BREAKTHROUGH IN CORRUGATED CONICAL HORN RESEARCH IN QUEEN MARY COLLEGE. UNIVERSITY OF LONDON

DURING LATE 1960s

A REMINISCENCE

BY

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It is a little over 50 years since Prof. P. J. B. Clarricoats and his research student, Pradip Kumar Saha, applied their brains for an in-depth understanding of Corrugated Conical Horns – both Narrow-Flare as well as Wide-Flare (more popularly known as Scalar Horns). Prof. Debatosh Guha, on behalf of the Conference Executive Committee (INCAP 2020), suggested that I reminisce on the activities indicated in the title of this talk. Prof. Clarricoats is no longer with us. As one of his early students, certainly the first student after he took up a Chair in QMC, who could make some contribution, however small, in his illustrious career, I take this opportunity to dedicate the reminiscence to his memory.

During AEMC 2017, held in Aurangabad, I had presented an informal talk which was in a similar vein. Later, after listening to me, Prof. Raj Mittra mentioned that he was aware of 'Peter' doing good work on antennas in QMC with a student/an associate but had no idea until then that the latter person was me. He urged me to write up the history for his journal FERMAT. Encouraged, I did write though with some trepidation and got it published in FERMAT. Today's talk will be very much similar to my previous ones but perhaps less technical.

Let us begin with a quick review of the major achievements in low-noise feeds for reflectors during 1960s.

[SLIDES with necessary comments]

Perhaps Kay's wide-flare conical horn with circumferential corrugations was the most remarkable breakthrough. Apart from the low noise property, emphasis of research works in this area was on achieving E- and H-plane pattern symmetry. Such a feature of the feed radiation pattern could not be

achieved with pure-mode horns. It was shown that specific hybrid modes in feed horns with modified boundary were necessary and that transverse corrugations would provide the appropriate surface impedance.

Armed with these information, Professor Clarricoats with his research student Pradip Kumar Saha embarked on a new project in QMC. Aim: Study of Propagation and Radiation Characteristics of Fast Waves in Corrugated Circular Waveguides and Corrugated Conical Horns. My involvement in the research and development of scalar horns was rather serendipitous (or fortuitous if I use a less pompous word). I had earlier (sometime in 1966) joined Leeds University as a research student of Prof. Clarricoats to work on a project which was high-sounding but the topic not so interesting to a fresher from India like me (who did not have a very solid background in microwaves). The topic was: Development of Backward-Wave Delay Line for Pulse-Compression Radar. The backward wave was supported in circular waveguides with axially loaded high-dielectric-constant cylindrical rods. Needless to mention, the azimuthally dependent modes in such waveguides are necessarily hybrid. If I remember correctly, Propagation in Circular Waveguides with Axially Loaded Ferrite Rods was the Ph.D. thesis topic of PJBC. When Prof. Clarricoats took up a Chair in the Electrical Engineering Department of QMC in 1968, he offered me to join him to start a new project on antenna. I really had no choice as none of the faculty members at Leeds University was willing to supervise me on the original problem if I had decided to stay on in Leeds. So, the project had to be terminated and I submitted my completion report on an incomplete project. As I later understood, nobody pointed out to me (or should I say – cared to point out) that I could have and should have submitted the final report as a M. Phil. Thesis in Leeds University. In fact, I do not have any documents on whatever I did at Leeds, not even a copy of that completion report. The output from the project was nothing worth mentioning, only my knowledge base was improved. I learned programming in Algol and also several numerical techniques. The project required enormous computational effort and I had to churn out piles of data on junctions between dissimilar inhomogeneously loaded circular waveguides from KDF9 main-frame computer. What wastage of paper!

I started afresh in QMC on a new project on corrugated circular waveguide and corrugated conical horn: their propagation and radiation characteristics. While in Leeds I was referred to the great book (but admittedly somewhat tough for me at that time): "Field Theory of Guided Waves" by R. E. Collin (this remained my Bible ever since). Now in QMC, I

had to start with another wonderful book: "Microwave Antenna" by Samuel Silver in the Radiation Laboratory series. Another book that was invaluable and was a constant companion: "Handbook of Mathematical Functions" by Milton Abramowitz and Irene Stegun.

I began with fast wave modes, both hybrid and circularly symmetric, in corrugated cylindrical waveguides with large number of corrugations per wavelength to simulate impedance boundary and their radiation characteristics. The beginning was not as promising or as fast-paced as PJBC would have liked. When I first met him with the computed dispersion diagrams of the fast wave modes, both circularly symmetric and hybrid, he commented that those results were not going to get me a Ph.D. degree, though later, we managed to publish a paper on the topic in Electronics Letters. However, things started moving faster as I grasped the feel of the new problem better and realised that the field was highly competitive because there was intense activity by several groups in different countries, Minnette and Thomas in Australia, being the one with whom we had close contact. The most remarkable result of the early phase of our investigation was attenuation of the dominant hybrid HE11 mode. We found that the theoretical attenuation under Balanced Hybrid Condition can be lower than that of the dominant TE11 mode in conventional circular waveguide over bands of frequencies. The low-loss feature was not pursued further at that time. After our results were published, I remember receiving a letter from Minnette and Thomas, who too were working on the problem, to resolve a confusion. It transpired that in my computer program, a numerical factor was inadvertently missing from the expression for the surface resistance. Fortunately, it affected the corrugated and un-corrugated guides similarly so that our conclusions remained unaltered. Only a few years ago, a colleague in IRPE drew my attention to the Nobel Lecture of K. C. Kao. It gives me immense pleasure to show the first slide from that lecture where our theoretical low-loss results are reproduced to project corrugated circular wave guide carrying the dominant HE11 mode as a low-loss guide.

