Establishing the Fundamentals of a Surface Ship Survivability Design Discipline

THE AUTHORS

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ABSTRACT

This paper describes a conceptual structure of ship survivability definitions and concepts and deals with the need to incorporate a total-ship approach to surface ship combat survivability as part of the philosophy used to guide a ship's design. Included are:

- **A discussion of the increasing emphasis placed on ship survivability during the ship system development process.**
- **Definitions of the different aspects of ship survivability, in order to suggest a coordinated and coherent understanding of their relationships.**
- **A discussion of the value of making survivability considerations an integral part of the ship design philosophy, to ensure a requirements-based systems approach to all of the ship's required attributes, including survivability.**

INTRODUCTION

The U.S. Navy can justly pride itself in the survivability of its ships. Dedicated U.S. Navy engineers have concerned themselves with ensuring that our ships are capable of meeting and defeating an enemy and bringing their crews home safely. The *Laffey* (DD 724), displacing only 3200 tons, when operating off Okinawa late in World War II, sustained hits from four Japanese bombs and 5 bomb-laden kamikaze airplanes while shooting down nine. Thanks to her high-survivability design (and her heroic and determined crew), she began her return trip to the U.S., on her own power, just 17 days later. This ship was clearly designed by U.S. Navy engineers who were concerned with ensuring her ability to survive.

BACKGROUND

In recent years, survivability has become a much more common subject of discussion than in the decades immediately preceding. For a time in the '60s and '70s, the Navy seemed to have accepted the thinking that nuclear weapons posed such on overpowering threat to ships that there was little need to emphasize features which would permit them to survive damage. A hit ship was a lost ship. Emphasis was placed primarily on offensive capability—shooting the archer before he could shoot his arrows. One can not deny that destroying the enemy before he can get off a shot is a highly desirable action. However, the rules of engagement, the changing world situation, and the increasing likelihood of Navy ships finding themselves engaged in combat from a "peacetime" footing all work toward making it more and more obvious that we must also consider the other half of survivability: the ability to survive a hit. A few years ago, the CNO's "Ship Operational Characteristics Study," SOCS (1988), listed "survivability and the ability to fight hurt" among the three Priority A imperatives for future surface combatants in a list of 12 such imperatives.

Furthermore, a number of legislative initiatives have mandated increased attention to survivability of weapons systems, including Navy ships (Public Law 95-485, 1978 and Public Law 99-718 of 1984). This legislation has been implemented by Navy and Defense Department directives (OpNav Instruction 9070 of September 1988). Today, survivability is clearly seen to be a critical concern.

Yet apparently not all naval engineers mean the same thing when they speak of survivability and confusion is even more evident in discussions of some related concepts. Is survivability the "ability to fight hurt?" Some authors use the term "staying power;" is that survivability? A CNO directive defined it as the capacity to "absorb damage and maintain mission integrity." Yet clearly the ability to avoid being hit in the first place can be a major contributor to a ship's survivability, even though this facet can take several forms. Low observability which prevents detection and targeting of the ship and shooting the "archer" before he fires his "arrows" are both ways to avoid being hit.

A discussion of survivability and a description of how these related, yet dissimilar, aspects of survivability fit together in a coherent conceptual framework is one purpose of this article.

Survivability concepts as well as design and measurement tools and techniques have been used in the aircraft design world for a number of years. In fact, survivability of aircraft, as a design discipline, is quite well-advanced. Clearly there are many similarities that can be applied profitably to Navy ships, but many differences remain. One of the most applicable features of aircraft survivability is its conceptual framework for describing, partitioning and teaching the concepts involved. The authors find these concepts to be essential in teaching survivability to naval officers at the Naval Postgraduate School in courses associated with both ship and aircraft design.

SURVIVABILITY PRINCIPLES

As we all well know, a Navy surface combatant must possess many attributes to meet its imposed requirements and many of these attributes conflict; trade-offs are the inevitable lot of the designer. Survivability is one (though a very important one) of those attributes. Of course, many ship features can enhance survivability. Let's define what we mean by survivability:

Definitions

We define surface ship combat survivability as "the capability of a surface ship to avoid and/or withstand a man-made hostile environment while performing its mission." The phrase "to avoid and/or withstand" is key to the definition. The inability of a ship to *avoid* the sensors, weapons and weapons effects of that man-made hostile environment is called *susceptibility*. In addressing the other half of that key phrase, the inability of the ship to *withstand* the effects of the hostile environment is called *vulnerability*.

