Analysis and Modeling of IR Signatures by Optoelectronic Techniques and Countermeasures – A Technical Tutorial and Review

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Resumen

En el campo de las tecnologías engañosas para el análisis y modelado de firmas y contramedidas IR ha llamado recientemente la atención de varios investigadores debido a su importancia en la "Supresión de las firmas IR". Varios tipos de tecnologías como: tecnología de búsqueda de misiles infrarrojos, contramedidas infrarrojas direccionales (DIRCM), bengalas, contramedidas electrónicas (ECM), ECM de radar, ECM de aeronaves, ECM a bordo, sigilo utilizando materiales de baja observación, futuros materiales de aislamiento térmico, sigilo de raptor, IR Stealth, Radar Absorbing Materials y otras técnicas relacionadas han sido técnicamente analizadas y revisadas. La utilidad de las ventanas Emisividad y Aislamiento reflectante también se ha resaltado. Se espera que la revisión sea de gran ayuda para los nuevos participantes en el campo, y también para los diseñadores que se dedican a explorar las nuevas técnicas y aplicaciones en este campo.

Palabras clave: Actitud, Segundo grado, Educación, Física, Profesión docente.

Abstract

The field of Deceiving Technologies for Analysis and Modeling of IR Signatures and Countermeasures has recently drawn the attention of various researchers because of their importance in the "Suppression of the IR Signatures". Various types of the technologies like - Infrared Missile Seeker Technology, Directional Infrared Countermeasures (DIRCMs), Flares, Electronic Countermeasures (ECMs), Radar ECM, Aircraft ECM, Shipboard ECM, Stealth using Low Observable Materials, Future Thermal Insulating Materials, Raptor Stealth, IR Stealth, Radar Absorbing Materials, and other related techniques have been technically analysed and reviewed. The usefulness of the Emissivity windows and Reflective Insulation has also been highlighted. The review is expected to be of great help for the new entrants to the field, and also the designers engaged in exploring the novel techniques and applications in this field.

Keywords: Infrared Missile Seeker Technology, Directional Infrared Countermeasures(DIRCMs), Flares, Electronic Countermeasures (ECMs), Radar ECM, Aircraft ECM, Shipboard ECM, Stealth using Low Observable Materials, Thermal Insulating Materials, Raptor Stealth, IR Stealth, Radar Absorbing Materials, Emissivity Windows and Reflective Insulation.

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I INFRARED COUNTERMEASURE

An infrared countermeasure (IRCM) is a device designed to protect aircraft from infrared homing (*heat seeking*) missiles by confusing the missiles' infrared guidance systems so that they miss their target. A large amount of literature [1, 2] is available on this topic. One of the important studies is by Willers *et al.* [3], who have discussed the development and optimisation of the IR systems including the simulation systems to create the radiometrically realistic representations in the form of images of infrared scenes. These simulation systems are used in signature prediction, the development of surveillance and missile sensors, signal/image processing algorithm development, and the development and evaluation of the aircraft self-protection countermeasure system. It is now well understood that the presentation of an object's instantaneous signature is affected by various factors like the emissivity, spatial/volumetric radiance distribution, specular reflection, reflected direct sunlight, reflected ambient light, and atmospheric degradation. Hence for the accurate presentation of the object's signature by a computer simulation, the equations have to take account of all the elements of the signature. The term infrared signature is used to describe the appearance of objects to infrared sensors. An infrared signature is a complex factor depending on various factors like the shape and size of the object [4], temperature [5] and emissivity, reflection of external sources like sunshine from the object's surface [6], the background against which it is viewed [7] and the waveband of the detecting sensor. It has to be appreciated that it is not possible to formulate a complete definition of infrared signature, and also to design simple means of measuring it. It has also to be understood that the IR signature of a vehicle viewed against a field varies significantly with changing weather and time. Chopra [8-10] has briefly discussed the evolution of the "IR Sensors" and also the recent trends in this evolving field. There are many types of IRCM systems, and some of these are briefly described below: (i) INFRARED MISSILE SEEKER TECHNOLOGY Infrared missile seekers of the first generation typically used a spinning reticle with a pattern on it that modulates infrared energy before it falls on a detector (A mode of operation called Spin Scan). The patterns used differ from seeker to seeker, but the principle is the same. By modulating the signal, the steering logic can tell where the infrared source of energy is relative to the missile direction of flight. In more recent designs, the missile optics rotates and the rotating image is projected on a stationary reticle (a mode called Conical scan) or stationary set of detectors that generates a pulsed signal which is processed by the tracking logic. Most shoulder launched (MANPADS) systems use this type of seeker, as do many air defence systems and air to air missiles. The working principle of a type of missile is that it shoots off false heat targets, and thus confuses the missiles' IR guidance system so that it misses the target. The system has been improved over the years to be lighter, more portable, and more reliable, but the basic principle is the same. (ii) INFRARED SEEKERS BASED ON IRCM PRINCIPLES Infrared seekers are designed to track a strong source of infrared radiation (usually a jet engine in modern military aircraft). IRCM systems are based on modulated source of infrared radiation with a higher intensity than the target. When this modulated radiation is seen by a missile seeker, it overwhelms the modulated signal from the aircraft and provides incorrect steering cues to the missile. The missile will begin to deviate (wobble) from the target, rapidly breaking lock. Once an infrared seeker breaks lock (they typically have a field of view of 1 - 2 degrees), they rarely reacquire the target. By using flares, the target can cause the confused seeker to lock onto a new infrared source that is rapidly moving away from the true target. The modulated radiation from the IRCM generates a false tracking command in the seeker tracking logic. The effectiveness of the IRCM is determined by the ratio of jamming intensity to the target (or signal) intensity. This ratio is usually called the J/S ratio. Another important factor is the modulation frequencies which should be close to the actual missile frequencies. For spin scan missiles, the required J/S is quite low; but for newer missiles, the required J/S is quite high requiring a directional source of radiation (DIRCM) [1].

