JOURNAL OF PROPULSION AND POWER
Vol. 19, No. 3, May–June 2003

Improvement of Inlet Flow Characteristics of LE-7A Liquid Hydrogen Pump

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LE-7A engine inducers require high head rise and high suction performance in spite of cavitating conditions because a low-speed, low-pressure pump is not used in front of the main pump in the LE-7A engine. During the development phase, use of the LE-7A fuel turbopump with an original inducer resulted in a noticeable deterioration of suction performance near the required net positive suction head. When the pump inlet pressure was gradually reduced, the inducer caused sudden remarkable head degradation, and 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 caused by a rotating-stall-type phenomenon, which is considered to be closely related to backflow cavitation at the inducer inlet. Improvement of the inducer was indispensable for enhancement of the reliability of the hydrogen turbopump. Thus, an inlet flow coefficient larger than that of the original inducer was selected to reduce the inlet backflow. A redesign of the original inducer and test results of the hydrogen turbopump with the newly developed inducer are reported.

Nomenclature

H = head rise, m
p = pressure, MPa
p_v = vapor pressure, MPa
Q = flow rate, m³/s
U = peripheral velocity, m/s
V = axial velocity, m/s
W = relative velocity, m/s
α = incident angle, deg
β = blade angle, deg
ρ = density, kg/m³
σ = cavitation number, $2(p_1 - p_v)/\rho W_{1t}{}^2$
τ = cavitation parameter, 2(net positive suction head)$/\rho U_{1t}{}^2$
ϕ = flow coefficient, V_1/U_{t1}
Ψ_{ind} = inducer head coefficient, $H_i/\rho U_{2t}{}^2$
Ψ_{pump} = pump head coefficient, $H_p/\rho U_{\text{imp}t}{}^2$

Subscripts

d = design
i = inducer
imp = main impeller
n = nominal
t = tip
1 = inlet
2 = outlet

Presented as Paper 2002-4161 at the AIAA/ASME/ASEE 38th Joint Propulsion Conference and Exhibit, Indianapolit, IN, 7–10 July 2002; received 14 August 2002; revision received 27 December 2002; accepted for publication 27 December 2002.

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I. Introduction

THE H-2A launch vehicle, Japan's present expendable launch vehicle, which will be capable of carrying a 4-ton-class payload into a geostationary transfer orbit, has been under development since 1995.[1,2] The LE-7A engine, which is used in the first stage of the H-2A rocket, provides a thrust of 1100 kN using liquid oxygen and liquid hydrogen as propellants.[3] This engine, an improved version of the LE-7 engine that was used in the H-2 launch vehicle, was designed to increase reliability by simplifying the engine system and reducing the number of engine components, which also results in a decrease in manufacturing costs.

The LE-7A fuel turbopump (FTP) was also developed to decrease manufacturing costs, as well as to achieve higher reliability utilizing experience gained in the development of the LE-7 FTP.[4–6] This turbopump has two centrifugal impellers and a single inducer, which is required for high durability and stable operation under all operating conditions during flight.

In the LE-7A engine tests, the original inducer of the LE-7A FTP showed good suction performance at a flow rate higher than that of the nominal operation, which is lower than that of the design. The change of this operating condition was made to complete the engine system. However, it was clarified that the inducer did not achieve the required suction performance at a flow rate lower than that of the nominal operation and that the inducer also showed rotating cavitation. Furthermore, the inducer showed sudden remarkable head deterioration near the required net positive suction head (NPSH) based on the design specifications. Simultaneously, unacceptable rotor vibrations occurred. This degradation of inducer suction performance was caused by a rotating-stall-type phenomenon, which is closely related to backflow cavitation at the inducer inlet.[7] Excessive backflow cavitation produced by the insufficiency of the inlet flow coefficient is considered to obstruct the flowfield around the inducer inlet, which results in an unstable head capacity curve at the constant inlet pressure.[8] The rotating speed of this phenomenon is less than that of the rotating blades, which showed definite difference from rotating cavitation. The rotating speed of rotating cavitation is higher than that of the rotating blades.

A program to develop an alternate inducer was commenced in October 2000 to improve the flow characteristics of the inducer inlet and to suppress rotating cavitation. To suppress the excessive backflow, the inlet flow coefficient was increased by reducing the tip diameter of the inducer inlet, which resulted in a decrease of the flow incidence angle α compared with that of the original inducer.

Testing of the FTP with the alternate inducer was performed using both liquid hydrogen and also water as test fluids. In the water tests, visual observations of the flowfield were performed, and data for the inducer's structural integrity were obtained by measuring the strain on the inducer blades using strain gauges placed on the surface of the blades.

