# SHOCKING MECHANICS

**Defence radar development is challenging because radar functionality under extreme operating conditions needs to be guaranteed using delicate and complex electronic hardware. Contemporary radars use digital beam-steering phased-array technology to create an almost instantaneous spatial awareness in a 3D sector without rotation. Their development requires quick multidisciplinary design analysis cycles where dynamic shock loads tend to dominate the design. Testing and validation ensure that the final product meets the requirements within the given time and financial constraints.**

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## Introduction

This article describes how current radars work and addresses a few typical considerations in the multidisciplinary development of defence radars from a mechanical perspective. It discusses the loads that are typical for defence radar structures and their impact on the design via the shock-response-spectrum method. It also discusses pitfalls in current finite-element analysis method modelling codes that should be geared towards quick response cycles rather than including everything applicable in one model. Finally, it lists a few design considerations when integrating such a system on a naval vessel and the need for testing in the design process.

## Defence hardware

Accuracy is a relative term. At Thales Netherlands, our defence radar systems do not operate on the nanoscale, but neither do the systems of aircraft and ship manufacturers. We are generally satisfied with part accuracies of several tens of microns for the function-critical elements. Creating family-car-size radar systems containing delicate electronics that survive bone-breaking shocks and keep operating within accuracy specifications under extremely uncomfortable vibrations and temperature ranges, whilst handling high power electronics and cooling; that is our challenge.

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GM200-MM/C mobile multi-mission radar.

From a historical perspective, Thales was leading in the mechanical systems that performed on-the-spot calculations for gunfire control in the 1950s; mechanical precision engineering at its best. Those systems are long gone, and we would have to re-iterate the knowledge that left the company as people retire. But then again, the technology has moved on and still offering mechanical calculators for contemporary radar operations would definitely not guarantee a successful business.

## Keeping up in the race

Developing a radar system generally takes many years from the conception of a system-level principle to the first prototype and eventual product. It generally starts with a new operational concept, a novel mathematical technique or improvement of computing power to enable object detection and classification in an ever-changing environment. Developments can be driven by the type, number and agility of threats, new electronic threats, and changing target-stealth characteristics to even the availability of energy and rare-earth materials. On top of that, there are also continuous research efforts made to improve the energy efficiency and electronics cooling capacity.

The research findings, not all having the same level of maturity, need to come together in a next-generation radar system. This requires a clear strategy that involves planning many years in advance and collaboration with governments, research institutes and industry partners. It is continuously keeping steps ahead of the competition, achieving a functionality that others do not have or others can only achieve with unsustainable resources, that keeps one relevant in today's radar-systems market.

**AUTHOR'S NOTE**

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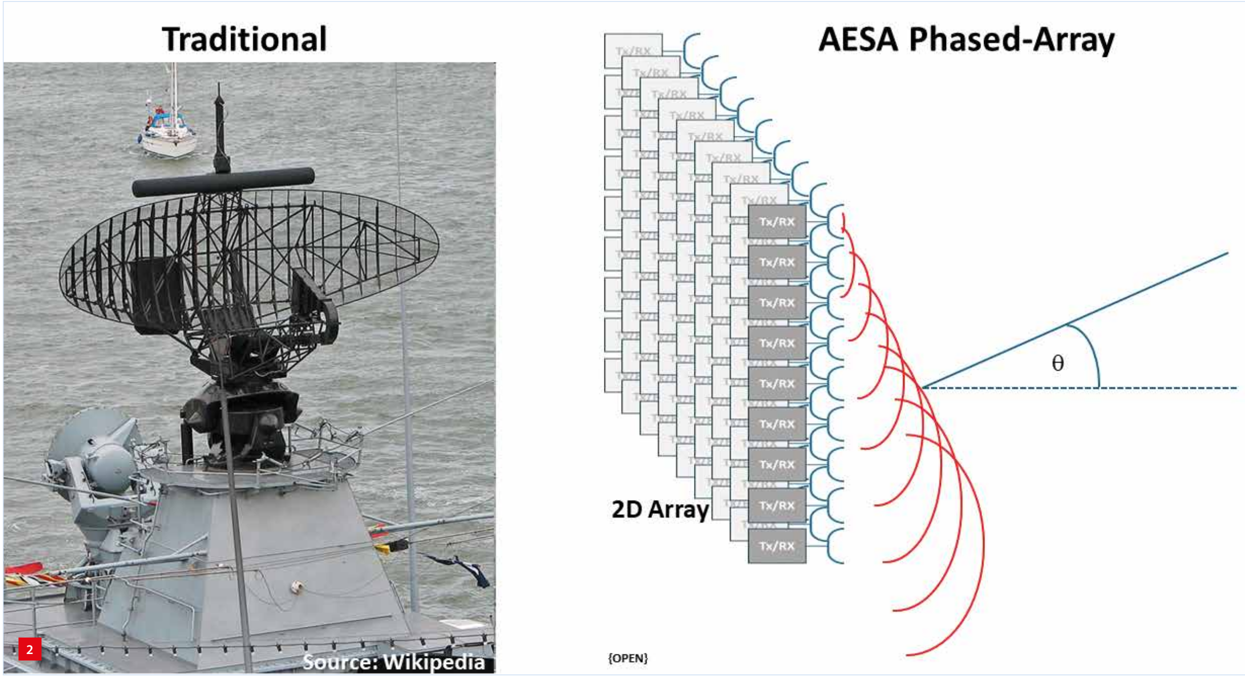



