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Ground-Test and Flight Results of LE-7A FTP with an Alternate Inducer

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An alternate inducer for the LE-7A fuel turbopump (FTP) was newly developed to eliminate the deterioration of suction performance of the original inducer at low net positive suction head (NPSH). Detailed data of the pump inducer were obtained in tests of both the turbopump alone and the engine system. In these tests, a hydrogen inlet feed line of the same configuration as that employed in actual flight was used. The tests were conducted in wide ranges of inlet pressures and flow rates. The second test flight of the H-IIA launch vehicle, in which the LE-7A FTP with the alternate inducer was installed, was successfully carried out in February 2002. Many flight data concerning the LE-7A FTP were obtained and analyzed. The results of both ground tests and test flights of the FTP with the alternate inducer are presented in this paper.

Nomenclature

C = absolute flow velocity, m/s
D = inducer diameter, m
K = cavitation number, $= (P_1 - P_v)/(\rho W^2/2)$
N = rotational speed, min^{-1}
P = static pressure, MPa
Q = flow rate, m^3/s
Q/Q_d = flow ratio, $= (Q/N)/(Q_d/N_d)$
U = peripheral blade speed, $= \pi D_t N/60$, m/s
W = relative velocity, $= (U_{1t} + C_{1m})^{1/2}$, m/s
α = incidence angle, deg
β = blade angle, deg
ρ = density, kg/m^3
ϕ = flow coefficient, $= C_m/U_t$
φ = pressure rise coefficient, $= (P_2 - P_1)/\rho U_2 t^2$

Subscripts

d = design value
ind = inducer
m = meridional component
t = inducer tip
v = saturated vapor
1 = inducer inlet
2 = inducer discharge

I. Introduction

VARIOUS kinds of problems closely related to unsteady characteristics of rocket pump inducers have occurred during the development of recent rocket engines because the inducers require high head rise, high load, and high suction performance even under conditions of cavitation. The LE-7A fuel turbopump (FTP) with its original inducer caused the deterioration of suction performance under low net positive suction head (NPSH) during the developmental phase. When the pump inlet pressure was gradually reduced, the inducer caused sudden remarkable head degradation. Simultaneously, the rotor vibration was greatly amplified because the frequency of the vibration almost coincided with that of the second critical speed of the turbopump. This vibration was considered to be caused by rotating stall closely related to severe backflow cavitation at the inducer inlet.[1]

It was concluded that improvement of the LE-7A hydrogen inducer was indispensable for enhancement of the reliability of the hydrogen turbopump. Thus, an inlet flow coefficient, which is larger than that of the original, was selected to reduce the inlet backflow and suppress the blade load at the inducer inlet. Experimental data of the FTP with the newly designed inducer were obtained under wide ranges of inlet pressures, flow rates, and rotational speeds, taking the actual flight conditions into consideration.

The second H-IIA launch vehicle, in which the LE-7A FTP with the alternate inducer was first used, was successfully launched on 4 February 2002. The third, fourth, and fifth H-IIA launch vehicles were also successfully launched. Many flight data of the LE-7A FTP were obtained and analyzed. Regarding the FTP with the alternate inducer, the present paper shows a comparison between the results of the actual flights and those of ground tests.

II. LE-7A FTP

The H-IIA launch vehicle, an advanced expendable launch vehicle, which will be able to carry a four-ton-class payload into a geostationary transfer orbit, has been under development in Japan since 1995 (Refs. 2 and 3). The LE-7A (Fig. 1), the first-stage engine of the H-IIA, can provide 1100 kN of thrust using liquid oxygen and liquid hydrogen as propellants.[4] This engine, which is an improved version of the LE-7 engine used in the H-II launch vehicle, was designed to increase reliability by simplifying the engine system and reducing the number of engine components, which also resulted in a decrease of manufacturing cost. The LE-7A engine required high-pressure and high-power liquid-oxygen and liquid-hydrogen

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Table 1 FTP nominal operating point