II. LE-7A FTP with Original Inducer

Mechanical Configuration

Figure 1 shows the mechanical configuration of the LE-7A FTP with its original inducer. The two-stage centrifugal pump with an inducer is driven by a single-stage gas turbine. Table 1 presents the FTP standard operating conditions. The large flow rate, high suction performance, and high head rise require that the inlet tip have a large diameter. Therefore, the inducer and the main pump impellers are arranged as shown in Fig. 1. Guide vanes between the inducer and the first impeller are used to support the housing for self-lubricated ball bearings.

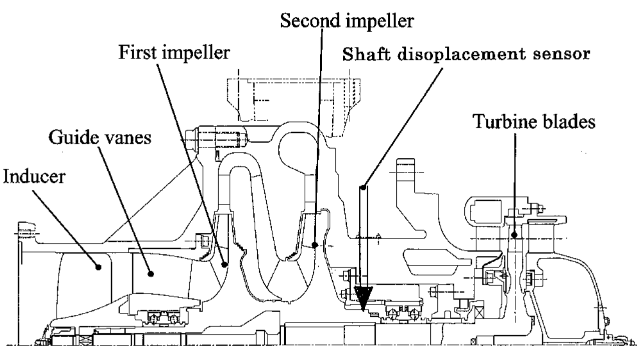


Fig. 1 LE-7A liquid hydrogen turbopump with original inducer.

The FTP is operated at a speed higher than the third critical speed of the rotor. The calculated critical speeds and the shape of the shaft vibration mode of this turbopump are presented in Fig. 2 to facilitate understanding of the following discussion of test results. The shape of the mode of the first critical speed is primarily due to the overhang motion of the turbine. The shapes of the modes of the second and third critical speed are characterized by comparatively large amplitude at the inducer.

The major design specifications of the original inducer are shown in Table 2. This axial-flow inducer with three helical blades is characterized by a low inlet flow coefficient and a high head coefficient ($\Psi_{\text{ind}} \risingdotseq 0.24$). The blade angle variation is parabolic in the axial direction. Therefore, the curvature of the camber line changes linearly from inlet to outlet. Furthermore, this inducer has fairly thick blades, which decrease the blade stress, particularly near the hub. The inducer was machined from titanium alloy (5 Al–2.5 Sn). Blade

Table 1 LE-7A LH2 turbopump design parameters

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

Table 2 Major design parameters of original and alternate inducers

Design parameter[a]	Original inducer	Alternate inducer
Inlet flow coefficient ϕ_{1d}	0.0672[b]	0.08[c]
Inlet diameter D_{1t}, mm	174.0	161.8
Inlet blade angle β_{1t}, deg	6.36	7.14
Outlet diameter D_{2t}, mm	174	168
Outlet blade angle β_{2t}, deg	11.1	11.5
Outlet flow coefficient ϕ_2	0.0782	0.0835
Sweepback angle θ_s, deg	55.6	90
Tip solidity S_t	2.13	1.83

[a]Nominal flow coefficient. [b]Coefficient $\phi_{1n} = 0.064$. [c]Coefficient $\phi_{1n} = 0.08$.

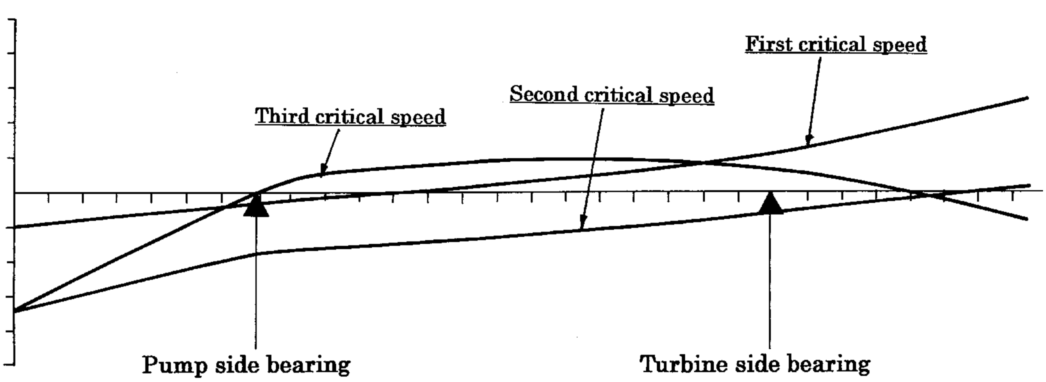


Fig. 2 Calculated critical speeds and shape modes of shaft vibrations: first critical speed, 14,500 rpm; second critical speed, 20,500 rpm; and third critical speed, 31,100 rpm.

