國科會專題研究計劃精簡報告
二維週期結構理論應用研究(總計劃)
89-2213-E-009-223

Surface-Wave Suppression of Resonance-Type Periodic Structures

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ABSTRACT

Periodic structures of the resonance type are investigated with a focus on the utilization of structure dispersion to achieve a wide-band operation for the surface-wave suppression. Both approximate and exact formulations are presented to illustrate wave processes involved in the resonant structure and to develop useful criteria for design purpose.

I. INTRODUCTION

The resonance-type periodic structures have attracted considerable attentions in the recent literature, and many applications have been demonstrated [1, 2]. So far, most of the research work has been limited to experimental studies and numerical simulations, but the physical mechanism involved in such a class of structures remains to be better understood. As far as periodic structures are concerned, at a given frequency, there are two important factors affecting their guiding characteristics: the basic dispersion and the period of the structures. The purpose of this paper is to provide a theoretical basis for exploring the utilization of resonance-type periodic structures for the suppression of surface waves. As an example, a corrugated metal surface is carefully studied to provide reliable numerical data for physical explanations. Specifically, the major contributions of this research work may be summarized as follows:

(1) to provide a clear physical picture of the wave processes involved in the resonance-type periodic structures.
(2) to clarify the basic concepts and to evaluate the validity of modeling a periodic structure as an impedance surface.
(3) to develop useful criteria for the design of the periodic structures by utilizing the structural resonance for the broadband operation of the Bragg reflection.

II. STATEMENT OF PROBLEM

The inset in Fig. 1 shows the configuration of a periodic structure that is composed of infinitely many identical cavities, each with an opening to the air half-space. With the coordinate system attached, the corrugated structure has a period d in the x-direction and is uniform in the y-direction. Each cavity may be viewed as a parallel-plate waveguide that is completely short-circuited at one end and partially short-circuited at the other end. The opening of each cavity has the width a and is centrally located on the top cover. Furthermore, the structure is horizontally infinite in extent and has a height h. Hessel and Oliner [3] had used such a structure as an example to explain Wood's anomaly in the scattering of light and to establish a basis for modeling a periodic structure as an impedance surface. Assuming that both the structure and the incident wave are invariant in the y-direction, we may treat the guiding of either TE or TM wave separately as a boundary-value problem. For practical interest, we try to keep the height of the corrugated structure sufficiently small, so that we may consider the TM polarized wave only, although our theory applies to the other polarization, as well.

III. METHOD OF ANALYSIS

Since the structure under consideration is periodic along the x-direction, a set of Fourier components or space harmonics is generated in the air region, with the propagation constant of the n^{th} harmonic given by:

$$k_{xn} = k_x + n\frac{2\pi}{d}, \quad for\ n = 0, \pm 1, \pm 2, \ldots \quad (1)$$

where k_x is the propagation constant of the fundamental harmonic. In the air region, each space harmonic propagates independently as a plane wave, and the general field solutions can be expressed as a superposition of the complete set of space harmonics. On the other hand, in the corrugated region, the general field solutions can be easily represented as a superposition of the parallel-plate waveguide modes. By imposing the boundary conditions at the structure-air interface, at $z = 0$, the existence of non-trivial solution in the absence of any incident wave leads to the transverse-resonance condition:

$$\det\left[\mathrm{P}^{+}(\mathrm{k}_x^{*})\mathrm{Z}_{\mathrm{in}}\mathrm{P}(\mathrm{k}_x)+\mathrm{Z}_{\mathrm{a}}\right]=0 \qquad (2)$$

Such an equation defines the dispersion relation to determine the guided modes of the corrugated structure. Here, P is the coupling matrix with its elements that can be obtained analytically from the overlap integrals of the waveguide modes in the corrugated region and the space harmonics in the air region. Z_{in} is a diagonal matrix with the input impedance of the m^{th} parallel-plate waveguide mode as its m^{th} element, as given by:

$$Z_m^{(in)} = j\frac{\mu £_o}{©_m}\tan ©_m h\,, \quad for\; m = 0,1,2,\ldots \qquad (3)$$

where $©_m$ is the propagation constant in z-direction of the m^{th} parallel-plate waveguide mode, and can be given as:

$$©_m = k_o\sqrt{1-\left(\frac{m a}{2d}\right)^2} \qquad (4)$$

Finally, Z_a is also a diagonal matrix with the wave impedance of the n^{th} space harmonic in the air region as its n^{th} diagonal element, as given by:

$$Z_n = \frac{k_{zn}}{\mu £_o} \qquad (5)$$

where k_{zn} is the propagation constant in the z-direction of the n^{th} space harmonic. Thus, all the parameters in (2) are defined.

The dispersion relation in (2) is a determinantal equation of infinite order; it requires a suitable truncation to a finite order to yield numerical results. We have implemented a computer code on the basis of the exact formulation described above to determine the dispersion roots of the structure under various conditions. The results so obtained and their physical implications are given in next section.