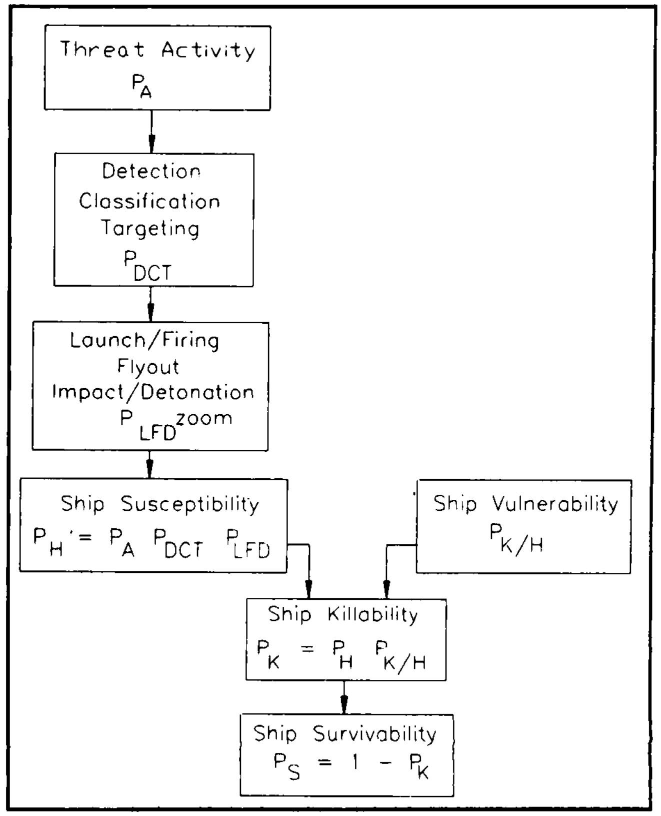

Figure 1.

Susceptibility

A ship's susceptibility, in a very general way, can be quantified by P_H, the probability the ship is hit by a weapon or its damage mechanisms (such as fragments). In assessing susceptibility we consider three sequential phases: the probability the threat is active (P_A); the probability of the enemy's detection, classification and targeting of the ship (P_{DCT}); and the probability that the enemy's weapon will successfully launch, fly out and impact (P_{LFI}).

Numerous factors under the control of the ship's designers, operators and requirements-setters affect susceptibility. Signature levels of various kinds; maneuverability; tactics; method of employment; electronic countermeasures; defensive and offensive weapons carried by the ship all affect its own susceptibility and its level of inability to avoid the effects of the hostile environment.

Vulnerability

The ship's vulnerability can be measured in a general way by $P_{K/H}$, the conditional probability of being killed, given a hit. Vulnerability has been referred to as the "post-hit phase" and features that reduce vulnerability will increase post-hit survivability. Vulnerability is also influenced by many ship and equipment attributes. Some of the features that reduce vulnerability include the ability of vital components to operate after a hit; design features that prevent or suppress the spread of damage to components not affected by the original hit; use of redundant systems and redundant components, and separation and protection of vital components.

In attempting to quantify overall survivability in light of the concepts of susceptibility and vulnerability, we must recognize that the words deal with complements—mathematical "opposites," if you will. Survivability is the *ability* to survive. Susceptibility and vulnerability are the *inability* to avoid or withstand, respectively, the effects of the hostile environment. This causes us to introduce the term "killability," the mathematical complement of survivability. If killability is measured by P_K, the probability the ship will be killed, then:

Killability = Susceptibility x Vulnerability

or

$$P_K = P_H * P_{K/H}$$

The ability of the ship to survive the hostile environment is measured by its probability of survival, P_S. The relationship between survivability and killability is:

Survivability = 1 - Killability

or

$$P_S = 1 - P_K$$

and, therefore:

$$P_S = 1 - (P_H * P_{K/H})$$

Figure 1 shows the relationship of these various measures of probability.

Ship Kills

The idea of a ship kill was used in the above discussion. We can, of course, define a kill in several ways and it need not necessarily imply total ship destruction. A ship kill can be defined in a way that is most useful in considering survivability features or in considering the ship's employment. Some common ship kill definitions (in order of decreasing severity) are:

- Total Kill: Ship is lost entirely because sinking occurs or fire (or other phenomenon) forces abandonment.
- Mobility Kill: immobilization or loss of controllability occurs.
- Mission Area Kill: Particular ship mission area (e.g. anti-air warfare) is lost.
- System Kill: Damage to one or more components results in loss of a system.

There is an obvious hierarchy in the above definitions; a system kill can lead to a mission area, mobility or total kill. A time element is involved also and any kill level can evolve into one above or below it. For instance, crew repairs may restore a lost system or mission area; progressive flooding or fire could, over time, turn a system or mission area kill into a total kill.

The purpose of our considering survivability concepts is, of course, to enhance the survivability of our ships. Recognizing the relationship of the various elements combined in the overall concept of survivability, as described above, permits us to address survivability enhancement in a coherent and complete way. Almost any feature we design into a ship will have penalties associated with it in the form of cost or weight or impact on other features. Therefore, it is useful to assign any feature under consideration to a category of survivability enhancement. This allows us, when developing the ship's design philosophy, to prioritize or assign weights to various categories. The evaluation of the value of a given feature is aided by our clear understanding of where it affects susceptibility, vulnerability and overall survivability. The following table illustrates twelve generic survivability enhancement concepts that are likely to apply to any survivability-related feature under consideration during the design of the ship:

Table 1. Survivability Enhancement Concepts

SUSCEPTIBILITY REDUCTION	VULNERABILITY REDUCTION
Threat Warning	Component Redundancy (with separation)
Jamming and Deception	Component Location
Signature Reduction	Passive Damage Suppression
Expendables (Decoys)	Active Damage Control
Threat Suppression	Component Shielding
Tactics	Component Elimination

Susceptibility reduction concepts are those that reduce P_A, P_{DCT}, or P_{LFI}. Survivability is enhanced through early warning of a threat and successful defeat of the threat's attack via jamming, deception or destruction of the threat. A low signature level or tactical measures may make the threat unable to successfully engage. Of course, threat suppression—destroying or disrupting the threat before the enemy can fire a weapon at us—is a survivability enhancer for a ship.