(iii) DRAWBACKS OF IRCM. One of the drawbacks of standard IRCM systems is that they broadcast a bright source of infrared. If the modulation of the signal is not effective against a particular seeker system, the IRCM will enhance the ability of the missile to track the aircraft. The aircrews typically brief about potential threats and choose an IRCM modulation that will be effective against likely threats. This problem can be overcome by using a directional source of radiation, as explained below: (iv) DIRECTIONAL INFRARED COUNTERMEASURES (DIRCMs). The principle and working of Directional Infrared Countermeasures are very simple. They are able to overcome the above mentioned drawback by mounting the energy source on a movable turret (much like a FLIR turret). They only operate when cued by a missile warning system of a missile launch, and use the missile plume to accurately aim at the missile seeker. The modulated signal can then be directed at the seeker, and the modulation scheme can be cycled to try to defeat a variety of seekers. Countermeasure success depends on threat's tracking techniques and requires threats' analysis capabilities [2]. Defeating advanced tracking systems requires a higher level of DIRCM power. Issues of Laser Safety are also taken into account. (v) Common Infrared Countermeasures (CIRCMs) and Flares CIRCM is a laser based IR countermeasures solution against current and future IR threat systems. Currently many commercial firms are making devices for such countermeasures. Flares create infrared targets with a much stronger signature than the aircraft's engines. The flares provide false targets, mislead the missile to make incorrect steering decisions, and hence result in the missile's rapidly breaking off a target lock-on.

II ELECTRONIC COUNTERMEASURE

An electronic countermeasure (ECM) is an electrical or electronic device designed to trick or deceive radar, sonar or other detection systems, like infrared (IR) systems or lasers. It may be used both offensively and defensively to deny targeting information to an enemy. The system may make many separate targets appear to the enemy, or make the real target appear to disappear or move about randomly. It is used effectively to protect aircraft from guided missiles. Most air forces use ECM to protect their aircraft from attack. It has also been deployed by military ships and recently on some advanced tanks to fool laser/IR guided missiles. It is frequently coupled with stealth advances, so that the ECM systems have an easier job. Offensive ECM often takes the form of jamming. Defensive ECM includes using blip enhancement, and jamming of missile terminal homers. (i) RADAR ECM Radar ECM is very strategic from the point of view of ECM systems. The various strategies have been briefly mentioned in the following paragraph: Basic radar ECM strategies are (i) radar interference, (ii) target modifications, and (iii) changing the electrical properties of air. Interference techniques include jamming and deception. Jamming is accomplished by a friendly platform transmitting signals on the radar frequency to produce a noise level sufficient to hide echoes. The jammer's continuous transmissions will provide a clear direction to the enemy radar, but no range information. Deception may use a transponder to mimic the radar echo with a delay to indicate incorrect range. Transponders may alternatively increase return echo strength to make a small decoy appear to be a larger target. Target modifications include radar absorbing coatings and modifications of the surface shape to either "stealth" a high-value target or enhance reflections from a decoy. Dispersal of small aluminum strips called chaff is a common method of changing the electromagnetic properties of air to provide confusing radar echoes.

(ii) AIRCRAFT ECM. The ECM is an essential part of all the modern military aircraft, and is practiced by nearly all modern military units—land, sea or air. Aircraft, however, are the primary weapons in the ECM battle because they can "see" a larger patch of earth than a sea or land-based unit. When employed effectively, ECM can keep aircraft from being tracked by search radars, or targeted by surface-to-air missiles or air-to-air missiles. On aircraft ECM can take the form of an attachable under wing pod or could be embedded in the airframe. Active Electronically Scanned Array (AESA) radars like those mounted on the modern fighter aircraft can also act as an ECM device to track, locate and eventually jam enemy radar. The Previous radar types were in general not capable of performing these activities. The dedicated ECM Aircraft are very useful in completing the assigned task, and the various examples of the dedicated ECM Aircraft are Compass Call, communications jammer, multi-band track breaking system, tactical jammer pods.

(iii) SHIPBOARD ECM The ECMs have also been usefully employed on ships. The deception transmitter and the ECM package providing warning, identification and bearing information about radar-guided cruise missiles were the early designs of ECM installed on the ships. These are briefly explained in the next paragraph.

A type of deception transmitter was one of the earlier shipboard ECM installations. The commercially available ECM package is in three versions providing warning, identification and bearing information about radar-guided cruise missiles. Another type of system includes quick reaction electronic countermeasures for cruisers and large amphibious ships and auxiliaries in addition to the RBOC (Rapid Blooming Off-board Chaff) launchers found on most surface ships.

(iv) HEAT AND SOUND ANALOGIES Sound detection and homing systems used for ships are also susceptible to countermeasures. A number of research works on electronic warfare and the related electronic countermeasures have been reported in the literature, and some of the studies are very important for the technologists engaged in this field. IR homing systems can be decoyed with flares. Some systems are used to create small air bubbles around a ship's hull and wake to reduce sound transmission. Surface ships tow noisemakers to decoy homing torpedoes. Submarines can deploy similar acoustic device countermeasures (ADCs) from a signal launching tube. Some ballistic missile submarines can deploy mobile submarine simulator decoy from torpedo tubes to simulate a full size submarine.