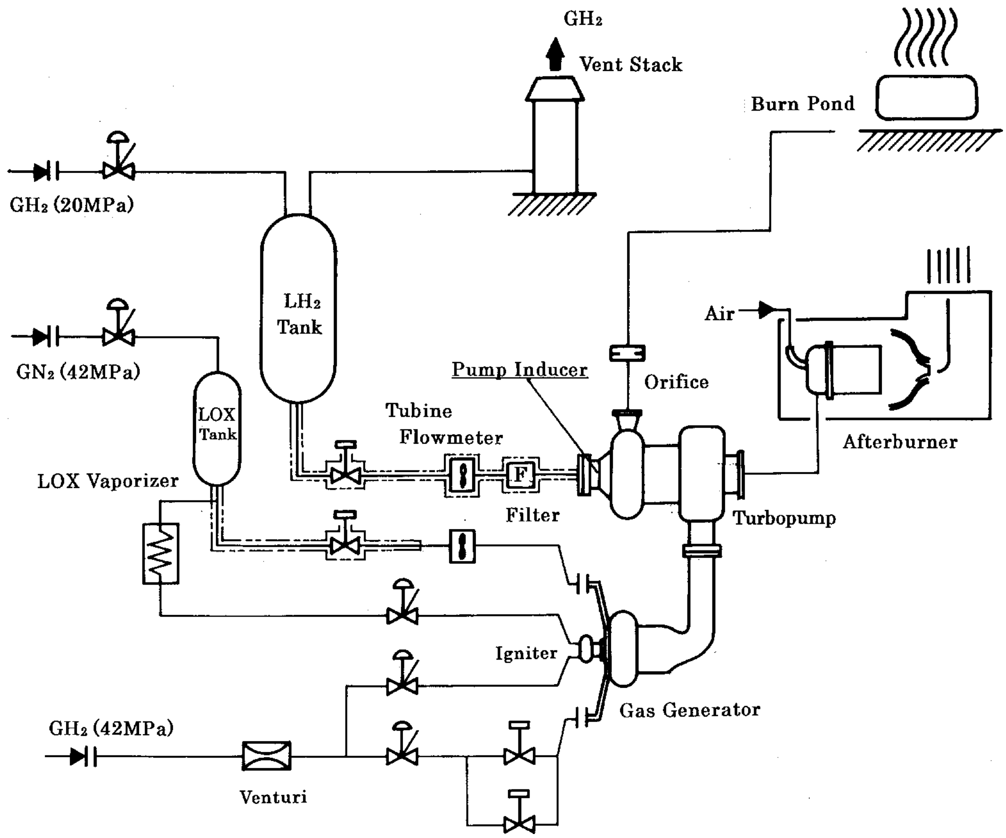


Fig. 3 Test facility of LE-7A liquid hydrogen turbopump.

sweepback angle, which affects both suction performance and blade load, is about 56 deg. The values of the ratio α/β_{1t} are 0.396 and 0.431 at the design and nominal operating conditions, respectively, where β_{1t} is the inlet tip blade angle.

Test Facility and Procedures

The performance of the inducer with liquid hydrogen was investigated during the operation of the LE-7A FTP using the Integrated Propellant Feed Systems Test Facilities at the Kakuda Propulsion Center (KPC) of the National Space Development Agency of Japan. A schematic diagram of the facility is shown in Fig. 3. The duration of an LE-7A FTP test using this facility is about 20 s. The turbine is driven by the working gas produced by a gas generator.

The flow rate through the liquid hydrogen pump was measured by turbine-type flowmeters. Rotational speed was measured with a combination of a toothed wheel set in the turbopump shaft and a magnetic pulse pick-up. The shaft displacement of the turbopump was measured by an eddy-current-type sensor. Cryogenic temperatures were measured by platinum resistant thermometers. Static pressure measurements were carried out with strain-gauge-type sensors. Dynamic pressures were measured using quartz-type pressure sensors with a separate charge amplifier.[7]

Figure 4 shows the inducer part of the LE-7A FTP, which was used as a test article. Dynamic pressures were measured at section A (inducer inlet), section B (inducer middle), and section C (inducer outlet). The two wideband pressure sensors were installed at circumferentially different points for each section[7] to investigate phase difference between the two dynamic pressures, by which we were able to detect the rotating-stall-type phenomenon mentioned later.