Vulnerability reduction concepts are those that reduce $P_{K/H}$. Concepts that decrease the likelihood of a ship kill given that the ship is hit include locating vital components in protected places; providing redundancy (while separating the redundant elements); shielding components, and intelligent design which reduces the number of components subject to damage. Passive damage suppression features and active damage control capabilities serve to control and limit damage and to restore capabilities, and are obvious reducers of $P_{K/H}$.

The recognition of these survivability enhancement concepts, and their relation to either susceptibility or vulnerability will assist in accurately categorizing the various ship features that must compete, through the trade-off process, for inclusion in the final design.

DESIGN PHILOSOPHY

In order to effectively take a systems approach to ship design, the design team must develop and employ a design philosophy firmly rooted in requirements. As we have noted, the process of designing a modern surface combatant, more than most engineering design efforts, requires tradeoffs. Almost any aspect of a ship's performance can be improved only at the expense of adversely affecting some other performance or cost attribute. Increased watertight subdivision hampers arrangements and livability; increased machinery power density may increase cost and decrease reliability; increased range will usually result in increased size and cost; signature reduction through shaping or surface treatment imposes penalties in the form of less efficient utilization of volume, or increased weight and cost. At all levels of the design team, trade-offs must be made on a continuing basis. Top team leadership can not be involved in each of these decisions. Thus, it is necessary for all team members to have available to them a well-understood guiding document to assist them in making trade-off decisions and to ensure that the entire team is making their individual trade-off decisions in a consistent framework. The document that serves this purpose is the design philosophy.

Early in the design process, the design team should develop this philosophy. It frequently takes the form of a list of ship attributes in priority order or a list of attributes given numerical weights. The ordering and weighting should be the result of thorough discussion by appropriate members of the design team: technical team members, program manager members and requirements setters. When specific trade-off decision need to be made, those involved can refer to the philosophy to assist them in deciding how to make the trade-off call to determine which attribute in a conflict should be give the higher priority or weight. Because survivability is important and can be affected by nearly any aspect or detail of the ship's design, it must be carefully considered and integrated when developing the design philosophy. Many ship attributes seem to have—and, in fact, do have—an effect on ship survivability. Most naval engineers have a gut feeling that more effective weapons improve our ship's survivability. But we also know that if the ship is hit, there are damage suppression and control features that improve survivability, too. Some features contribute in more than one area. They may contribute both to offensive mission performance and to survivability or to only one and not the other.

A clear understanding of the survivability principles discussed in this paper can contribute to the clarity and effectiveness with which these considerations are sorted out in the development of the design philosophy. The designers will be able to intelligently weigh features for their overall contribution to the ship's military effectiveness, including survivability. Concepts such as active and passive survivability, susceptibility and vulnerability will be well understood and their relationship to total ship performance will be appreciated and properly assessed.

CONCLUSION

We believe the principles and conceptual relationships outlined in this paper form the basis for an organized and coherent structuring of survivability discussion and investigation and can contribute to clearer discussion and improved communication in the Naval Engineering community.

We believe, as well, that the orderly addressing of survivability during the design of a combat ship should be guided by a clear application of these principles. The result will be a coherent approach to the weighing of survivability values during the design process. Of course, trade-offs will still have to be made. Some features will have to be compromised in order to enhance others. But a clear understanding of survivability concepts will go far in ensuring the consequences of trade-offs that ultimately affect survivability are recognized and understood and properly incorporated in the design philosophy.

REFERENCES

"Ship Operational Characteristics Study on the Operational Characteristics of the Surface Combatant of the Year 2010," Chief of Naval Operations, Staff (OP-03K), 26 April, 1988.

Public Law 95-485 of 1978 included the language "It is the policy of the United States to modernize the combatant forces of the United States Navy through the construction of advanced, versatile, *survivable*, and cost-effective combatant ships in sufficient numbers... the Navy should develop plans and programs for the construction and deployment of weapons systems, including naval aviation platforms, that are *more survivable*, less costly, and more effective..." [emphasis added].

Public Law 99-718 of 1987, under section 2366 of Chapter 139 of Title 10, U.S. code, addresses "Major systems and munitions programs: survivability and lethality testing; operational testing". The law states, in part, that "a covered system *may not* proceed beyond low-rate initial production until realistic survivability testing of the system is completed..."

OpNav Instruction 9070 of September 1988 established policy and assigned responsibility for incorporating survivability features in new surface ship design, overhauls, and new/existing combat systems and equipment.

Dictionary of American Fighting Ships, Vol. IX, Navy Department, 1969.

Ball, Robert E., The Fundamentals of Aircraft Combat Survivability Analysis and Design, (New York: AIAA, 1985).