IV. NUMERICAL RESULTS AND DISCUSSIONS

Based on the exact formulation described in the preceding section, we are now in a position to carry out both qualitative and quantitative analyses of guiding characteristics of the corrugated metal surface. Before embarking on an elaborate numerical analysis, it is instructive to consider first the approximation by only one single mode in the parallel-plate waveguides. The periodic structure may then be replaced by a uniform surface having the impedance that is determined by the input impedance in (3) for any waveguide mode of interest. The propagation constant of a surface wave guided by such an impedance surface can be obtained explicitly as:

$$k_{sw}^{(m)} = \sqrt{k_o^2 + ©_m^2 \tan^2 ©_m d} \qquad (6)$$

Graphically, such a simple expression can be plotted into curves in the form of the Brillouin diagram, and the results are shown in heavy solid lines in Fig. 1 for the lowest four modes, $m = 0$, 1, 2, and 3. As far as the periodic structure is concerned, these four curves, and their reflection-symmetric ones with respect to the vertical axis may be regarded as the basic dispersion curves. For the overall structure, the Brillouin diagram can be constructed approximately by the periodic translation of the basic dispersion curves along the horizontal axis. It is well known that strong interactions of waves may take place in the vicinities of the intersection points among the unperturbed dispersion curves, as marked by the A's, B's and C's in Fig. 2. This allows us to identify easily possible physical effects associated with the structure and will be particularly useful for an initial design in practice.

It is well known that the Bragg phenomenon will occur at $k_x d/2\pi = 0.5n$, where n is an integer running from zero to infinity. For example, for the fundamental mode ($m = 0$) in Fig. 1, the first-order interaction between the fundamental harmonic ($n = 0$) and the first higher harmonic ($n = -1$) occurs in the vicinity of the intersection point A. Similarly for the next two higher-order modes, the intersection points are marked by B for $m = 1$ and C for $m = 2$. It is interesting to note that at the point marked by A′, two physical processes take place: one is the onset of propagation of the first higher order mode ($m = 1$)

and the other is the intersection point of two harmonics, $n = 0$ and $n = -1$, of the same mode. Similar explanation may be given for the points marked by B′ and C′ for the higher-order modes. Thus, we should expect stopbands to arise in the vicinities of not only the points marked by A, B, and C, but also those marked by A′, B′ and C′.

Based on the exact dispersion relation in (2), we have carried out a systematic evaluation of the guiding characteristics of the corrugated structure, and the results are displayed in the form of the Brillouin diagram in Fig. 2 for both real and imaginary parts of k_x. It is noted that the shaded area denotes the bound-wave region; otherwise, it is the radiating or leaky-wave region. When the frequency is increased from a small value, the real part of k_x falls first in the bound-wave region and the imaginary part of k_x stays zero until the occurrence of the stopband. Thereafter, the guided wave enters into the leaky-wave region, and the value of k_x stays complex, with non-zero imaginary part in general.

Returning back to Fig.1, if we start again from the low frequency range, the dispersion curve should follow closely that of the fundamental mode and continues up to the vicinity of the intersection point A, where a stopband occurs; this is indeed the case, as is evident in Fig. 2. It is striking to observe that when the frequency is increased further above the first stopband in Fig. 2, the actual dispersion curve does not follow that of the fundamental mode any longer; it jumps to that of the next high-order mode. Such a phenomenon of jumping from one mode to the next higher mode seems to be always the case, as is evidently seen in the vicinities of the points marked by B and C. This means physically that in a different frequency range, the model of impedance surface has to take the input impedance of a different waveguide mode. Thus, we may conjecture that the fields inside the corrugated regions are dominated by a single mode that may change from one to another, depending on the operating frequency. Furthermore, comparing Figs. 1 and 2, we observe that the first stopband exists over the range of frequency between the pair of points A and A′. In other words, in contrary to our original expectation, we do not have two stopbands separately around the points marked by A and A′. A physical interpretation may be given as follows. When the fundamental mode reaches the stopband region, the real part of k_x in the air region matches with the transverse propagation constant of the first higher mode of the parallel-plate waveguides, at the value $k_x d/2\pi = 0.5$. With such a phase matching condition, the fundamental and the first-order modes are strongly coupled, resulting in a single stopband, instead of two separate ones. A similar explanation may be given to the stopbands around the points B and C in Fig. 2 and they can be related back to the pair B and B′ and the pair C and C′, respectively.

