A practical systems-engineering approach to marine-vibrator design

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Summary

We apply a rigorous systems-engineering process to develop a new marine vibrator. Thorough requirements engineering, incorporating wide-ranging operational scenarios, ensures that our stakeholders' needs are fully addressed. We assess the requirements' technical feasibility iteratively in our architectural design and advanced development activities to define an optimized system. We then launch full-scale engineering development and will methodically integrate and test the resulting design. Throughout the process, we make extensive use of modeling and simulation to provide insight and reduce risk.

Introduction

Seismic vibrators have been used on land since the early days of seismic exploration, but their use at sea has hitherto been limited. There are two primary drivers for *marine* vibrators: reduced environmental impact and survey efficiency.

Marine seismic vibrators emit their energy spread out in time, as opposed to airguns, which emit the energy in a single, high-intensity pulse. This 'soft output' would give the marine vibrator an environmental advantage even if the total acoustic energy emitted was the same (Southall et al., 2007; LGL and MAI, 2011; Southall et al., 2019). A second environmental advantage stems from our ability to control the energy spectrum of the source. The spectrum can be tailored to be the minimum needed to satisfy the imaging requirements (Laws et al., 2018a). Because of this, the total acoustic energy emitted by a vibrator survey would typically be lower than that needed for the same survey using airguns.

The efficiency advantage of marine vibrators stems from the ability to control the phase of the emitted signal. Phase control for a marine vibrator is much more accurate than for a land vibrator as a result of the homogeneity, repeatability, and almost perfect coupling of the seawater medium. This feature can be harnessed to enable novel techniques that are not practicable with land vibrators, and limited with airguns. One example is the use of simultaneous sources with very high multiplicity: scenarios using synthetic-data studies show increased efficiency and image quality compared with airguns encoded with random dithering (Halliday et al., 2018).

The 'Vee' systems engineering model of Figure 1 provides the overall framework for our development process. This starts with the three activities that produce the system's requirements and architecture: requirements engineering, architectural design, and advanced development. These provide the basis to simultaneously design the individual components during engineering development. Finally, integration & test ensures that the combined system functions as required. To prevent integration problems late in the project, we perform continuous integration on computer models throughout the process in an internal 'Vee'. We employ this rigorous process, which involves many more activities and iterations, to develop a complete source system quickly and with reduced risk.

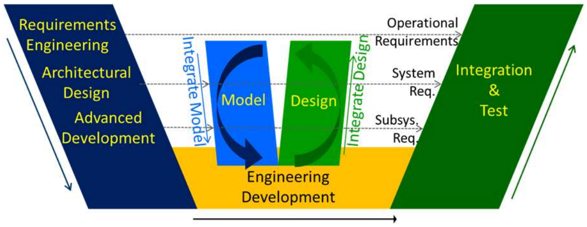

Figure 1: Systems-engineering 'Vee' process (derived from Forsberg and Mooz, 1991; and Kossiakoff et al., 2011)

Requirements Engineering

Before developing any new system, it is essential to understand *what* is needed from the system. Although the nature of marine-seismic operations is well established, a marine vibrator opens the door to novel operational models, which we explore through a variety of operational scenarios:

- Ocean-bottom nodes (deep water)
- Ocean-bottom nodes (shallow water)
- Ocean-bottom cable
- Towed-streamer (advanced)
- Towed-streamer (conventional)

These scenarios provide a deeper understanding of our stakeholders' (e.g. clients, field users, data processors) fundamental needs: reducing environmental impact, increasing operational productivity, and improving image quality. Our analysis shows us that we can address the full range of operational scenarios with a single system design, but that the system must be modular and field-configurable to support a variety of signal requirements and acquisition geometries. This is an important result, as it decouples the source design from the receiver. We also gain insight into the trade-offs among these high-level needs, and assign priorities to define our top-level operational requirements. These requirements are formal and specific, constituting the agreement between the system's sponsors and developers.

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We then convert the operational requirements, which are written in the language of stakeholders, into technical system requirements, which are expressed in the language of the engineers who will develop the system. At this stage the system is treated as a black box, with no assumptions about how it will be implemented. This distinction is important, as it ensures that the operational and system requirements fully address stakeholders' needs while providing developers the full freedom to pursue the most effective way of fulfilling these needs.