Rotational speed	42,500 rpm
Pump section	Two-stage centrifugal pump with single inducer
Inlet pressure	0.34 MPa
Inlet temperature	20.7 K
Discharge pressure	28.6 MPa
Discharge temperature	46.7 K
Flow rate	37.3 kg/s
Specific speed	148 m, m^3/min, rpm
Efficiency	0.69
Turbine section	Single-stage gas turbine
Inlet temperature	750 K
Inlet pressure	21.4 MPa
Outlet pressure	13.8 MPa
Flow rate	36.4 kg/s
Efficiency	0.69

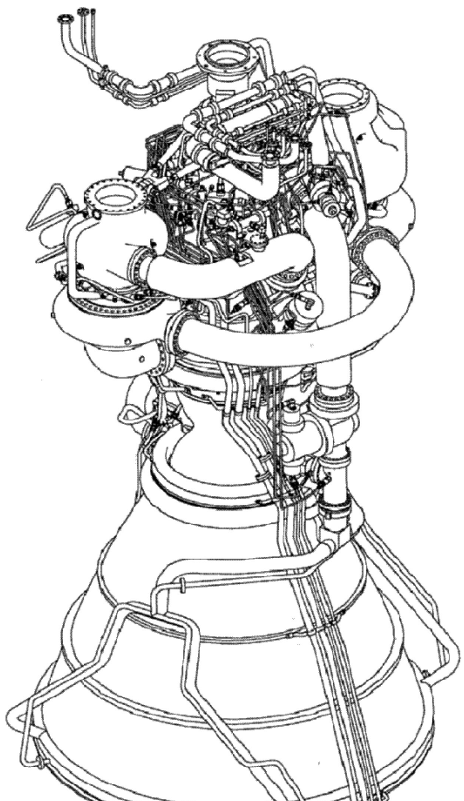

Fig. 1 LE-7A engine.

turbopumps to achieve the staged combustion cycle in which the combustion pressure is around 12.5 MPa. Furthermore, it was very important for both turbopumps to operate at higher rotational speeds to obtain a smaller, lighter-weight engine because the LE-7A engine does not have low-speed, low-pressure pumps positioned in front of both the high-pressure pumps. The nominal rotational speeds of the liquid-oxygen and -hydrogen turbopumps are 18,300 and 42,500 rpm, respectively.

The standard operating conditions of the LE-7A liquid-hydrogen turbopump is presented in Table 1. The rotor assembly is mainly comprised of a single inducer with three blades, two centrifugal impellers and a turbine wheel, as shown in Fig. 2. The hydrogen turbopump is operated at a rotational speed higher than the third critical speed of the rotor. The rotor assembly is supported by two sets of individually spring-loaded hydrogen-cooled duplex ball bearings, each of which is softly mounted with mesh wire dampers. Guide vanes between the inducer and the first impeller are used to support the housing of the just-mentioned bearings. The rotor assembly is axially positioned by a self-referencing balance piston, in which the backshroud of the second impeller is used as a balance disc.

Table 2 Major design parameters of the alternate inducer

Design parameters	Values of parameter
Inlet flow coefficient, ϕ_1	0.08
Inlet tip diameter, D_{1t}	162 mm
Inlet tip blade angle, β_{1t}	7.1 deg
Outlet tip diameter, D_{2t}	168 mm
Outlet tip blade angle, β_{2t}	11.5 deg
Outlet flow coefficient, ϕ_2	0.087
Sweepback angle, θ_s	90 deg
Tip solidity, S_t	1.8

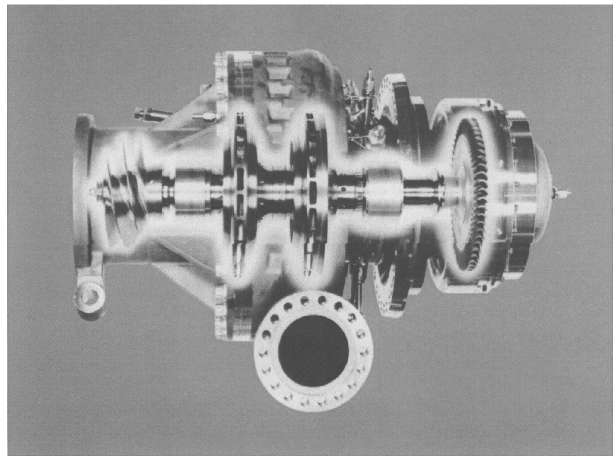

Fig. 2 LE-7A hydrogen turbopump.