(v) DIRECTIONAL INFRARED COUNTERMEASURES Directional Infrared Counter Measures (DIRCM) is a system to protect aircraft from infrared homing. Some of the notable DIRCM systems have been briefly described and explained below: Directional Infrared Counter Measures (DIRCM) are commercially available to protect aircraft from infrared homing i.e. heat seeking man-portable missiles. These are lightweight, compact systems designed to provide mission-vulnerable aircraft with increased protection from common battlefield threats. It is more advanced than conventional infrared countermeasures. The term DIRCM is used as a generic term to describe any infrared countermeasure system that tracks and directs energy toward the threat. The method of operating the DIRCM is very simple. The system uses an active method of jamming of infrared missile seekers through the sensor aperture. The system can be placed in either active or standby mode. In the standby mode the aircrew must select the active mode to begin jamming IR threats. The pulsing flashes of IR energy confuse the missile guidance system. The system consists of a missile warning system, an integration unit, a processor, and laser turrets (Small Laser Targeting Assembly, SLTA). While the early versions used an arc lamp to generate the jamming signal, the newer versions use diode-based pump systems.

(vi) IR COUNTERMEASURES (IRCMs) IRCMs are of two types – Passive and Active. The Passive countermeasures use exhaust system, and the important factors in these systems are: Fuselage IRSS, Aircraft skin heating/cooling, and the Emissivity optimization. However, these systems suffer from the limitations of IR suppressors. The Active countermeasures act as Counters for the countermeasures i.e. Counter–countermeasures.

(vii) MISSILE WARNING AND COUNTERMEASURE SYSTEMS IN-FIGHTING TESTING The Missile warning and countermeasure systems in-flight testing have been the subjects of great interest in the recent times. It has been emphasized that the testing a complex MWS/countermeasure system performance before deployment requires more realistic simulation of the threats in their natural backgrounds, and faster measurement of the radiometric output, directionality and time response of the countermeasures. This is because of various factors like **–** (i) The IR sensors are becoming more sensitive for longer range of detection, (ii) the spatial resolution is improving for better target detection and identification, and (iii) spectral discrimination is being introduced for lower False Alarm Rate (FAR), and (iv) the imaging frame rate is increasing for faster defensive reaction.

III STEALTH USING LOW OBSERVABLE MATERIALS

Stealth using low observable materials enables the control or reduction of the signatures of weapon systems.

Signatures are those characteristics by which weapon systems may be detected, recognized, and engaged. The modification of these signatures can improve the survivability of military systems, leading to improved effectiveness and reduced casualties.

Signature detection commonly amounts to the electromagnetic signature of an object. The spectral regions of interest for low observable technologies are the visible range, the infrared (IR) range, and the radar portion of the spectrum. The emphasis to date has been on radar stealth, and thus radar-absorbing materials have received significant attention. However, with the development of infrared (IR) detection technology such as missile guidance systems and thermal cameras, the need for effective IR stealth capabilities is pressing for air, land, and sea defenses. The low observable coatings render IR detection of an object more difficult. These coatings are multipurpose materials that may be tuned for specific missions, or used in standard configurations. For example, they may be designed solely for IR stealth (without compromising the radar cross section of the host), or for both IR and radar stealth simultaneously.

(i) RAPTOR STEALTH Raptor stealth is one of the important deceiving technologies, and is described and discussed below: Some aircraft have an adherence to fundamental shaping principles of a stealthy design. The leading and trailing edges of the wing and tail have identical sweep angles (a design technique called plan form alignment). The fuselage and canopy have sloping sides. The canopy seam, bay doors, and other surface interfaces are saw-toothed. The vertical tails are canted. The engine face is deeply hidden by a serpentine inlet duct and weapons are carried internally. Advances in low-observable technologies provide significantly improved survivability and lethality against air-to-air and surface-to-air threats. The aircraft using the combination of reduced observability and super cruise accentuates the advantage of surprise in a tactical environment. The most publicized and most revolutionary technology for aircraft is stealth. Stealth makes an object become very difficult to detect by sensors such as radar, heat seekers (infrared), sound detectors and even the human eye. While not invisible, some aircraft's radar cross section is comparable to the radar cross sections of birds and bees, and hence is much more difficult to detect. Low observability is achieved by a range of measures like (i) employing the planform shaping and faceting with blended facet boundaries, for achieving high performance aerodynamics, (ii) using serrated edges to control the returns from panel boundaries. The planform results in a multiple lobe design, as the boundaries of the major surfaces are not parallel with respect to each other. Planform return lobe structure is defined by the radiation pattern lobes resulting from surface wave reflections which occur at the leading and trailing edges of the airframe's major surfaces. To make a stealthy aircraft, designers had to consider five key ingredients: reducing the imprint on radar screens, muffling noise, turning down the heat of its infrared picture, stifling radio transmissions and making the plane less visible. The leading and trailing edges of the wing and tail have identical sweep angles (a design technique called planform alignment). The fuselage and canopy have sloping sides. The canopy seam, bay doors and other surface interfaces are saw-toothed. The vertical tails are canted. The engine face is deeply hidden by a serpentine inlet duct and weapons are carried internally.