*Traditional versus an active electronic scanned array (AESA) phased-array radar.*

Time, budget and human resources are always limited but still, using these scarce resources wisely, Thales NL managed to develop 2D-multibeam phased-array radars that can scan electronically in two directions to detect and identify aircraft, rockets, drones and mortar-fire simultaneously. A highly successful, highly mobile radar system using this technique is shown in Figure 1.

A traditional radar (radio detection and ranging) consists of a single transmit-and-receive (TX-RX) chain and a mechanically directed antenna, this only being capable of tracking targets in a single vertical plane. A phased-array radar (see Figure 2) is composed of multiple TX-RX channels arranged in a 2D array. It does not require a radar antenna face to physically point towards the target. It allows for an almost instantaneous view of targets in a volume sector spanning – without rotation – an azimuth, elevation and radial range, up to 2,000 km, depending on the radar type. This significantly improves the reaction time and therefore the time to take countermeasures. Also, digital beamforming and processing techniques deliver flexibility to prevent hostile interference susceptibility.

But what does this all have to do with precision engineering? The answer is: "Everything, if one views accuracy from a scarcity perspective." Every type of industry aims to use their required accuracy and tolerance capability to obtain a product that just meets the requirements. A too precise product is wasteful on the limited available resources; not reaching the minimum requirements yields defective products, which is even more wasteful since all the preceding actions to create the product are wasted. Precision and tolerance, combined with material use, are among the most important features affecting the resource claim.

## Radar structures engineering and fat-bikes

Diving into the radar structures, locational precision of the TX-RX elements in a 2D array literally creates more focus and reduces the radar's susceptibility to hostile interference. TX-RX element surfaces that are in close contact to cooling manifolds release their heat better compared to ones that do not mate well. From a purely mechanical perspective, rotating radar systems require drive-part tolerances that are comparable to machinery with gears, pumps, motors and ball-bearings. The accuracy of radar structures is comparable to that of aircraft structures.

What distinguishes naval defence radar systems from general mechanical systems is the severe overload capacity needed to survive shock loads (see later in this article). It is safe to state that the vast majority of radar systems will never encounter the shock loads for which they have generally been designed. It is this insurance policy that sets military radar systems apart from most other radar products. The latter might provide some radar functionality at a fraction of the cost but fail at the moment it matters most. Note that the threat is also evolving as commercially available electronic hardware (drones for instance) can be weaponised, also at a fraction of the costs. Being able to handle changes requires agility and diligence in every step of the engineering process, which is aimed at reducing the effort in creating and operating the product whilst maximising its performance.

This brings us to one of the design considerations that is often overlooked; structures with effective load-paths. Where does one place/orient which material with its specific joining technique? From that perspective, every mechanical design engineer should have followed an aircraft structural design engineering course, because it is there where optimal and economical use of material is drilled into the way of thinking. Take for example fat-bikes that nowadays roam the streets and compare these to competition race-cycling bikes, which are highly weight-optimised for stiffness and aerodynamics within the strength boundaries. Fat-bikes are built for portraying a specific image whilst almost completely disregarding weight and durability. Load-bearing members are rife with eccentricities and ineffective load paths, creating completely unnecessary extra material stresses at multiple locations. From a sustainability perspective, the fat-bike concept begs for significant improvement.

