One Man's Corner

Part 1.D Lessons Learned from My Early FEA Career

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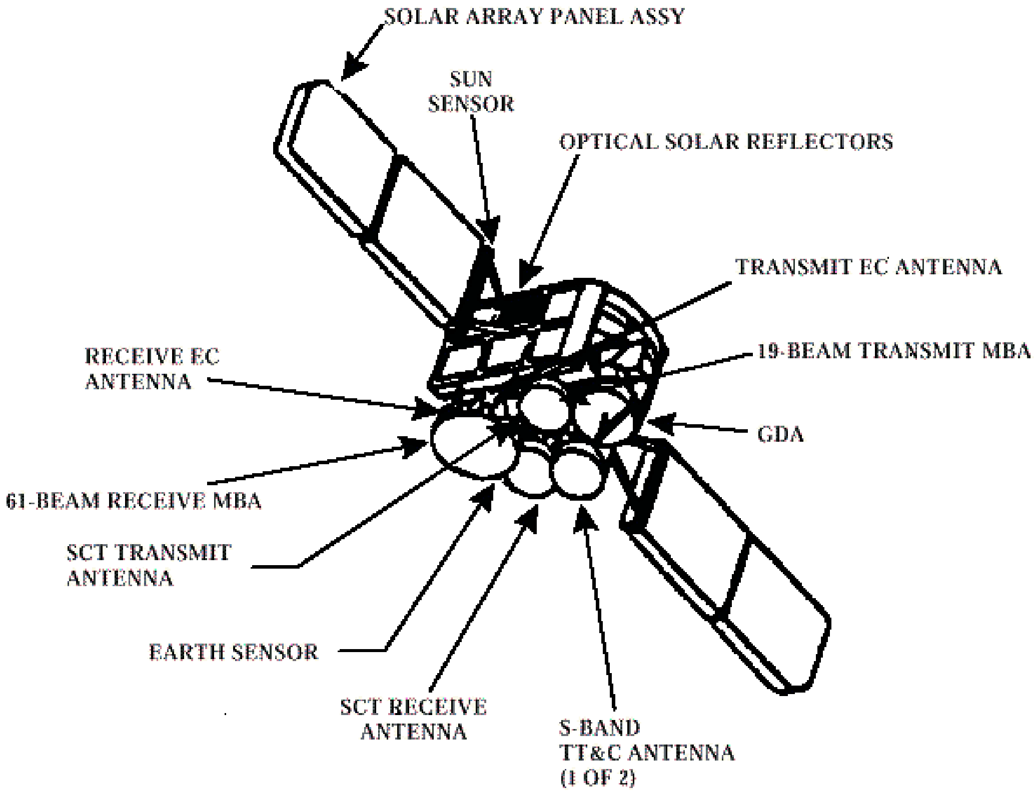
Introduction

This article continues the discussion of the fourth, and final, structural analysis project in my early aerospace career: (**Part 1.D**) Nonlinear FEA of elastomeric potting materials in traveling wave tubes (TWTs) – which were high-frequency, signal amplification and communication electronic devices used in defense satellites, as well as in commercial communications satellites.

1.D Nonlinear FEA of Elastomeric Potting Materials in Traveling Wave Tubes

1.D.1 Background – USAF's *DSCS (Defense Satellite Communications System)*



DSCS III Satellite

In the 1970s, the U.S. Air Force (USAF) began developing a *Defense Satellite Communications System (DSCS).* This network of deep-space (operating about 22,300 miles above the equator), wideband military communications satellites facilitated the DOD's classified communications. The network of *DSCS* satellites covered much of the earth's surface. The *DSCS III* satellites were designed to have an operational life of ten years; they were scheduled to be launched into operation in the period 1997 through 2003.

The *DSCS III* satellite contract was awarded to General Electric-Space Division (Valley Forge, Pennsylvania), with Hughes Aircraft Company's Electron Dynamics Division (HEDD) as a subcontractor for the TWTs placed in these satellites. Acting as technical monitor for the USAF was Aerospace Corporation.

1.D.2 Hughes-EDD TWTs

HEDD. Torrance, California, was (and still is) a leading producer of both helix-type TWTs and coupled cavity-type TWTs, for defense and commercial satellite customers.

One example of Hughes EDD's High-powered Traveling Wave Tube from the 1970's

After launch and operating in deep space for a while, telemetry evidence showed that some of these TWTs were "shorting out" and failing, causing the expensive *DSCS III* satellites to be disabled. Needless to say, these TWT failures had the USAF and DOD deeply worried, and an exhaustive failure investigation was undertaken in 1979-1980. Results of simulations later revealed that the culprit was most probably the cracking of ("fully-constrained") elastomeric potting materials in the HEDD TWTs, which were used for thermal and shock insulation purposes of the electron tubes. The challenge was – how to re-design the TWTs to prevent this shorting and malfunctioning.