(ii) RADAR STEALTH Several existing technologies address the problem of radar stealth. The principle of this technology consists of designing the exterior geometry of a mobile or stationary unit to reflect radar radiation in a direction that makes it difficult to detect. A drawback of this technology is that it imposes geometrical constraints that may decrease the performance of airborne units. Geometrical constraints prove less problematic for ships, land vehicles and stationary infrastructure.

(iii) INFRARED STEALTH Infrared stealth is a part of stealth technology, which is used for reducing IR signatures [11]. This is used for the reduction of the platform's susceptibility to IR guided weapons and IR surveillance sensors [12]. IR Stealth is also an important deceiving technology, which covers the IR spectrum, and is discussed below: IR discretion techniques focus on bands II and III which are transmission bands in the earth's atmosphere. Band II covers the range 3 to 5 mm while band III covers the range 8 to 12 mm. Band II is exploited primarily by missile guidance systems and band III by thermal cameras. Another wavelength of interest is 1.064 mm, which is the wavelength used by the majority of laser range-finders. IR discretion technology may be divided into two areas: IR suppression and IR deception.

IV IR SUPPRESSION TECHNOLOGY

IR suppression technology focuses on three areas: (i) Reducing the target's radiation intensity; (ii) Simulating the IR characteristics of the background; and (iii) Deformation of the IR signature. Some materials work in areas (i) and (iii) simultaneously. They are low emissivity materials, and thus reduce the target's radiation intensity. As their emissivity may be tuned, they may be used to modify the IR signature of the target.

(i) CURRENT TECHNOLOGIES FOR IR SUPPRSSION There are many technologies for the IR suppression. These are based on the fact: The current low emittance materials are based upon electronically conductive materials such as aluminum alloys with varying geometries and granularity. These materials are suspended in a varnish that is painted onto the equipment. This approach proves economically attractive, but suffers from two major disadvantages: (i) It is possible to recreate the real temperature of an object from a spectral analysis of the emission, and (ii) A high concentration of the active substance is needed to achieve a low emittance, which in turn compromises any pre-existing RAM properties.

(a) ACTIVE COATING METHODS A technique to decrease the temperature of hot gases expelled by engines is to inject cold air into the hot gas stream. The majority of aircrafts that enjoy a reduced radar cross-section (RCS) use this technique. However, this technique prevents manufacturers from exploiting post-combustion, which reduces the maximum thrust achievable with these engines.

(b) Thermal insulating materials /radar absorbing materials (RAMs) It is possible to place thermal insulating materials over a thermal source to alter its IR signature. However, a disadvantage of this strategy is that the temperature of the thermal source will rise; resulting in possible damage to the source (it may contain sensitive electronics or mechanical components). In addition, it is difficult to maintain large thermal gradients over thicknesses comparable to that of typical IR stealth coatings, so that thermal insulating materials often come with a high thickness and weight penalty. RAM may be applied to critical parts of air born units as well as to land vehicles and infrastructure. An inconvenience of this type of treatment is that it is not effective against all radar frequencies. In addition, for longer wavelength radar the thickness of the coatings must increase (increasing the weight of the coating as well). The active materials used in RAM consist of different types of ferrites as well as conducting polymers such as polyaniline or polypyrolle.

(ii) IR CAMOUFLAGE NET/ /IR DECEPTIONS IR camouflage nets can effectively reduce the radiation contrast of a target at hot or ambient temperatures with the background. They can also change the radiation distribution of the target. IR deceptions are mainly Luring and Decoys, each of which is briefly explained below:

The original means of luring first generation missiles consists of flying the aircraft towards the sun, and then, if possible, performing a drastic evasive maneuver in the hope that the missile's guidance system locks onto the signal coming from the sun. Currently the main technique used for luring involves launching a packet of chaff from the unit being targeted in order to create a secondary radar image that overwhelms the original image. This technique is problematic for naval vessels due to the possibility of variable winds that may blow the chaff in undesirable directions. In addition certain missiles are equipped to counter this lure and to remain locked onto the original target. Another technique involves flying in pairs along the same direction, but separated by several miles. The trailing aircraft performs an evasive maneuver in the hope that the missile locks onto the lead aircraft, which is beyond the missile's range. Second generation guidance systems operate in band II and are not deceived by the techniques described above. One deception technique useful against these systems is the launching of thermal decoys by the aircraft in such a way as to lure the missile toward the false target. This technique proves relatively ineffective against guidance systems that contain imaging capabilities since these systems allow the missile to remain locked onto the original thermal image of the aircraft. Possible means of evading these missiles include modifying the thermal image of the aircraft, reducing the thermal emission of the aircraft to make detection more difficult, or increasing the thermal emission of the aircraft in order to saturate the missile's detectors.

V ACTIVE NEUTRALIZATION

The technology of neutralization consists of analyzing the radar environment in which a unit is immersed in order to generate and emit a radar signal of equal magnitude but opposite phase resulting in the nullification of the total radar signal reflected by the unit. This system can be adapted to all radar frequencies but requires powerful calculation capabilities in order to analyze the radar environment in real-time. In addition the problem of emitting a multitude of radar frequencies is currently not resolved, especially for aircraft.

(i) COOLING COATINGS The primary cooling method for most thermal spray operations is forced air cooling using compressed air jets. However, the oxygen, residual moisture and hydrocarbons in the cooling air are often detrimental to the coating quality. Because air cooling alone is usually insufficient, interpass cooling breaks must be introduced into the process, which reduces productivity. In addition, when the spray gun is moved away from the part during these cooling breaks, it continues firing, resulting in wasted feed powder and process gases.

