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Development and flight test of metal-lined CFRP cryogenic tank for reusable rocket

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Abstract

A cryogenic tank made of carbon fiber reinforced plastic (CFRP) shell with aluminum thin liner has been designed as a liquid hydrogen (LH_2) tank for an ISAS reusable launch vehicle, and the function of it has been proven by repeated flights onboard the test vehicle called reusable vehicle testing (RVT) in October 2003. The liquid hydrogen tank has to be a pressure vessel, because the fuel of the engine of the test vehicle is supplied by fuel pressure. The pressure vessel of a combination of the outer shell of CFRP for strength element at a cryogenic temperature and the inner liner of aluminum for gas barrier has shown excellent weight merit for this purpose. Interfaces such as tank outline shape, bulk capacity, maximum expected operating pressure (MEOP), thermal insulation, pipe arrangement, and measurement of data are also designed to be ready onboard. This research has many aims, not only development of reusable cryogenic composite tank but also the demonstration of repeated operation including thermal cycle and stress cycle, familiarization with test techniques of operation of cryogenic composite tanks, and the accumulation of data for future design of tanks, vehicle structures, safety evaluation, and total operation systems.

1. Introduction

Weight saving of structures of a reusable rocket vehicle is one of the essential factors towards realization of a future fully reusable space transportation system. A lightweight cryogenic propellant tank is the key technology of it.

ISAS's operational reusable rocket vehicle flew several times in 1999 and 2001 and had repeatedly performed lift-off, flight, landing, and refueling [1,2]. The vehicle put to use for the reusable vehicle testing (RVT) is a vertical lift-off and vertical landing type rocket propelled by liquid hydrogen (LH_2) and liquid oxygen (LOX). The engine of the RVT rocket is a pressure-fed system, for simplicity. In order to expand the operational flight envelope, a lighter structure was required. A composite tank is expected to have a significant impact on weight saving of the vehicle for

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the new flight-testing campaign in 2003. A composite cryogenic propellant tank, which is discussed in this paper, has been researched and designed for actual operation in a flight test of ISAS reusable rocket vehicle than just for experimental research on such kinds of tank. The LH_2 tank made of composite materials has been newly developed, and the new LOX tank has been made of aluminum, instead of the stainless-steel LH_2 tank and stainless-steel LOX tank for the previous flight-testing campaigns.

2. Fundamental design

2.1. Design conditions

The LH_2 tank is not just a container of fuel, but a high-pressure vessel to feed fuel to a combustion chamber, because the pressure-fed engine is not equipped with any mechanical pump. The fuel in the tank is pressurized by accumulated helium gas (GHe). The newly developed tank must be designed to be ready onboard to replace the conventional tank, because the system of the RVT had been prescribed. Interfaces such as tank outline shape, bulk capacity, maximum expected operating pressure (MEOP), thermal insulation, pipe arrangement, and measurement of data, should meet the current RVT specifications. The tank must be equipped with inner devices such as a sloshing stabilizer to suppress the ruffling motion of fuel in the tank during ballistic flight, piping ports for a differential pressure type level gauge, and a diffuser of pressurizing helium gas flow. Thermal deformation of the composite tank due to temperature change and mechanical deformation due to pressurization must be allowed, and the tank should be held steadily against flight load, vibration, and landing shock.

2.2. Fundamental strategy

The pressure vessel for extremely low-molecular-weight contents such as helium and hydrogen must be airtight against the content gases. For this purpose, the structure of the cryogenic pressure vessel is bi-layer, which is a combination of an outer layer made of filament-wound (FW) carbon fiber reinforced plastic (CFRP) for strength element at cryogenic temperature and an inner layer made of aluminum as gas barrier. Micro-cracks in CFRP are permissible in this case, because the thin metallic liner serves as a gas barrier. This means that the thickness of the CFRP wall is designed only from a mechanical viewpoint, not from a viewpoint of leakage of gases, and so the FW CFRP can be used up to its full strength of the material. By adopting the thin liner in the design, we can avoid a debatable problem of what is the necessary CFRP wall thickness for low-molecular-weight gas impermeability in the case of CFRP application under ultimate circumstances such as numerous cycles of a cryogenic temperature and the conjugated stress. For these reasons, adopting of a thin liner has an advantage in the design of a lightweight pressure vessel of cryogenic propellant for reusable vehicles.

The thin metallic liner has to be consistently maintained when attached to the outer CFRP shell in order to function integrally. Interlayer separation forces may be generated in the following two cases. If the tank is not pressurized at a cryogenic temperature, interlayer tensile forces occur due to the variance of thermal expansion of inner metal and outer CFRP. Pressurization over the elastic limit of the liner material causes a residual stress between the thin metallic liner and CFRP outer shell after pressure release. The residual counter-stress, compressively between the liner and CFRP shell, helps the bi-layer structure to prevent detachment at a cryogenic temperature. On the other hand, a spherical shell under compression is subject to a structural buckling. The buckling tendency of the inner shell may induce interlayer separation, in reverse. Satisfactory adhesiveness is required in order to avoid the thin shell buckling of the liner.

The mechanical design is made by an FEM analysis based on an elasto-plastic model, which implies material nonlinearity and the kinematic hardening rule as Bauschinger effect. Fig. 1 illustrates a conceptual rendering of the pressure–strain relationship of CFRP. The diagram differs according to the position and direction of strain measurement, CFRP fiber orientation, CFRP thickness, and liner thickness. In the design, the elasto-plasticity analysis of stress and strain follows all the history of manufacturing and test process from the liner component pressure test before filament winding, to the end of the LH_2 proof pressure test. Strain in Fig. 1 starts from the origin for