At HEDD, the top executives and engineering managers were mostly physicists, or electronics engineers. Explaining FEA terminology and jargon like: "fully constrained" boundary conditions, "incompressible" materials (whose Poisson's ratio was nearly 0.5 – and why this caused tremendous analytical difficulties?), basic thermostructural analysis concepts, and nonlinear FEA issues ("locking" in certain types of 2D/3D finite elements, mesh refinement and convergence, singularities, crack propagation, etc.) to the HEDD managers and technical staff, as well as to the bulk of the audiences at these regular USAF "design reviews," was like explaining the subtleties of pronouncing various Mandarin Chinese tones to them. The *DSCS III* program was way behind schedule, and the Air Force generals and DOD officials were pissed.

One foul-mouthed Air Force Colonel (unnamed here) screamed "bloody murder" and demanded to see "heads roll." At the beginning of every design review, there was always a long period of eerie silence in the big room – when this Colonel ranted and raved, and demanded to know: why are we behind schedule, who screwed up, and who should be fired? The pressure was *on*, folks – big time! [I later learned from experienced HEDD and Aerospace Corporation colleagues, who were long-time, seasoned observers at such meetings, that this was the Colonel's "management style", and his (quite effective, I might add) way of getting his messages across to the contractors.]

1.D.3 Challenges in Nonlinear FEA of Elastomeric Potting Materials in TWTs

At that time in my career, I had not done any "incompressible FEA" before, knew little about nonlinear FEA codes like *MARC* and *ABAQUS*, and so I sought the advice of my mentor, UC Berkeley Professor Robert L. Taylor*. Bob suggested that I contact Thomas J.R. Hughes* at Caltech, himself a recent Berkeley PhD in 1974 – who had just published an outstanding paper (co-authored with David S. Malkus) in 1978 on *selective and reduced integration*, and they had shed some understanding on *locking, hourglassing*, and *over-constrained* 2D and 3D elements,. Because of Bob's kind introduction, Tom agreed to spend one Friday afternoon in 1979 with me, but invited me to first have lunch with him at the *Caltech Athenaeum* faculty lunch club.

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Caltech Athenaeum, Pasadena, California

Strange indeed was my "connection" with Caltech. Although I myself could not get admitted into Caltech as a freshman in 1960, for some odd reason, in my life and my career, I kept running into well-known Caltech professors, researchers, and alumni. I have a brilliant godbrother, Professor Hung Cheng (who has spent his entire career teaching and doing outstanding research in particle physics and mathematics at MIT), who had received his PhD in physics at Caltech at 23. And, after reading about Theodore von Kármán and Qian Xue-sen's work on the buckling of thin shells in my graduate school days, and now having met Professors Chuck Babcock and Y.C. Bert Fung* , here I was, having lunch with Tom Hughes at *the* Caltech Athenaeum. In these hallowed halls, there had walked such renowned Nobel laureates as Linus Pauling, Murray Gell-Mann, Richard Feynman, William Shockley, Charles Townes, and so forth. I was truly awed, looking around to see if I could recognize anyone famous, and hardly touched my lunch. [In 1979, I also had the pleasure of meeting and working with another Caltech Professor, Wolfgang G. Knauss,* an expert on elastomers, who had served as GE's consultant in our *DSCS III* TWT potting redesign study – see Part 1.D.]

After lunch, Tom took me back to his office, offered me coffee, and gave me an intense 3-hour tutorial on: *incompressibility issues in FEA*, *locking*, *hourglassing*, *selective and reduced integration techniques,* and *"overly-constrained"* problems in certain 2D and 3D finite elements. (Of course, most of the fancy mathematics he scribbled on the white board were way beyond me – I nodded, as if I understood all his tensorial equations.) After this tutorial, I finally began to understand (and truly appreciate) why the nonlinear FEA of nearly incompressible elastomers was so difficult. Furthermore, Tom cautioned me why one must be very careful in applying commercial, general-purpose FEA codes for incompressibility studies, because some of their popular elements, for instance, did not even pass the standard *patch test* (which guarantees accuracy and convergence), and that some of their other elements might be *"over-constrained"* (and thus are inherently incapable of producing accurate results in incompressible FEA). [Over lunch – much to my amusement – Tom admitted to me that once when he was much younger, he had seriously considered pursuing a career as a professional bowler! I wondered to myself – what's the correlation between picking up spares, stringing together strikes, and "selective integration" techniques in FEA?]