Architectural Design

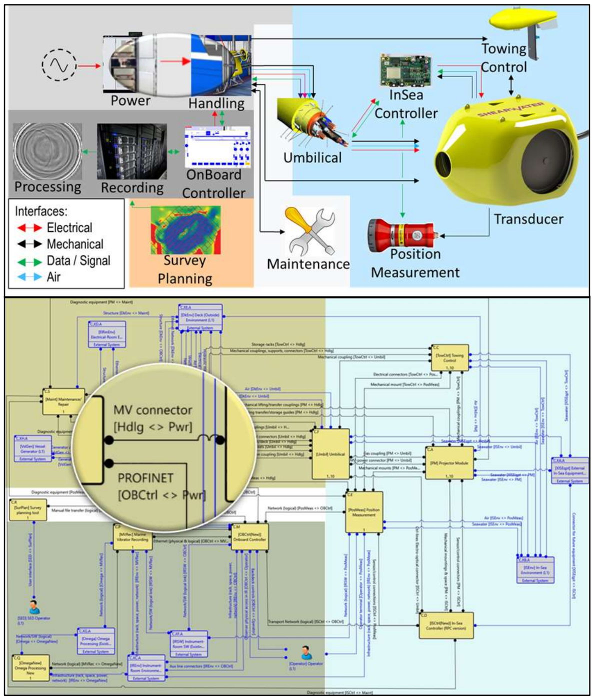

Figure 2: System-level physical architecture: simplified (upper panel) and detailed (lower panel). The magnified view illustrates the relative density of information.

From the system requirements, we describe the activities that the system's constituent components need to perform, combining these into the functional architecture. Although easily omitted in the rush to 'build something', this step is essential to better understand the system's external and internal interactions before limiting ourselves to a particular physical implementation. This process reveals important functionality that might otherwise have been excluded, especially because a marine vibrator may not be able to use the same infrastructure that air-gun designers take for granted, for example handling systems, compressors, and umbilicals. We also establish that our system should incorporate survey-design, processing, and maintenance functionality, which may have been omitted with a less thorough process. We then define the physical architecture that will perform these functions and iterate between the two architectures as needed.

Figure 2 shows an example of the block diagrams produced by this process. These system-level diagrams are then decomposed into hundreds of entities on multiple architectural layers until the individual entities are precise enough to be designed by a single developer.

Advanced Development

Before launching the full development effort, we need to perform advanced development to confirm the feasibility of key technologies and determine the optimal technical trade-offs for the final requirements and architecture.

Starting with a legacy design, we develop and test a series of reduced-scale prototypes of the core subsystem: the transducer that emits the acoustic signal. The physics of acoustic transduction dictate that the long wavelengths of seismic signals require mechanically large transducers, so even the scaled-down prototype shown in Figure 3 represents a significant engineering effort and expense. This testing helps us establish that such transducers are indeed practical and provides insight into the trade-offs incurred at larger scales.

Figure 3: Reduced-scale prototype testing at Seneca Lake in 2013

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One of the fundamental technical challenges is driving the transducer, as this requires an actuator exerting high forces over long displacements through the full 3-150 Hz bandwidth mandated by our requirements. We broaden the set of candidates and analyze each against key criteria in a systematic multi-stage trade-off study, reaching the conclusion that the optimal drive technology is electrohydraulic.

A viable system needs to support safe and efficient deployment from the existing seismic fleet, imposing tight constraints on the system design. We design a series of storage and handling concepts, integrating them with computer-aided design (CAD) models of our existing gun-decks. We also use these to estimate deployment times, which are an important input to the operational downtime.

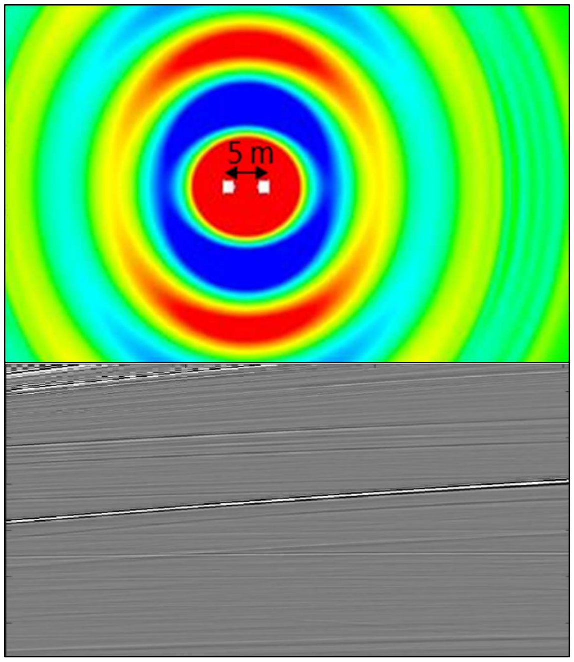

Figure 4: Examples of modeling domains. Upper panel: computational fluid dynamics simulation of pressure field from two transducers emitting in phase. Lower panel: synthetic seismic modeling.

Limiting operational downtime is vital for the financial viability of field operations, in particular when new technologies are introduced. We develop linked probabilistic models of operational productivity and system reliability, applying them in statistical simulations. This produces two important results: we confirm that our system can achieve the required operational uptime, and we apportion our reliability budget realistically to individual subsystems.

Our operational requirements dictate that the source be towed from existing seismic vessels, but this can be accomplished by a variety of means. We can maximize the acoustic energy by matching the depth of each transducer to the frequency band of its sweeps, but the resulting multi-depth geometry results in mechanical challenges. Similarly, producing a directional signal by combining two transducers into a gradient source (Laws et al., 2018b) places stringent demands on the precision of the towing geometry. We develop finite-element models of potential hardware designs and apply them in simulations under realistic current and sea-state conditions.