III. Design of the Alternate Inducer

An inlet flow coefficient, which is larger than that of the original inducer, was selected to reduce the inlet backflow and the blade load at the inducer inlet. Therefore, the alternate inducer was changed to a kind of mixed-flow type with a tapered tip and hub as against the original axial-type inducer with a cylindrical tip and tapered hub as shown in Fig. 2.

The major design specifications of the newly designed inducer of the LE-7A FTP are shown in Table 2 (Ref. 5). The alternate inducer with three helical blades is characterized by a low inlet flow coefficient and a high head coefficient ($\varphi_{\text{ind}} \fallingdotseq 0.22$). The curvature of the camber line changes linearly from inlet to outlet. The sweepback angle of the alternate inducer is 90 deg to decrease the load and the bending stress of the blades near the hub. The value of the ratio α/β_{1t} is 0.36 at the design and nominal operating conditions where β_{1t} is the inlet tip blade angle. The blade tip clearance is 0.5 mm in the operating condition. The inducer liner has an oblique step at the inducer inlet to suppress rotating cavitation, which causes very large oscillatory stress on inducer blades.

IV. Ground-Test Results

Qualification of the LE-7A FTP with the alternate inducer was carried out in a series of two ground tests. First, the suction performance of the alternate inducer was certified in ground tests of the hydrogen turbopump alone. Next, various types of performances, including durability, of the alternate inducer were validated in the LE-7A engine firing tests. In these qualification tests, a wide range of the FTP operation was tested to cover any operating conditions which might occur during actual flights.

A. Test Ranges of the FTP with the Alternate Inducer

The suction performance was estimated by cavitation number at the inducer inlet rather than by NPSH, because the required NPSH would change with rotational speed. We selected an available minimum cavitation number ($K = 0.0230$) that was significantly lower than the lowest cavitation number experienced during any flights. The ranges of the qualification tests including that of cavitation number are shown in Figs. 3 and 4. These ranges were determined taking the following matters into consideration: 1) the transition of operating points during flight and 2) dispersion of component characteristics, such as flow resistance of injectors, heat-transfer rate of regenerative cooling, and efficiency of hydrogen and oxygen turbopumps.

Operation points of the FTP calculated using the items of 1 and 2 are presented in Fig. 3. The FTPs are operated within a rhombus drawn with dotted lines in Fig. 3. "Standard engine" means an engine having the components with the standard performance; "2σ distribution" and "-2σ distribution" in Fig. 3 present the engines that have the component performance of $\pm 2\sigma$ dispersions, respectively. The results of operation points of the actual turbopomp tests and engine firing tests are also shown in Fig. 3. The operation condition of the FTP is shown in Fig. 4, which is presented using parameters of cavitation number and flow ratios. The minimum cavitation number was determined considering the allowable maximum rotational speed, the probable difference between acceptant tests and flights, etc.

In tests of the turbopump alone and of engine firing, the FTP was driven under various operating conditions by changing the flow ratio Q/Q_d and rotational speed N in order to demonstrate that the inducer would operate well under any operating conditions experienced during flight.

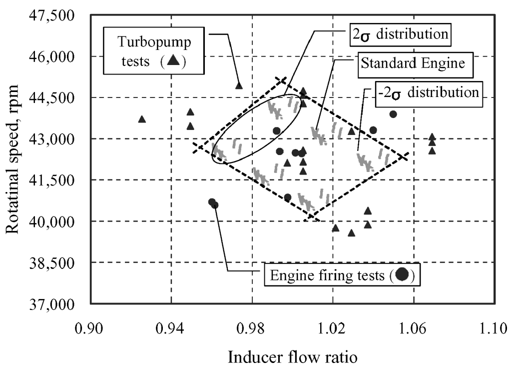

Fig. 3 Operation range of the FTP.