To substantiate the explanations described above, we plot the amplitudes of the first four modes of the parallel-plate waveguides in Fig. 3. In the low frequency range, the fundamental mode is obviously dominant, but the contribution from the next higher-order mode, $m = 1$, increases significantly with increasing frequency. Toward the frequency $k_o d/2\pi = 0.5$, we see a sudden switch of domination from the fundamental mode to the next higher mode. A similar behavior occurs also around the frequencies $k_o d/2\pi = 1.0$ and 1.5. This demonstrates the effect of the structural resonance, and suggests the utilization of the mode switching for the design of the dispersion characteristics of a periodic structure.

In Fig. 2, the first stopband is in the bound-wave region and it will be good for the application to the suppression of surface waves. In an attempt to increase the width of the stopband in the bound-wave region, Fig. 4 shows the effect of the structure height on the width of the first stopband. Here, we can achieve a bandwidth of over 20% of the operating frequency, while still keeping the operation with a single mode.

V. CONCLUSIONS

We have presented a rigorous treatment of guided waves on a corrugated metal surface. Numerical results are systematically carried out and are displayed in the form of the Brillouin diagram and also in the form of amplitude distribution of the waveguide modes, in order to identify the wave interactions and to show the stopband structure of the dispersion curves. The approximation of a resonance-type periodic structure by an impedance surface is examined and a simple criterion is suggested, so that the frequency dispersion of the impedance surface may be accounted for by switching from one waveguide mode to another in a single-mode approximation. The effect of the structural dispersion on the Bragg phenomenon is carefully evaluated, and it is demonstrated that a wide stopband can be achieved with a proper design of the resonance-type periodic structure. Much more numerical data have been obtained and will be presented in the talk.

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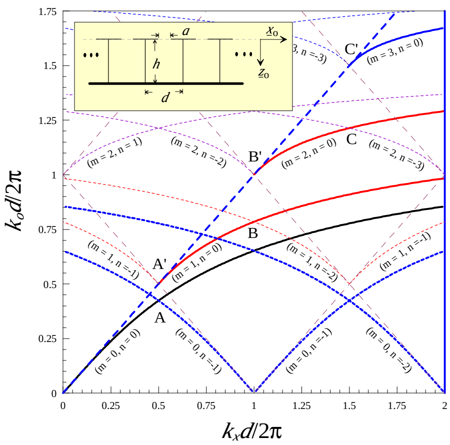

Fig. 1- Unperturbed dispersion curves for the case of $h = 0.21d$ and $a = d$.

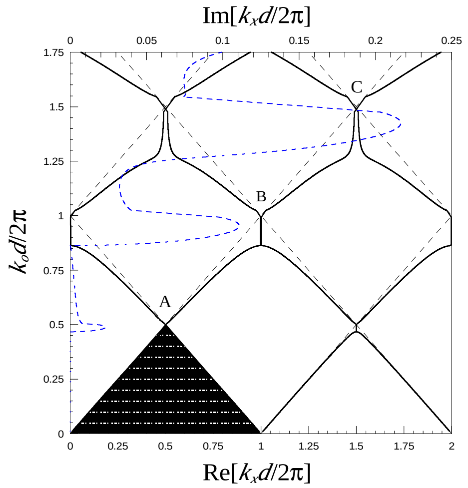

Fig. 2- Brillouin diagram of a corrugated metal surface for the case of $h = 0.21d$ and $a = d$.

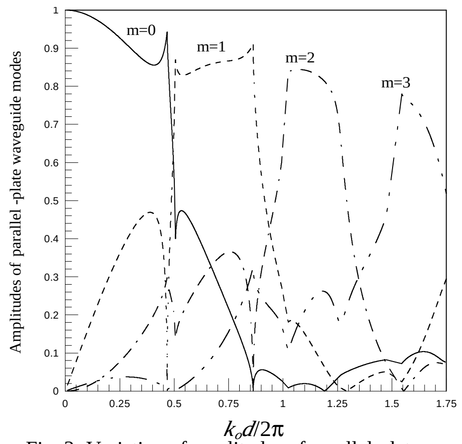

Fig. 3- Variation of amplitudes of parallel-plate waveguide modes against normalized frequency $k_od/2\pi$ for the corrugated metal surface with the parameters: $h = 0.21d$ and $a = d$.

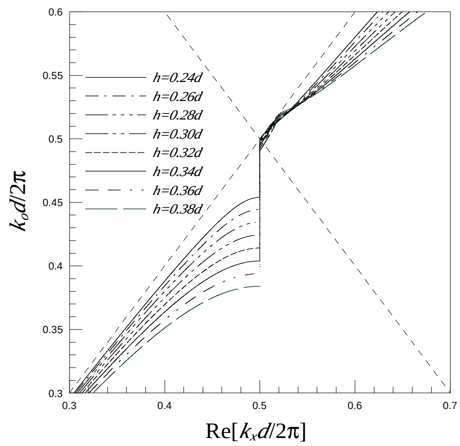

Fig. 4- Variation of the width of stopband with respect to the structure heights for the case of $a = d$.