We input the expected system performance to geophysical models, producing operational scenarios of increasing realism. We begin with idealized survey scenarios, perhaps using novel acquisition techniques, but designed using perfect vibrators and a perturbation-free, noise-free acquisition. Then we make the acquisition scenario realistic by incorporating acquisition perturbations such as positional errors, inaccuracies in source-signature estimation, residual shot noise, vessel noise, ambient noise, and rough-sea effects. This shows us whether a ‘perfect’ vibrator could achieve the acquisition scenario that has been modeled. If it can, then we proceed to add the effects of imperfections in the source itself: distortion, limitations of output energy, inaccuracies of phase control, errors in positions within the array, and rough-sea towing effects. These simulations then reveal whether the device engineering is adequate or overly restrictive.

One of the key outcomes of this process is modularity: the size and number of individual acoustic emitters, and the range of available combinations. The transducer tests and actuator trade-off study establish limits on the acoustic output of each transducer, and the corresponding weights, dimensions, and power consumption. The results of the handling study further constrain the range of options to those that can be safely deployed while enabling high operational uptimes. The power consumption of each individual transducer is constrained by the power-carrying capacity of the umbilical cable, which is itself a function of transducer technology, existing vessel infrastructure, and limitations imposed by towing considerations. These physical concerns interact with geophysical goals. For example, the goal of maximizing the signal-to-noise ratio calls for powerful individual transducers, while the differences among operational scenarios call for dividing the acoustic output among a number of individual transducers emitting distinct signals from separate positions. To better understand these complex multi-dimensional trade-offs, we link the results of different modeling domains (Figure 4). We conclude that distributing the output among five to eight independently towed transducers is the optimal way to achieve our operational scenarios. For example, six transducers provide the required signal-to-noise ratio for the towed-streamer (conventional) scenario (Laws et al., 2018a).

Engineering Development

Having defined exhaustive requirements and architectures, we commit to the full-scale development of a commercial system. The comprehensive system definition enables this work to be divided into parallel and substantially decoupled sub-projects, reducing development time and risk. Although the transducer remains the system's core, the surrounding support infrastructure consumes the bulk of the project's development resources.

Our development strategy is based on incrementally reducing risk by continuously testing our design in models and simulations (Figure 5). Most of the models are domain-specific, for example computational fluid dynamics (CFD) to characterize the acoustic field emitted by the transducer, or towing simulations to optimize the transducers' positions in the water. We use these results to define simplified models with faster execution times, which we integrate in a higher-level system-integration model. Finally, we use these results to update the geophysical results produced earlier and ensure that our imaging objectives are achieved.

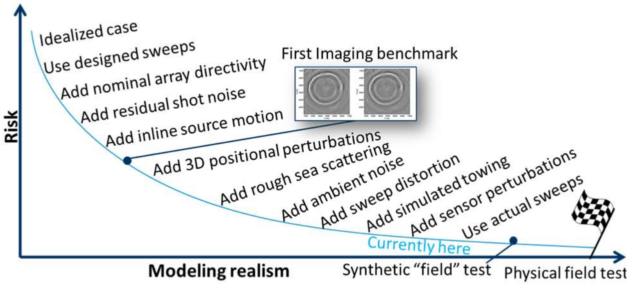

Figure 5: Incremental modeling-based risk reduction

Integration & Test

We will conclude the engineering-development process by individually testing each developed component, and then incrementally integrating multiple components into subsystems of increasing scope and complexity. At each step in this bottom-up integration process, we will perform thorough testing to ensure that all our requirements are fulfilled before proceeding to higher-level integration.

Although this methodical process does not produce seismic data as early as immediately combining the components in the field (known as 'big bang' integration), it exposes potential problems early when there are more options to resolve them. This approach lowers the risk of late-stage iterations, and we expect it to shorten our development time. We use models developed earlier to predict the expected results, and we will seek to confirm our expectations in physical tests. The test results will in turn be used to calibrate our models, in particular our geophysical results. We will test in increasingly realistic – and expensive – environments, with specific objectives at each step:

1. Software-testing environment
2. Environmental-test chambers
3. Acoustic-testing facility (Seneca Lake)
4. Supply boat for reduced-scale field test
5. Seismic vessel for full-scale deployment

We have finished development of our third-generation transducer, and at the time of writing are integrating and testing it in the laboratory. We plan to test the transducer and key supporting subsystems at the Seneca Lake Sonar Test Facility in the Summer of 2019. Our objectives are to validate our models of the transducer's mechanical design and full-power acoustic output.

Conclusions

We apply a systematic process, based on the classic 'Vee' systems-engineering model, to develop a new marine-vibrator system. We integrate computer models across technical disciplines to ensure that the physical system supports geophysical objectives, thereby reducing risk and accelerating development. The resulting modular, field-configurable system supports the full range of operational scenarios with five to eight transducers. We are preparing to test key subsystems, including the full-scale transducer, and will present performance measurements at the 2019 SEG Annual Meeting.

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