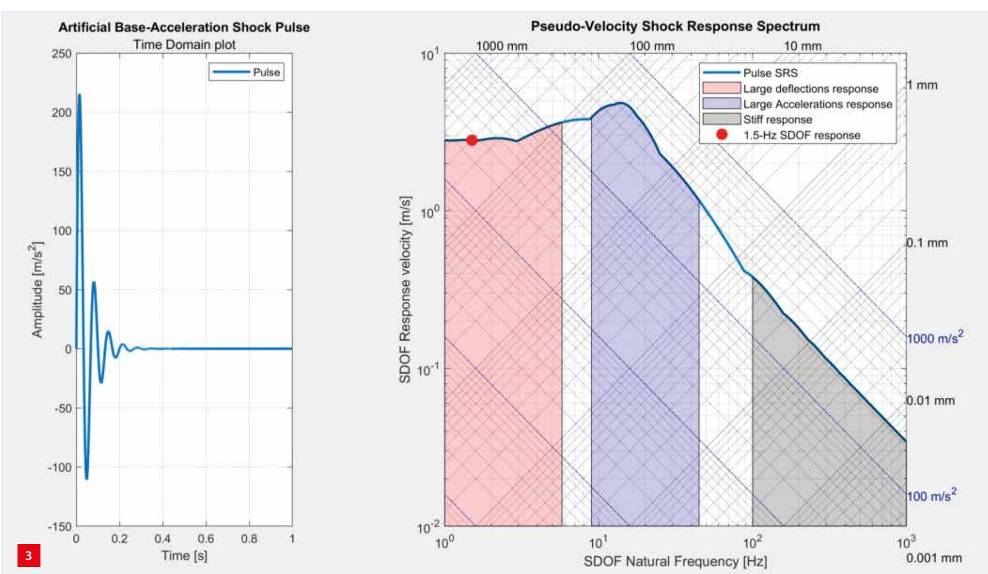
## Shock-response spectra

Shock loads, where a system temporarily undergoes violent shaking movements, are in essence transient dynamic loads that typically last from several tens to hundreds of milliseconds. The effect of such a load on a system is dominated by the resonance frequencies of a radar system. These frequencies are referenced in a shock-response spectrum (SRS) of the transient shock pulse. Such a spectrum lists how a range of single-degree-of-freedom (SDoF) spring-mass-damper systems react to the same shock load. An SRS typically registers the peak response acceleration, velocity and deflection across the pulse duration and beyond, as a function of the SDoF natural frequency (which generally ranges from 1 to 1,000 Hz). By referencing a system's dominant modal frequency in this SRS one gets a first sense of the effect this specific shock would have on the radar system. This is demonstrated in Figure 3 with the pseudo-velocity SRS plot on the right.

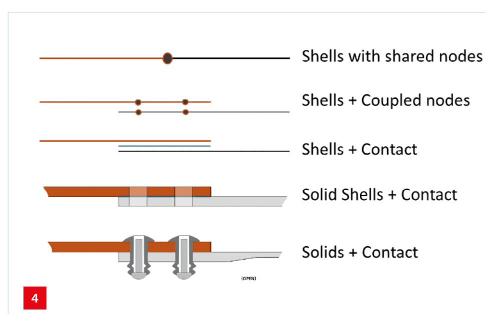
The pseudo-velocity SRS plot is a convenient way of assessing the shock effect, because it shows both the response accelerations and relative deflections in one figure. It is calculated by dividing the SRS absolute (not relative) acceleration by the corresponding SDoF natural radial frequency and is plotted on a double-logarithmic scale. Horizontal grid lines correspond to constant pseudo-velocity, which is a measure of the shock severity; grid lines slanted left-to-right upwards correspond to constant relative-to-base deflections; grid lines slanted downwards correspond to constant absolute response accelerations.