(ii) COOLING WITH CRYOGENIC NITROGEN With the cryogenic nitrogen thermal spray cooling technology, the part's temperature is maintained within a much tighter range during the spray operation. Also, the spraying time and amount of powder and process gases consumed are cut in half, and productivity is improved.

VI IMPROVED QUALITY AND PROCESSES

The effects of cooling on silicone-based masking tapes during HVOF spray application have been studied. The new cryogenic nitrogen vapor cooling technology has been shown to reduce thermal fluctuations during spray operations. The microstructure, mechanical and physical properties of nitrogen-cooled coatings were tested and proved to be as good as or better than those of air-cooled coatings. Testing of nitrogen-cooled parts showed substrate hardness and micro porosity improvement over air-cooled samples, while bond strength, coating hardness, residual stress and surface roughness of the as-sprayed coatings were essentially unchanged. In addition, oxygen pickup and carbon loss in the coating were the lowest for the nitrogen-cooled sample.

(i) LOW EMISSIVITY Low emissivity (low *e*) is a quality of a surface that radiates, or emits, low levels of radiant energy. All materials absorb, reflect and emit radiant energy. Emissivity is the value given to materials based on the ratio of heat emitted compared to a blackbody, on a scale of 0 to 1. A blackbody would have an emissivity of 1 and a perfect reflector would have a value of 0. Reflectivity is inversely related to emissivity and when added together their total should equal 1. Conversely, a low-*e* material such as aluminum foil has an emissivity value of 0.03 and a reflectance value of 0.97, meaning it reflects 97% of radiant energy and emits only 3%. Low-emissivity building materials include window glass manufactured with metal-oxide coatings as well as housewrap materials, reflective insulations and other forms of radiant barriers. The emissivity values of the surfaces of some materials in use are: Asphalt 0.90-098, Aluminum foil 0.030-0.05, Fiber glass 0.8-0.9, Plaster 0.91, Silver 0.02, and Steel 0.12.

(ii) EMISSIVITY WINDOWS Window glass is by nature highly emissive as indicated in the table above. To improve thermal efficiency (insulation properties) thin film coatings are applied to the raw soda-lime glass. There are two primary methods in use: pyrolytic CVD and Magnetron Sputtering. The first involves deposition of fluorinated tin oxide (SnO2:F see Tin dioxide uses) at high temperatures. Pyrolytic coatings are usually applied at the Float glass plant when the glass is manufactured. The second involves depositing thin silver layer(s) with antireflection layers. Magnetron sputtering uses large vacuum chambers with multiple deposition chambers depositing 5 to 10 or more layers in succession.

Silver based films are environmentally unstable and must be enclosed in an Insulated glazing or Insulated Glass Unit, IGU to maintain their properties over time. Specially designed coatings, are applied to one or more surfaces of insulated glass. These coatings reflect radiant infrared energy, thus tending to keep radiant heat on the same side of the glass from which it originated, while letting visible light pass. This results in more efficient windows because radiant heat originating from indoors in winter is reflected back inside, while infrared heat radiation from the sun during summer is reflected away, keeping it cooler inside.

Glass can be made with differing emissivities, but this is not used for windows. Certain properties such as the iron content may be controlled changing the emissivity properties of glass. This is "naturally" low emissivity, found in some formulations of borosilicate or Pyrex. Naturally low-e glass does not have the property of reflecting IR radiation, instead this type of glass has higher IR transmission leading to undesirable heat loss (or gain) in a building window.

(iii) REFLECTIVE INSULATION Reflective insulation is typically fabricated from aluminum foil with a variety of core materials such as low-density polyethylene foam, polyethylene bubbles, fiberglass, or similar materials. Each core material presents its own set of benefits and drawbacks based on its ability to provide a thermal break, deaden sound, absorb moisture, and resist combustion during a fire. When aluminum foil is used as the facing material, reflective insulation can stop 97% of radiant heat transfer. Recently, some reflective insulation manufacturers have switched to a metalized polyethylene facing. The long-term efficiency and durability of such facings are still undetermined.

Reflective insulation can be installed in a variety of applications and locations including residential, agricultural, commercial, and industrial structures. Some common installations include house wraps, duct wraps, pipe wraps, under radiant floors, inside wall cavities, roof systems, attic systems and crawl spaces. Reflective insulation can be used as a stand-alone product in many applications but can also be used in combination systems with mass insulation where higher R-values are required.

(iv) EXHAUST GAS COOLING The commercially available exhaust gas cooling (ECG) products help today’s engine, truck and passenger vehicle manufacturers. They meet the increasing requirements for reduced emissions by cooling the exhaust gas being returned to the intake of the engine, also known as Exhaust Gas Recirculation (EGR).

The three types of EGC products available are: the traditional Shell and Tube, the high performance Bar and Plate and the new Drawn Cup. The Shell and Tube product is an economical design of proven construction that meets all of today’s Passenger Vehicle emission requirements. The Bar and Plate product has more packaging flexibility, is higher performing and can meet the more demanding emissions requirements of today’s Commercial Vehicles. The new Drawn Cup design is targeted to be a moderate cost, high performing unit that can meet the demands of tomorrow’s increasingly rigorous emissions requirements.