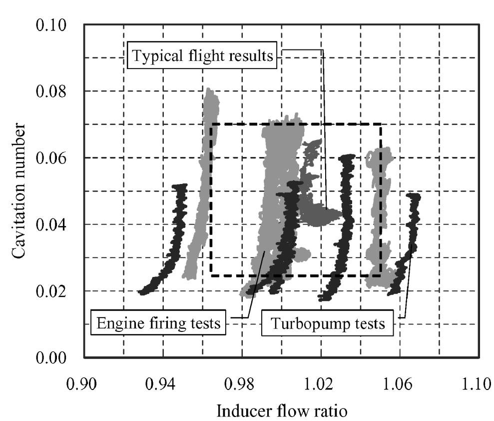

Fig. 4 Test range shown with cavitation number and flow ratios.

B. Turbopump Tests (FTP Alone)

Tests of the turbopump alone were carried out using the Propellant Feed Systems Test Stand in the Kakuda Propulsion Center of the National Space Development Agency of Japan (NASDA) in December 2001. The suction performance of the alternate inducer was evaluated at operating points that cover all of the qualification test ranges. In the tests of turbopump alone, the FTP was operated for a duration of about 20 s at the planned rotational speed and flow ratio. To investigate both the steady-state performance and unsteady behaviors at low cavitation numbers, both static and dynamic data were obtained at a constant rotational speed and a constant flow rate by reducing the inducer inlet pressure from sufficiently high to low. The inlet pressure was precisely reduced by controlling the tank pressure.

The following efforts were made to maintain the operating conditions of the FTP equivalent to those in the LE-7A engine:

1) Liquid hydrogen was intentionally used as the pump fluid in order to determine the exact suction performance that was influenced by the thermodynamic suppression head.

2) The turbine working fluid was hydrogen-rich hot gas with liquid-oxygen/hydrogen combustion gas, almost the same operating condition for the turbine as that installed in the LE-7A engine.

3) The propellant feed line was exactly the same as that used in actual flight, which simulates the flow at the interface between the feed line and the turbopump, in particular, distortion and prewhirl at the inducer inlet.

Backflow and backflow vortices of an inducer are closely related to unsteady cavitation phenomena. A visual observation of the inducer using particle image velocimetry (PIV) was performed using the actual feed line shown in Fig. 5, in which water was the working fluid. A photograph of the inducer inlet flow obtained by PIV is shown in Fig. 6. A fairly large backflow toward the upstream of

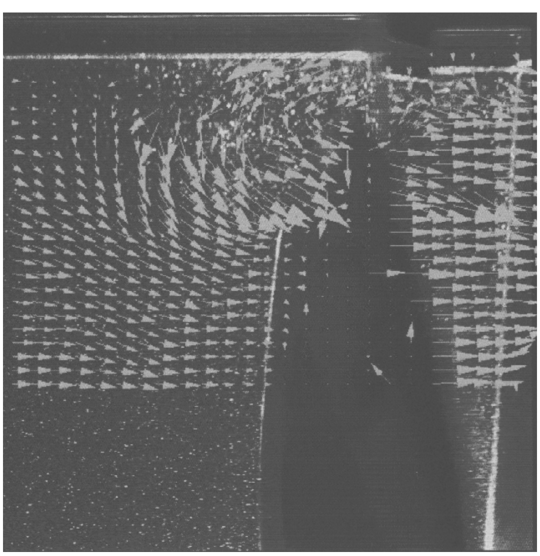

Fig. 6 Typical backflow from the inducer ($Q/Q_d = 1.00$).