Three regions are identified in the SRS where a deliberate choice needs to be made to set or avoid system-specific natural frequencies. If for instance one prefers a low-frequency shock-absorbing support ('Large deflection response' frequency 1 to 9 Hz region in the SRS) the response accelerations are low, but one must be able to endure large relative displacement. A 1.5 Hz natural frequency (see red dot in Figure 3) would require damper strokes of 30 cm. If the system has a natural frequency in the (say) 10-40 Hz 'Large Accelerations' range, the response accelerations will be disproportionally amplified.

Similar steps can be taken when assessing the radar's response to vibration spectra, be it either deterministic or random spectra. These analyses are quick-and-dirty and give the first feedback whether a radar system has a frequency behaviour that reacts favourably or unfavourably to a specific shock load. This explains why initial radar structural design is based




*Artificial base acceleration shock pulse with corresponding (pseudo-) velocity SRS plot (made with 5% damping).*




*Several ways to join FEM-model parts, listed from quick (top) to slow (bottom) FEM analyses.*

Stiff-rotation, flex-translation support of an NS100 AESA radar.

Holland-class ocean-going patrol vessel (OPV) with radars integrated in the superstructure.

on stiffness rather than strength. In a stiffness approach, the radar is designed for a less adverse region in the SRS. Strength evaluation is done in the detailed design phase.

## Simulations, iterations and the FEM trap

Design and analysis of radar systems is a multidisciplinary, multi-phase effort where close to 80% of the final product cost is established during the preliminary design. This requires an engineering process that is both agile and quick to gain insight. Structural analyses are generally done using purpose-built finite-element method (FEM) models, where the first analysis performed is generally a modal analysis. This yields the design's characteristic resonance frequencies and corresponding mode shapes. FEM models and analyses play a dominant role in system design, because they allow for analyses that go beyond the quick-and-dirty SRS method discussed above. FEM models should aim for quickest response time given the required accuracy. On many occasions a reduced-order model, with only a few (1 to 100) degrees of freedom, but with the essential (sometimes complicated) non-linear behaviour, is used to obtain system-level dynamic responses.

Contemporary software codes are quite good at generating FEM models but come with a hidden danger. Given the ease with which these codes are able to generate complicated lifelike analysis models, with complicating contact and joining schemes, it is easy to fall for the 'everything-in-one-model' trap in system analyses. This is illustrated in Figure 4, showing a cross-section of several joining schemes between two FEM-model parts, listed from quick (top) to slow (bottom) FEM analyses.

Especially the last two joining techniques, where system FEM models are extracted from as-drawn production-grade CAD-models, suggest detailed knowledge of stress levels at all locations at any time, but this is both dangerous and wrong on many levels.

These models can generally not be used for full transient dynamic analyses, requiring 500+ load steps for each shock analysis, without very potent computing facilities. The reason for this is that they are created from as-drawn CAD models using SOLID, SOLIDSHELL and CONTACT elements that are computationally intensive. These models also complicate extraction of member-to-member transfer loads at joints. If important forms of nonlinearity are applicable one cannot use mode-superposition dynamic analysis techniques to speed up the analysis process.

From a system analysis perspective, these models therefore lack the required agility and the ability to keep up with the evolving design, where several crucial changes and iterations must be evaluated and compared. In the initial phase, one is not interested in a stress peak at a specific location and time in a transient dynamic analysis. This can, and should, be addressed in the detailed design phase using sub-modelling techniques.

The everything-in-one-model approach acts as a choke point. It creates a huge burden to include all details that are not all equally relevant for many of the (constant stream of) questions. Designers are kept waiting instead of providing them with the information that allows them to perform the relevant detailed analyses themselves. Beware of this trap.

## Design considerations

Shock and vibration absorbers are examples where the deliberate choice is made for a (low) natural resonance frequency. They attenuate dynamic response accelerations by factors, enabling the use of delicate electronics in the radar. A very common example of this is a car suspension. The car's first natural frequency is set at low frequencies (typically around 1 Hz), where the suspension acts a low-pass filter for the high-frequency input caused by bumps or potholes in the road. It filters out the high-frequency vibrations that affect the reliability of electronics. The hydraulics in the shock absorbers dissipate the shock energy so that violent (resonant) movements are quickly dampened. But a radar system is not a car. It requires a stable and accurate TX-RX face orientation to allow accurate radar processing, since small angular deviations cause a large targeting offset at great distances. There are several ways to achieve the required pointing accuracy. The first one can be a hard-mounted rugged radar system, which is sensible for small radar systems. Really small systems (like a smartphone) are by nature more resilient to shock loading. Larger systems become more susceptible but can be hard-mounted as well. However, this also requires more stiffness from the ship's structure supporting the radar.