(v) EXHAUST PLUME REDUCTION AND COOLING SYSTEM A radiation suppressor for exhaust turbine or other engines reduces the lock-on range in infrared seeking missiles. Engine exhaust gases drive an exhaust turbine which includes a self-contained turbo-fan assembly and a surrounding plenum-shroud assembly both of which are structurally supported by the aircraft. The turbo-fan assembly consists of a turbine wheel having a top or outer fan for providing both hot metal and plume cooling air and a central centrifugal blower to partially cool the hollow turbine blades. The duct assembly in conjunction with ambient air passages distributes plume cooling air. Also, a plenum-shroud assembly surrounding these assemblies includes internally cooled radial vanes disposed in a turbine shroud for cooling air

(vi) EJECTOR PLUME COOLING SYSTEM Air-to-air Ejector Plume Cooling System is used to achieve a reduction in the exhaust gas plume temperature for a vertical uptake. A typical device will cool the plume to below 250 degrees C. However, lower plume temperatures can be achieved by increasing the size of the device. The Ejector Plume Cooling System is comprised of the three main components: (i) A multi-lobed nozzle, (ii) A mixing tube, and (iii) A plume dispersion system. The mixing tube is located downstream of the nozzle and provides a flow channel within which the ejected cool air is mixed with the hot exhaust gas. A plume dispersion system can optionally be specified to separate the plume into multiple cores, accelerating its dispersion once the gas exits into the free stream. The Ejector Plume Cooling System provides the same plume cooling performance as the Davis device. In some applications, the interest is in the plume cooling, in which case, the Eductor/Diffuser is selected in order to also achieve low IR signature.

The main benefits of the Davis Ejector Plume Cooling Systems are: (i) Scalable to fit any sized uptake; (ii) Shape can be customized to direct the plume away from ship structure and mast; (iii) Passive operation requires no maintenance; and (iv) Simple design for easy integration

(vii) COOLING SYSTEM FOR A DIVERGENT SECTION OF A NOZZLE A nozzle cooling system having apparatus to over expand the exhaust flow in a divergent section of an aircraft gas turbine engine nozzle, relative to the air in the engine nozzle's bay and a valve to allow ambient air from the bay to flow over divergent flaps and seals of the divergent section, and rapidly cool the divergent section of the nozzle for IR suppression.

An area ratio control apparatus may be used to change a ratio of the nozzle exit area to the nozzle throat area to an over expanded level that reduces static pressures along at least a longitudinally extending portion of the surfaces to below the ambient pressure of air outside the nozzle to draw the ambient air into the exhaust gas flowpath, and a valve apparatus to controllably flow the ambient air into the exhaust gas flowpath when the static pressures are below the ambient pressure.

Further embodiments of the present invention provide alternative area ratio control apparatus, such as a variable exit area control apparatus to vary the exit area or a variable throat area control apparatus to vary the throat area, or both. Valve apparatus with a gap apparatus to controllably open gaps between the circumferentially adjacent divergent flaps and seals are provided. These are - the spring loaded divergent seal retainers and flapper valves sealingly disposed over corresponding cooling apertures through the divergent seals.

VII INFRARED SUPPRESSORS FOR A GAS TURBINE

An IR suppressor produces a thin "ribbon" exhaust plume using a tapered exhaust manifold which has a plurality of discrete exhaust nozzles that are longitudinally aligned with the exhaust manifold. Optionally, the nozzles extend within but are spaced apart from mixing ducts which are open to the ambient air at both ends. The mixing ducts mix ambient air with the exhaust plume. In another aspect of this invention, a single nozzle (which is longitudinally aligned with the manifold) is substituted for the plurality of discrete exhaust nozzles. In this aspect, the nozzle extends within but is spaced apart from a mixing duct which is open at both ends and has a curve sufficient to block a line of sight to the nozzle. A helicopter that has a rotatable IR suppressor so that the exhaust can be directed substantially parallel to the helicopter blades when the blades are not turning to protect them from exhaust heat is also disclosed.

(i) APPARATUS FOR SUPPRESSING INFRARED RADIATION EMITTED FROM GAS TURBINE ENGINE An apparatus for and method of suppressing infrared radiation emitted from hot metal parts at the aft end of a gas turbine engine and from the exhaust gas plume thereof is provided and such apparatus comprises a dual purpose ejector vane assembly operatively attached to the engine for introducing cooling ambient air into the hot engine exhaust gases and hiding the hot metal parts.

(a) METHOD OF SUPPRESSING IR RADIATION EMITTED FROM GAS TURBINE ENGINE The vane assembly has a duct structure for receiving and confining the engine exhaust gases and the assembly provides at least one stream of cooling ambient air across one full dimension of the duct structure and exhaust gases confined thereby with the stream of cooling ambient air mixing with the hot engine exhaust gases across the full dimension of the duct structure to assure optimum mixing thereof.

(b) RADIANT ENERGY SUPPRESSOR Three concentric circular cylinders having a common vertical axis form an assembly which bolts to the louvered top of the heat engine enclosure of a military vehicle. The inner cylinder receives the tailpipe of the exhaust system and terminates in a horizontal plane above the tailpipe end. The outer cylinder terminates in a second horizontal plane above the first plane. The intermediate cylinder lies between the two horizontal planes. The annular spaces between the cylinders are open-ended for the upward flow of cooling air through the spaces. The intermediate cylinder substantially narrows the cone of visibility of heated interior surfaces to infrared radiation sensors.

(c) RADIATION SHIELDING APPARATUS Radiation Shielding Apparatus is a device for shielding a heated surface from infra-red detection through an opening adjacent to the heated surface. The device includes a gas-conducting member, which is adapted to receive heated gases, and has an exterior surface, an interior surface, an inlet for receipt of heated gases from the opening, and an outlet for the discharge of gases. The gas-conducting member has a configuration which blocks the inlet to the member from line-of-sight view through the outlet to the member.