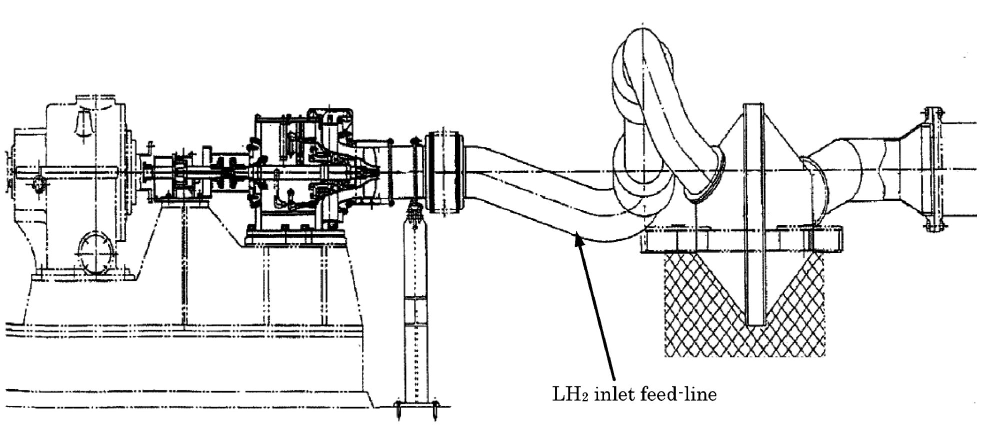

Fig. 5 Configuration of the test section connected with a LH_2 feed line in water tests.

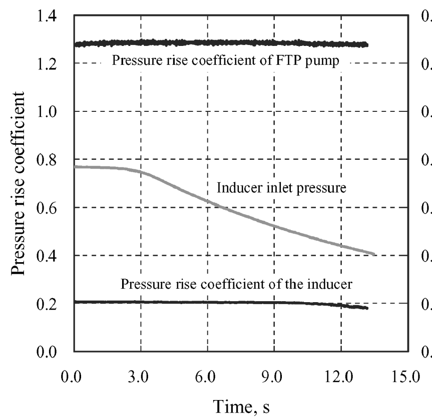

Fig. 7 Typical results of the turbopump test.

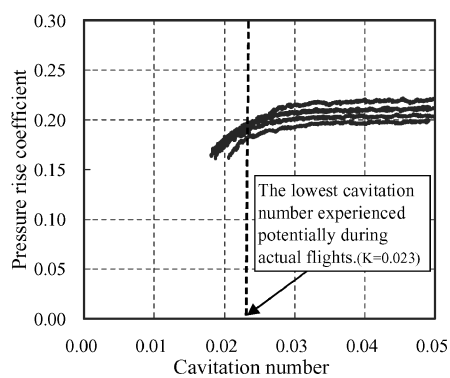

Fig. 8 Suction performance of the LE-7A inducer in turbopump tests.

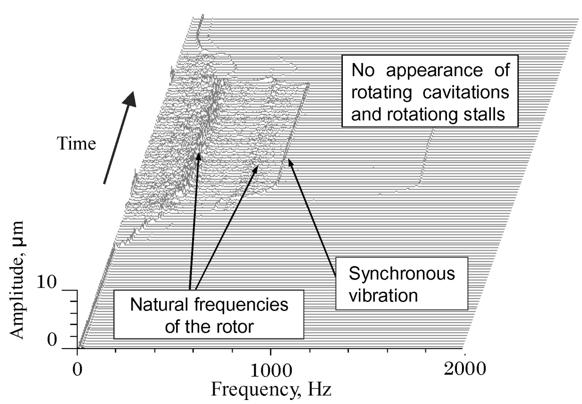

Fig. 9 Shaft vibration of the FTP.

the inducer was observed in particular near the leading edge. From this picture it is easily concluded that the inducer backflow and mainstream affect each other.

Figure 7 shows typical ground-test results of the hydrogen turbopump, and Fig. 8 shows the inducer suction performance obtained in the FTP tests. The inducer did not show a rapid head drop at the lowest cavitation number, which is assumed to occur during flight. In addition, unsteady phenomena, such as cavitation surge, rotating cavitation, and rotating stall, did not appear in any tests, as shown in Fig. 9.

The alternate inducer was completely confirmed to work well under the required conditions in these turbopump tests.

C. LE-7A Engine Hot Firing Tests

One year after the tests of the turbopump alone, firing tests of the LE-7A engine with the alternate inducer were conducted using the Engine Firing Test Stand at the Tanegashima Space Center of NASDA. With the hot firing tests, the engines were operated under a wide range of operating conditions within the qualification range.