If the radar is soft-mounted the pointing accuracy needs to be guaranteed. One method is to make the radar system stiff in rotation but weak in translation, since the shock loads are predominantly translational. This can be realised with a considerable amount of hardware, as shown in Figure 5.

Another method is to also omit the rotation stiffness and dynamically correct the radar processing (not the radar itself), such that radar rotations are compensated (many times a second) in the processing. The instantaneous radar orientation can be obtained by performing real-time displacement measurements of the radar deflections relative to the (stiff) surroundings, and calculating the rotations from these measurements. Another method is by incorporating an absolute orientation measurement device. Both methods come at considerable extra cost.

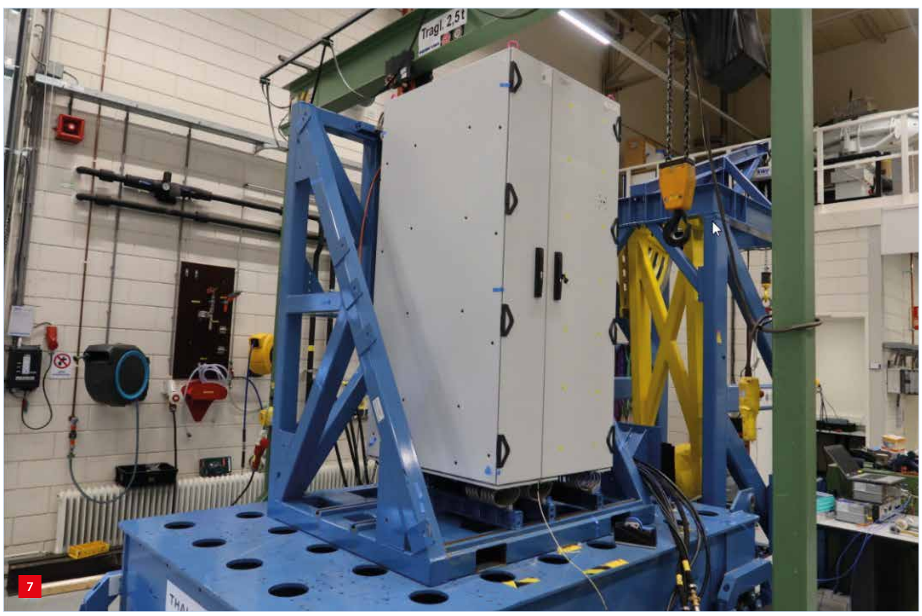
The position of the radar system on the ship is also important. The higher the radar system is mounted, the more its mass affects the ship's roll stability, affecting the ship's sailing performance in rough seas or the roll stability under flooded conditions due to hostile actions. Very large radar faces will also have to contribute to the ship's superstructure load-bearing structure (see Figure 6). Large openings in the ship's superstructure, allowing the radar to 'see', would severely compromise its load-bearing capability. These are clear examples of some of the design considerations for a radar system concept. Apart from size, which is mainly governed by physics, weight, location, ease of integration, maintainability, accessibility, and line-replaceable-units definition (the list is long) also affect the design. This explains the large diversity in radar systems.

## Testing & verifications

Doing all kinds of analyses is one thing, but how does one validate analysis models? There are ways to overcome this hurdle, such as mesh refinements, recalculating textbook examples with the chosen modelling approach, but also testing. Small business enterprises generally do not have the facilities to test physical models for shocks, vibration or environmental behaviour. At Thales, we are in the fortunate position of having facilities at our Environmental Competence Center (ECC), where equipment can be tested or models can be validated at several stages of development (see Figure 7). Generally, we are able to predict the global natural frequencies within typically 5% error and even better. This is generally accurate enough, since in the end nearly all of our equipment is validated by qualification tests using the design levels.

## To conclude

Like system development in other industries, defence radar development has its own unique challenges. This article highlights some of the design aspects from a (mainly) mechanical perspective. We are currently working on the radar systems that will be operational in five to ten years; the excitement is constant.

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*Equipment shock testing at Thales Netherlands.*