function has been considered in this paper for wave propagation at three different angles. As shown in Fig. 1a, the transducer is designed in the wavenumber domain first, considering three different excitation frequencies at

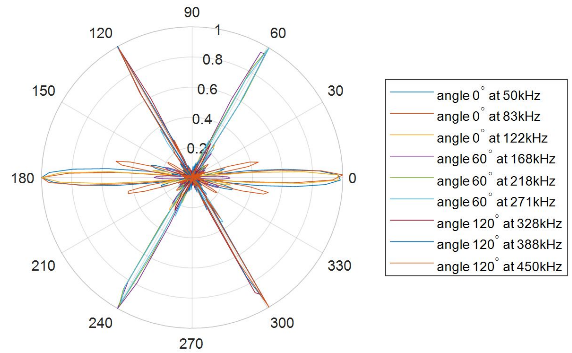

Fig. 2: Normalized directivity patterns at different frequencies.

each chosen direction. Accordingly, the load distribution $f(x)$ has been quantized by means of a specific threshold which is necessary to counteract the problem due to continuously modulated amplitude that would have been required when computing the geometry directly via the FT (Fig. 1b). The thresholding function is defined in this way: it assumes value $+1$ when $f \geq \epsilon$, 0 when $|f| < \epsilon$, and -1 for $f \leq -\epsilon$. In Fig. 1d, the final geometry obtained after quantization is displayed. The normalized radiation patterns corresponding to the directivity function described above are shown in Fig. 2. As can be seen, three different subbands co-exists in each of the three directions, the latter corresponding to 0° (50, 83, 122 kHz), 60° (168, 218, 271 kHz), 120° (328, 388, 450 kHz).

III. A novel Spread Spectrum–based modulation technique

Spread Spectrum techniques are conveniently exploited in the standard radio communication context thanks to their inherent robustness to interference and jamming, which are amidst the most critical factors hampering the proper transmission capabilities in multi–user propagation environments. These strategies are superior in that they can achieve comparatively higher transmission rates by spreading the frequency content of the transmitted signal over a larger bandwidth, while maintaining the same power spectrum [7]. Among the different kinds of spreading mechanisms, two strategies are particularly promising for GWs–based applications thanks to their high channel noise immunity and implementation via low–power electronics: *i*) Frequency Hopping (FH) solutions, which make use of rapid and pseudo-random variations of the carrier frequency according with a determined jumping pattern [8]; *ii*) Chirp Spread Spectrum (CSS), where the spreading operation is performed by means of wideband linear chirp-modulated pulses [9].

In this work, a novel modulation approach built on the combination of the above discussed modulation techniques is proposed to maximize the performances of acoustic data communication, hence designing a solution (hereinafter called as CSS+FH) which is superior in that: *i*) it takes advantage of the full bandwidth exploitation and high resistance to multi–

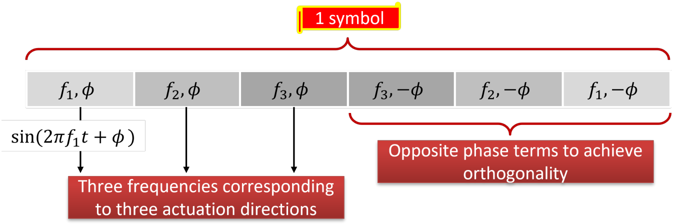

Fig. 3: Symbol structure according with the novel CSS+FH communication protocol

path fading of CSS (including reflections from the mechanical medium and reverberations), and *ii*) it provides high resistance to narrowband interference and sniffing thanks to the pseudo-randomness typical of FH.