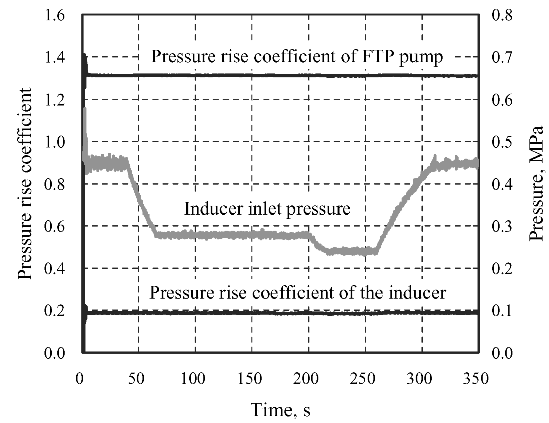

Fig. 10 Typical results of the engine firing test.

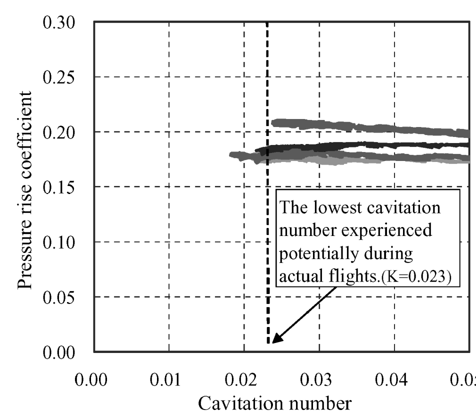

Fig. 11 Suction performance of the LE-7A inducer in the engine firing tests.

Figure 10 shows typical results of the hot firing tests. Durations of the tests were from 50 to 350 s depending on the purpose of each test. Duration of an endurance test was 350 s, which roughly corresponds to a mission duty cycle. Nine firing tests with a total duration of 2040 s were successfully performed in August 2002. After these tests, the LE-7A engine was disassembled into its components for nondestructive inspections. No imperfections were found in these components, thus completely certifying the required endurance. Figure 11 shows the suction performance of the alternate inducer. The suction performance of the inducer is slightly different between turbopump tests and engine firing tests, which is considered to come from the difference of hydrogen temperature of the inducer inlet. The hydrogen temperature in the engine tests was higher than that of the turbopump-alone tests. The inducer functioned well at the cavitation number of $K = 0.0210$. Above the cavitation number of $K = 0.0230$, the inducer did not show a conspicuous head drop; such a drop would have had a negative influence on the engine system. In addition, anomalous rotor vibrations, pressure fluctuations, and accelerations related to unsteady phenomena of the inducer did not appear with a sufficient margin of NPSH.

V. Flight Results

The second H-IIA launch vehicle, in which the LE-7A FTP with the alternate inducer was first installed, was successfully launched on 4 February 2002. Since then, the third (on 10 September 2002), fourth (on 14 December 2002), and fifth flights (on 28 March 2003) have been successful. Many flight data concerning the LE-7A FTP have been obtained and analyzed. The rotational speed, inducer inlet pressure, inlet temperature, inducer discharge pressure, bearing temperature, etc. were acquired during the actual flights using measurement apparatuses with high sampling speed. Because data of flow rate, rotor vibration and turbopump acceleration, etc. were not directly obtained, they were estimated using other measured data. The operating conditions of the FTP, such as the inducer inlet

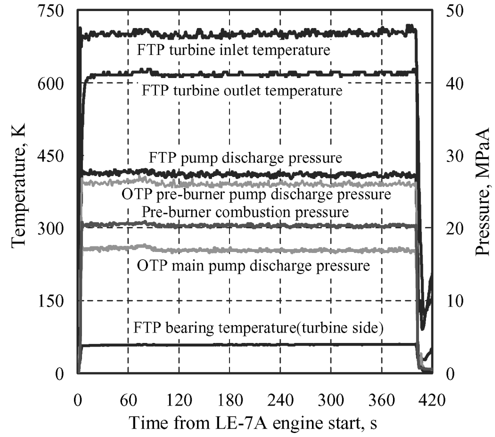

Fig. 12 Typical flight data of the LE-7A FTP.