(d) GAS DIFFUSION APPARATUS Additionally, the device draws cooling air over the exterior surface of the gas-conducting member. The cooling air may then be mixed with the heated gases within the gas conducting member. This provides cooling of the gas-conducting member to prevent the member from being visible to infra-red detection and may also provide cooling of the gases which are discharged from the outlet of the gas-conducting member by mixing of the heated gases with the cooling air.

(e) INFRARED SUPPRESSION SYSTEM FOR A GAS TURBINE ENGINE. An infrared suppression system is provided for an aircraft gas turbine engine for reducing the level of emitted infrared radiation from the engine exhaust. The hot exhaust stream emitted from the engine is mixed with the cooling airflows received from a plurality of sources in order to more effectively reduce the level of emitted infrared radiation. In addition, the infrared suppression system prohibits a direct line of sight back into the core engine.

(ii) COMBINED IR AND SOUND SUPPRSSIOR FOR AIRCRAFT JET ENGINE For reducing line-of-sight, infrared radiation and exhaust noise from the tailpipe of a jet aircraft engine, a plurality of hollow helical vanes with porous walls and supplied internally with pressurized coolant fluid are mounted co-axially and in symmetrically distributed arrangement, within a hollow tailpipe, the inner wall of which is also porous. Each vane has circumferential extent within the tailpipe sufficient to completely mask line-of-sight exposure into the engine from any point aft of the plane of the exit end of the tailpipe and to provide acoustic baffling and swirl for external mixing. Where the engine has an axial tail cone or bullet, the inner edges of the vanes may define a hollow axial core equal in diameter to the bullet.

(a) ACOUSTIC DAMPING AND COOLING OF TURBOJET EXHAUST DUCTS The invention proposes a solution to the problem of noise damping and cooling in high-temperature zones in turbojet exhaust ducts. A material which consists basically of one or more single corrugated cores having a standardized profile and clearly defined characteristics in regard both to its dimensions and its flexural properties lengthwise of the corrugations, is associated in accordance with this invention to other materials for the purpose of constituting a plurality of chambers forming a separation duct between the hot and cool flows through a turbojet. These chambers, termed noise attenuating chambers when they lie on the side of the hot flow, or cooling chambers when they lie on the side of the cool flow, are arranged substantially longitudinally in relation to the direction of said flows, thereby to minimize the loss of thrust caused by wall friction.

(b) SERRATED NOZZLE TRAILING EDGE FOR EXHAUST NOISE SUPPRESSION A nozzle for a gas turbine engine is provided with undulations on a core and/or fan exhaust flow nozzle. An annular wall defines a fluid flow passage and includes a base portion and an adjoining exit portion. The base portion is typically generally frustoconical in shape and includes an arcuate (curved) contour in an axial direction. The exit portion includes undulations in a generally radial direction that provide lobes and troughs each respectively including trailing edges. One of the lobe and trough trailing edges are recessed from the other of the lobe and trough trailing edges in a generally axial direction. The other of the lobe and trough trailing edges form apexes with the apexes provided on tabs. The troughs extend radially inward in the axial direction towards the trough trailing edges.

(c) EFFECT OF SUCTION NOZZLE MODIFICATION ON THE PERFORMANCE AND AERO-ACOUSTIC NOISE OF A VACUUM The suction nozzle of a vacuum cleaner was modified to enhance the power performance and to reduce the airflow-induced acoustic noise. The suction power efficiencies of the vacuum cleaner were measured for various nozzles: (i) original nozzle, (ii) original nozzle with modified trench height, (iii) original nozzle with modified connecting chamber, and (iv) a combination of (ii) and (iii). In addition, the suction pressure and sound pressure level around the suction nozzle were measured to validate the reduction of acoustic noise. The power efficiency and mean suction pressure increased when the trench height of the suction nozzle was increased. This was attributed to the suppression of the flow separation in the suction channel. Modification of the connecting chamber in the original nozzle, which had an abrupt contraction from a rectangular chamber into a circular pipe, into a smooth converging contraction substantially, improved the suction flow into the connecting pipe. When both modifications were applied simultaneously, the resulting suction nozzle was more effective from the viewpoints of aerodynamic power increase and sound pressure level reduction.

(d) INFRARED SIGNATURE SRUDIES OF AEROSPACE Infrared (IR) emissions from aircraft are used to detect, track, and lock-on to the target. MAN Portable Air Defence Systems (MANPADS) have emerged as a major cause of aircraft and helicopter loss. Therefore, IR signature studies are important to counter this threat for survivability enhancement, and are an important aspect of stealth technology. The role of atmosphere in IR signature analysis, and relation between IR signature level and target susceptibility are very important. Also, IR signature suppression systems and countermeasure techniques are very effective.