A. The CSS+FH encoding protocol

The proposed encoding procedure leverages the directional properties of FSAT transducers. Indeed, each of the possible symbols to be transmitted (whose general structure is depicted in Fig. 3) is constructed by switching, in time, the carrier frequency of the signal; this modulating tone can be selected among three different values f_1, f_2, and f_3 corresponding to as many actuation directions. More in detail, every symbol consists of six different time slots (corresponding to five different frequency switches), in which the last three intervals have the same spectral content (but opposite phase) of the first three ones, a property which is necessary to allow for maximum orthogonality (i.e., minimum inter-symbol interference). Moreover, given that all the time slots have share the same duration, the sampling frequency has to be selected as the least common multiple between the three carriers. In this sense, each symbol globally replicates the working principle of FH, since the transmission of one single piece of information depends on the cascade of five different frequency hops, and it implements this by increasing (or decreasing) in time the frequency content, as it is required by CSS.

The entire dictionary of orthogonal symbols can be generated by 1) randomly shuffling the hopping pattern, namely by using a different frequency sequence (e.g., $[f_1 f_2 f_3]$, $[f_2 f_3 f_1]$), and 2) applying orthogonal (i.e., $\phi = k45°$, $k \in \mathbb{Z}$) phase rotations to the sinusoidal tones employed in every time slot.

IV. Numerical Validation

A. Materials and methods

As a proof–of–concept showing the suitability of the devised CSS+FH encoding mechanism for GWs–based communication in conjunction with directional transducers, the transmission of different symbol across an aluminum square plate (dimensions $1000 \times 1000 \times 3$ mm) has been simulated via a plane–wave model which replicates the spatial multiplexing capability of FSAT devices.

The deployment plan corresponds to the one schematically shown in Fig. 4, in which one FSAT actuator has been located in the proximity of the bottom–left corner and communicates

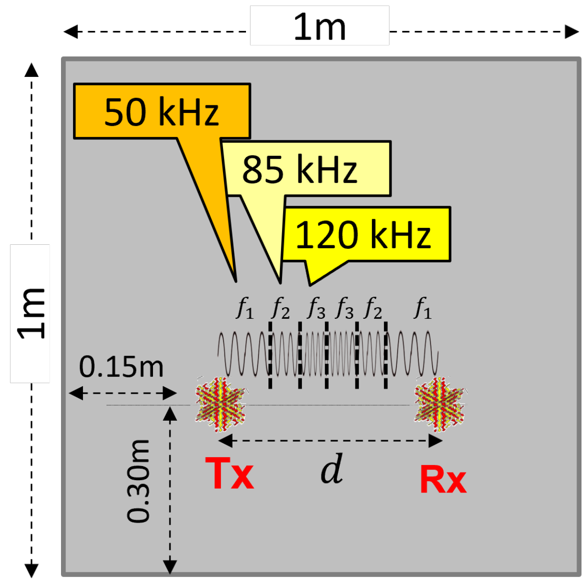

Fig. 4: Considered testbed for numerical validation.

with a second FSAT receiver placed at a distance d, along the 0° direction of Fig. 2: the latter quantity was varied from $0.2\,\mathrm{m}$ to $0.6\,\mathrm{m}$ with a constant step of $0.2\,\mathrm{m}$ to take into consideration the GW attenuation due to increasing propagation lengths. Similarly, the effects of inter–symbol interference (ISI) and those associate to channel noise were evaluated. To assess the first aspect, messages of different duration $L \in \{40, 100, 500\}$ were generated, while working on two noise–related configurations: one characterized by a favourable Signal–to–noise ratio (SNR) of $45\,\mathrm{dB}$, whereas the second one is affected by a SNR = $3\,\mathrm{dB}$ to replicate very poor propagation environments, as it might be the case in practical applications.

The three different frequencies were selected to be coincident with $f_1 = 50\,\mathrm{kHz}$, $f_2 = 85\,\mathrm{kHz}$, $f_3 = 120\,\mathrm{kHz}$, i.e., as much proximal as possible to the ones in the 0° direction, while the sampling frequency was set equal to $1.7\,\mathrm{MHz}$. A dictionary of 24 symbols was generated at a bit–rate of $5.7\,\mathrm{ksym/s}$, using the following frequency sequences $[f_1 f_2 f_3]$, $[f_2 f_3 f_1]$, $[f_3 f_1 f_2]$ and phase rotations of $\phi \in \{45°, 135°, 90°, 180°\}$. In Fig. 5, a spectrogram showing the time–frequency representation of the first 12 symbols so far generated is displayed: from this figure it is possible to notice that three main frequency components are present in each symbol (as evidenced by the strong yellow frames around 50, 85, and $120\,\mathrm{kHz}$), which are symmetrically alternated in time.