1.D.4 Stress Analyses of Elastomeric Potting Materials – Lessons Learned

As a result of our nonlinear FEA work using *MARC* and the special-purpose code *SAAS III* (whose 2D quadrilateral axisymmetric "Ed Wilson-element" did *not* "lock," fortunately), we were able to recommend TWT potting configurations to the HEDD TWT designers that were not "over- constrained" – thereby avoiding potential failures due to shorting and cracking. It had turned out that most of the original HEDD TWT designs used in the *DSCS III* satellites featured potting configurations that were almost rigidly-constrained – so that the potting material had nowhere to expand in actual operation at high temperatures. This condition then induced very high stresses that led to the eventual failure, cracking, and "shorting out" of the TWTs in deep space.

Our 2D/3D nonlinear incompressible FEA stress analyses using the *MARC* code (using a Poisson's ratio of exactly 0.500 in its special "incompressible elements") correlated well with the 2D results calculated by Aerospace Corporation's Dr. Dick Chang, who had used the *SAAS III* code and successively, a Poisson's ratio of 0.490, then 0.495, and finally, 0.499. Dick had also conducted extensive mesh refinement studies. And, Professor Wolfgang Knauss pointed out to us that, from his knowledge of such "filled" elastomeric potting materials (using, for instance, aluminum silica particles), the actual Poisson's ratio of the potting material was not 0.500, but more likely, had a value of 0.490-0.495.

In addition to the use of the *MARC* and *SAAS III* codes for the incompressible FEA studies, we also used the *ANSYS* FEA code for the 3D thermal, vibration, and packaging analyses of the TWTs. Separately, Dr. Herb Vichnin and his GE colleagues also performed 2D/3D stress analyses of the TWTs using the *MSC/NASTRAN* code. Because of Tom Hughes' advice, I carefully pointed out to Herb that, in modeling and analyzing the nearly incompressible TWT potting configurations, he had to be very careful using *MSC/NASTRAN's QUAD4* element (and some solid elements), because the *QUAD4* element [at that time, in 1980)] did *not* pass the patch test, had indeed "locked," and could not be trusted in the FEA of elastomeric materials to handle a Poisson's ratio beyond 0.495. Dr. Richard H. MacNeal*, later in 1984-5, fixed this *QUAD4* problem, and this enhanced *QUAD4* quadrilateral element then passed the *patch test* (which he and Bob Harder included in their proposed set of standard finite element (linear elastic and static) test problems, known as the *MacNeal-Harder Problems,* 1985.

I still remember at one of our final design reviews in 1980, the aforementioned USAF Colonel (after being obviously briefed beforehand by his USAF and Aerospace Corporation colleagues) opened the meeting by singling me out for praise for "my outstanding work" – "Mr. Fong is the *only* person, in this entire room, who knows what he's doing! All you clowns out there have a lot to learn from him." He then asked me (now thoroughly red in the face) to stand up and take a bow, to much applause. (After this rather surprising gesture, my "star" and prestige rose quite a bit at HEDD – I was asked by the HEDD management to teach a "brown bag" lunch seminar series on nonlinear FEA to about 25 physicists, chemists, material scientists, and electronics engineers; and I was invited to have lunches at expensive restaurants with some of the top HEDD executives and principal scientists. And, most importantly, I was assigned a special parking space with my name on it – located right next to the HEDD president's, and near the front entrance of the building – the only such "named" parking space perk I've ever had in my entire career.

Postscript: After I left HEDD, at the end of 1980, to accept a position at PDA Engineering, the HEDD *DSCS III* TWT project manager in charge, Harold A. Silverman, kindly awarded several "sole source" FEA consulting contracts to me at PDA (he asked me to please just name the price), in order "to maintain project continuity," and to impress the USAF Colonel and USAF/Aerospace Corporation that HEDD would "do anything possible" to prevent any quality degradation of the FEA engineering work being done on the *DSCS III* TWTs and their elastomeric potting compounds. Much later, I read that the *DSCS III* satellite system continued to operate successfully in space.

Lesson #8: *You better know what you are talking about, in any technical/business meeting – especially when dealing with "experts" from outside your company. Nothing beats being well-prepared – and having integrity and confidence in your own work.*

Lesson #9: *Sometimes in life, the most effective way to communicate may not be all that grammatical or using the most polite and eloquent English – just as long as it works.*

Lesson #10: *When using a finite element analysis code, the user better know everything possible about the finite elements used – such as, whether they pass standard element benchmark tests like the "MacNeal-Harder problems" (which include the patch test, Scordelis-Lo barrel roof,* *twisted cantilever beam, pinched spherical shell, etc.) Be especially vigilant when performing incompressible FEA.*

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-*End of Part 1.D*-