VIII MATHEMATICAL CALCULATIONS

The mathematical calculations of the Radiation in the Combustion Flows, Lock-on Envelope, and the Order of the IR Signature values are very important for these studies, and are explained below:

(i) RADIATION IN THE COMBUSTION FLOWS The radiation in the combustion flows can be comuted by using one of the models given in the literature. The weighted-sum-of-gray-gases model (WSGGM) is the commonly employed model, which is a reasonable compromise between the oversimplified gray gas model and a complete model which takes into account the particular absorption bands. This model is based on the assumption that the total emissivity over the distance S can be presented as:

$$\varepsilon = \sum_{i=0}^{I}[a\varepsilon_i(T)\{1-\exp(-K_i PS)\}], \tag{1}$$

where $a\varepsilon_i$ (T) are the emissivity weighting factors for the ith fictitious gray gas, being the function of temperature T, the bracketed quantity is the ith fictitious gray gas emissivity, K_i is the absorption coefficient of the ith gray gas, P is the sum of the partial pressures of all absorbing gases, and S is the path length. The values of the emissivity depend on gas composition, and temperature, while the value varies only with the gas composition, and the absorption coefficient.

The temperature dependence of aε,i can be approximated by the following function:

$$a_{\varepsilon,i} = \sum_{j=1}^{JI}[b\varepsilon_{,j}\{(T^{j-1})\}], \tag{2}$$

where $b\varepsilon_{,j}$ are the emissivity gas temperature polynomial coefficients. The coefficients $b\varepsilon_j$ and K_i are estimated by fitting Equation (1) to the table of total emissivities, obtained experimentally. In the general case, absorptivity α of the radiation from the wall is estimated as:

$$\alpha = -\{\ln(1-\varepsilon)\}/S. \quad (3)$$

If $_{KiPS}$ << 1 for all i, Equation (1) simplifies to:

$$\varepsilon = \sum_{i=0}^{I}\{a\,\varepsilon_i.(K_i PS)\}. \quad (4)$$

So the modeling is done by taking into account all these factors in the calculations. It has to be appreciated that the individual's experience with the case under study helps in choosing the values of the parameters accurately.

(ii) LOCK ON ENVELOPE There is strong mathematical analysis and various tools are employed for analyzing and modeling of the IR Signatures. The most useful tool is the finding of the Lock-on Envelope. The calculations for Lock-on Envelope are done by the following equations:

$$\begin{aligned} &V_s = \int \phi e(\lambda).RVd\lambda = \\ &[D^8 V_{nn} / (Ad\Delta f) I / 2] AO.q \\ &\Rightarrow V_s / V_n = SNR = [q / IFOV] / \\ &[NEP / AOIFO], \end{aligned} \quad (5a)$$

and

$$\begin{aligned} &SNR = [Q.(D^*)\pi(DO)^2.IFOV] / \\ &[4(AD.\Delta f)^{\frac{1}{2}}]. \end{aligned} \quad (5b)$$

here $\phi e(\lambda)$ is the spectral radiant power incident at the aperture of the optics, RV is the responsivity, IFOV is the instant field of view, Δf is the noise equivalent bandwidth in Hz, Vn is the rms noise voltage, D* is the detectivity, Ad is the area of the detector, DO is the aperture diameter, and Q is (q/ω). (iii) ORDER OF THE IR SIGNATURE VALUES AND THEIR DEPENDENCE ON VARIOUS FACTORS These equations are applied to the case under study for analyzing the IR Signatures and their suppression while designing the devices. Typical values for the normalized IR Signature for the various cases lie between ~ 50 to ~1000 Watts/ Steradian. The values depend on positions of the objects, and the wavelength region applied for the investigations. Some of the Techniques applied for the reduction of the IR Signature are – (i) Increase in engine bypass ratio, (ii) 2D nozzles for better mixing of jet with ambient, (iii) Masking of exhausts, and (iv) Application of IR paints for low emission. The Paints with the desired emissivities have to be applied at select locations of the object. They should be able to withstand the wear and tear and environment, and also be amenable for application in the form of thin layers without causing any weight increase or hampering any aircraft functions. Also, they should not glow in dark. The reduction is achieved taking into account the various factors, and the experience of the technical experts is of great use in the choice and combination of the techniques. The IR Signature Suppression ~ 5 - 10% of the original value can be easily achieved by the researchers and the designers.

CONCLUDING REMARKS

The IR sensor design from the missile plume prediction models is of prime importance while designing the devices for IR signature. Choi and Kim [13] have developed a program for generating the IR images by taking into account the radiation emission from the surface of the objects, which has important implications for the IR suppression computational studies. This technique is based on considering the spectral radiance received by a remote sensor to be consisting of (i) self-emitted component directly from the target surface, and (ii) the scattered component by the atmosphere. The first component is calculated by using the temperature and optical properties of the surface along with the spectral atmospheric transmittance. This is obvious that the temperature distribution on the object is necessary to get their IR images in contrast to the background. In this program, the object is assumed to be consisting of various materials with different values of properties like - conductivity, absorption, density, and specific heat. Also, the parameters e.g. air temperatures, wind directions, wind velocity, relative humidity and atmospheric pressure, solar irradiance and surface temperatures are taken into account for the final results. Another important literature on the topic has been provided by Dudzik *et al.* [14], in the form of a handbook on the Infrared and Electro-Optical Systems. The studies on this topic have to consider the system design, analysis, and testing, and methods such as trackers, mechanical design considerations, and signature modeling. Wilson *et al.* [15] have discussed the complications of modeling the IR signature of objects like ships and land vehicles by focusing on the difficulties in estimating the correct effect of the environment on the signature. It has been proposed that an experimental measurement of solar irradiance and sky radiance is more suitable for consideration in the signature models than their estimation by atmospheric radiation models. It is expected that some exciting devices based on the number of newly developed materials and the related technologies are likely to be to bring revolutionary changes in the field of IR Sensors, and their utility in the fabrication of devices for the IR signature suppression.

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