B. Results

Results were evaluated by computing the Symbol Error Rate (SER)

$$\mathrm{SER} = \frac{L_{wrong}}{L} \cdot 100 \qquad (3)$$

which measures the percentage ratio between the number of incorrectly reconstructed symbols (L_{wrong}) over the entire

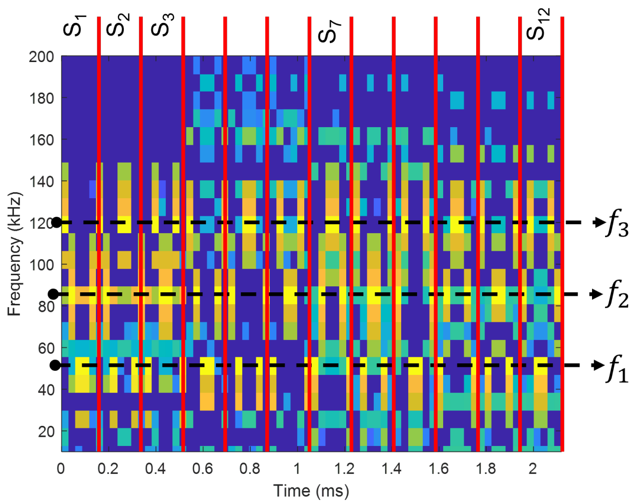

Fig. 5: Spectrogram of the first half of the symbols generated with the proposed CSS+FH encoding mechanism.

Noise	Distance	Payload length (L): 40	100	500
SNR 45 dB	0.2 m	0	0	0
	0.4 m	0	0	0
	0.6 m	0	0	0.57
	0.8 m	0	0	1.15
SNR 3 dB	0.2 m	0	0	0
	0.4 m	0	0	0.45
	0.6 m	0	0.05	1.30
	0.8 m	0	0	1.25

Fig. 6: SER percentages showing the communication performances of the CSS+FH protocol per varying signal length (L), channel noise (SNR) and propagation distance.

number of symbols. The communication performances obtained by varying the above mentioned parameters (i.e, d, L, and SNR) are summarized in the table of Fig. 6.

As can be observed, SER values are always below 1.3% even in the most critical configurations, which are associated to longest communication distances (above $0.6\,\mathrm{m}$) and payload lengths, and, hence, implicitly more prone to ISI. Nevertheless, it is important to specify that SER = 0% for $L = 40$ symbols is perfectly compatible with the prospective application scenarios, where the payload consists of a few scalars corresponding to damage indicators. Moreover, the robustness of the encoding mechanism with respect to channel noise needs also to be underlined, as proven by the minimal performance degradation (averagely below 0.4%) when moving from SNR = $45\,\mathrm{dB}$ to SNR = $3\,\mathrm{dB}$.

V. Conclusions

In this work, a novel encoding mechanism suited for GWs–based acoustic data communication has been presented and numerically validated in the framework of a metallic square plate. The proposed protocol is innovative in that it combines the benefits of two different spread spreading modulation techniques, i.e. chirp spread spectrum and frequency hopping, to suppress the inherent complexities affecting elastic wave propagation (such as dispersion and multi–path fading) and those associated with inter-symbol interference and channel noise. Results show that perfect symbol reconstruction (SER = 0%) can be achieved while transmitting data at a significantly high bit rate ($5.7\,\mathrm{ksym/s}$) over a communication distance of $0.4\,\mathrm{m}$, which represents a typical range for plate–like structures.

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