After detailed study of the radiation properties of corrugated circular waveguide (some results are shown in the power point presentation), we designed and successfully tested a narrow flare (12 degree half-flare) corrugated circular waveguide horn with corrugation teeth perpendicular to the guide axis. The aperture fields were calculated from the HE11 mode of corrugated waveguide together with quadratic phase error arising due to the small flare. The fabrication of the structure was a big challenge that was taken up by the workshop technician Mr. John Ede, a wonderfully gifted and

skilful person. The precision with which he produced the structure with a series of disks with tapered holes was an eye-opener to me. The agreement between the theoretical patterns and the experimental radiation patterns measured with a primitive set up (that made the process of measurement physically exhausting) was very much encouraging and of course satisfying.

The second phase of the research work involved corrugated conical horn with large flare angles where waveguide modes with quadratic phase error (as was done for narrow-flare horns) were not applicable to determine the aperture fields (over the spherical cap). The aperture field calculation was compounded by the fact that the surface boundary condition now depended on the radial distance from the horn throat. Some appropriate approximation became necessary in respect of the Hankel function. While I was working on the problem, PJBC got there first, introduced a suitable approximation and published a paper on spherical hybrid modes in corrugated conical horn. At that time we got hold of a research report of A.F.Kay that contained the diagram of his corrugated conical horn with 70^{o} half-flare and the measured radiation pattern. Determination of the theoretical radiation pattern of Kay's horn became the most urgent matter at that moment. With the help of PJBC's new paper, I could determine the aperture distribution and then worked out Kirchhoff-Huygen integration over the spherical phase-front to obtain the expressions for the far zone radiation fields. The computed theoretical pattern agreed so well with Kay's measured pattern (subject of course to the usual error in reading from a graph), it was simply incredible and satisfactory culmination of our efforts. (I thought, perhaps naively, that the achievement called for some celebration, but none was forthcoming.) We promptly got a paper published on the radiation from scalar horn and I was given some credit by referring to the work as a departmental research report submitted by me. Immediately after publication of the paper, a request for a copy of the research report came from a company, probably GEC. Since, such a report actually did not exist as a document in printed form, my derivations were quickly typed out to produce an official report (I did not think it looked impressive because of the way it was produced) for sending to GEC.

With the aperture distribution and radiation fields available, we explored number of aspects of the scalar horn. Another useful and interesting work was spherical wave expansion of the aperture fields applied to determine the radiation fields. The method worked very well and an interesting aspect of the technique was that the near-field pattern could be determined very

easily. Near field pattern by Kirchhoff-Huygen integration would have been much more complicated and computationally more time-consuming.

Mr. John Ede fabricated, once again with his characteristic precision, a corrugated conical horn of 60 degree flare angle where the corrugation teeth were perpendicular to the wall. Once again with the same primitive set up, the measured patterns agreed so well with the theoretical patterns.

We concluded our project with a modified corrugated horn where corrugations exist only near the aperture. After all, we need only radiation under balanced hybrid condition, Theoretically, I t was a junction problem (junction between uncorrugated and corrugated conical sections) which was solved numerically from the derived fields by a technique that was formulated by PJBC and his student P. H. Masterman (who was my contemporary at Leeds). The results were encouraging but were not investigated in greater details. Several months later, PJBC wanted to apply for a patent on the modified scalar horn. As desired by PJBC, I provided the necessary declarations forfeiting any claim. However, PJBC found, to his disappointment, that a patent was already taken out on the concept of modified conical scalar horn.

After submitting the dissertation for a Ph. D. degree of Leeds University sometime in early 1970, I stayed on in QMC as a PD Fellow for a few more months to continue our assault on scalar horn (I had started calculations on the performance of a Cassegrain system with scalar horn feed). If anybody is surprised about the submission to Leeds University, allow me to clarify that this was so because my registration remained with Leeds University even though I worked as a research scholar in QMC. I was told that it hardly mattered where the registration was. It did not sound quite right but I was in no position to argue. Perhaps, some project funds were saved by avoiding a re-registration. That is how I looked at the situation. PJBC was kind enough to offer a PD fellowship. It appeared to me that the fellowship amount was not fixed but depended on the recommendation of Prof. Clarricoats. He made sure that my fellowship did not exceed the starting salary of Masterman, his British student who had already obtained his Ph.D. from Leeds University and took up a job in SRDE. I continued as a PD fellow until I had to rush back home for my terminally ill mother. After her demise, I could never go back to QMC to resume the fellowship. Prof. Clarricoats was once again kind enough to add to my bank account one month's additional salary when the fellowship was terminated prematurely.