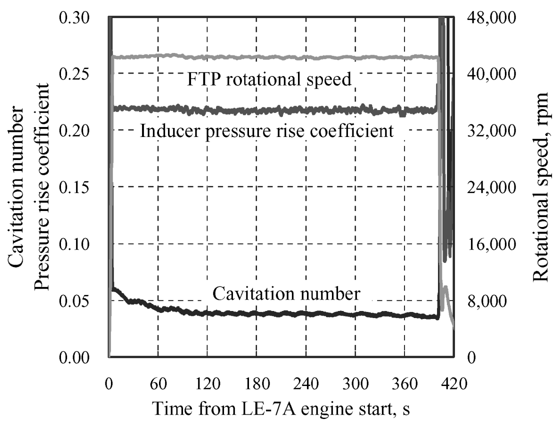

Fig. 13 Inducer pressure rise coefficient during the actual flight.

pressure and inlet temperature, were, of course, changed momentarily during the flight.

Figure 12 shows typical flight data of both the hydrogen and oxygen turbopumps of the LE-7A engine during actual flight time. The measured data of pressures and temperatures at the various portions of the LE-7A engine are highly stable, which show that both the turbopumps are operated perfectly throughout flight.

Figure 13 shows the inducer pressure rise coefficient, rotational speed, and cavitation number during the actual flight. The flow rate of the FTP during operation was estimated from the FTP performance, which was previously obtained in the ground acceptance tests. The cavitation number gradually decreased from the ignition of the LE-7A engine to around 100 s after engine startup because the LH_2 tank pressure was appropriately controlled taking the change of atmospheric pressure into account. After that time, the LH_2 tank pressure was also continuously controlled within the range, which was set in advance. The slight fluctuation of cavitation number denotes that the LH_2 tank pressure was precisely controlled with a computer. The wholly progressive decrease of cavitation number resulted from the gradual increase of inducer inlet temperature caused by the heat transfer from the heat insulation materials into the LH_2 tank and propellant feed line. The cavitation number had reached a minimum value of $K \fallingdotseq 0.036$, when the LE-7A engine was shut down. The inducer pressure rise coefficient was, however, constantly stable in spite of the change of cavitation number throughout the flight.

The suction performance of the alternate inducer is represented in Fig. 14, which shows the data of both the actual flight and the ground acceptance test (LE-7A engine hot firing test). The difference of the pressure rise coefficient φ_{ind} between the flight and ground test is caused by the difference of the flow rate. Ground acceptance tests have two purposes. One is to adjust an operation point to the

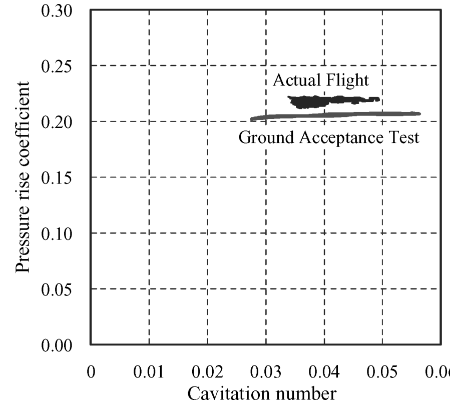

Fig. 14 Inducer suction performance during the flight.

predetermined point, and another is to confirm performances at the operation point. Although the operation point during an actual flight should be near that of the ground test, it slightly deviated because of some circumstantial differences. Flow ratio in the acceptance test was 2.5% larger than that of the flight, which would be difference of the pressure rise coefficients between the acceptance test and flight. Both pressure rise coefficient curves vs cavitation number showed almost the same characteristics. The required suction performance was confirmed by the high rotational speed tests, in which the peripheral speed at the inducer tip was around 380 m/s. Because the ground acceptance test was carefully conducted in the possible range of the cavitation numbers during actual flight, taking into considerations the repeatability of the operating points, accuracy of the measurement, and computer-controlled system of the LH_2 tank pressure and available minimum NPSH, it will be possible for the inducer to operate with a sufficient margin of suction pressure.

VI. Summary

The ground-test and flight results of the newly designed alternate inducer of the FTP for the LE-7A engine were presented. In tests of the turbopump alone as well as engine firing tests, the alternate inducer proved to be completely qualified. This alternate inducer has successfully operated during five flights of the H- IIA so far.

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