The test of the inducer alone was performed using the inducer test facility at the KPC of the National Aerosopace Laboratory using degasified water.[8]

Hydraulic and Mechanical Performance

Figure 5 shows the suction performance curves of the original inducer using cavitation parameter τ, inducer head coefficient Ψ_{ind},

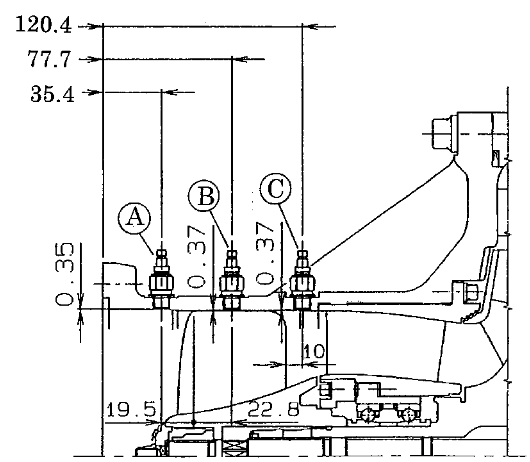


Fig. 4 Test section of LE-7A liquid hydrogen pump inducer.

and pump head coefficient Ψ_{pump}; here Q_d is the flow rate, which results in a velocity triangle similar to that of the design flow rate. Because the nominal flow rate Q_n of this inducer was changed to 0.94 Q_d ($\phi_{1n} = 0.064$) due to the change of the operating condition of the LE-7A engine, it was used in considerably off-design conditions. It was observed that the suction performance of this inducer was obviously influenced by the rotational speed. A fairly good suction performance was achieved at the rotational speed of 25,000 rpm. However, the rotational speed of 42,500 rpm caused a sudden drop in the head coefficient Ψ_{ind} at a flow rate of $Q/Q_d = 0.95$ ($Q/Q_n = 1.01$) when the cavitation parameter τ was reduced to around 0.029. The conspicuous sudden drop of the head coefficient did not occur even at a flow rate of $Q/Q_d = 0.92$ when the inducer was operated at a rotational speed of 25,000 rpm. Figure 5 definitely shows that this sudden head drop depends on the flow rate. Results of various tests indicated that this sudden head drop occurred at the rotational speed of 42,500 rpm when the range of the ratio α/β_{1t} was over 0.43 for this inducer.

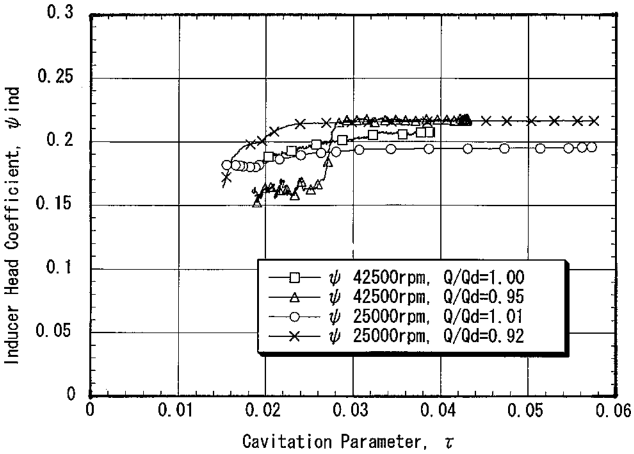


Fig. 5 Suction performance curves of original inducer.

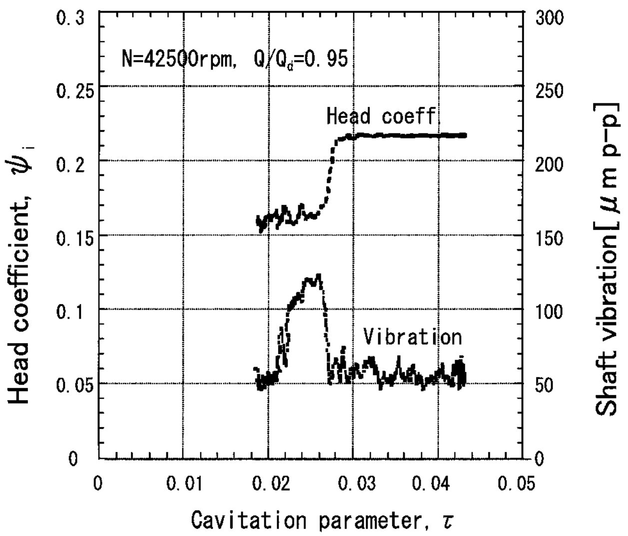


Fig. 6 Shaft vibrations related to suction performance (original inducer).

When this rapid head degradation occurred, unacceptable severe shaft vibrations simultaneously appeared, as shown in Fig. 6. The shaft vibration was restored to a small amplitude by further reduction of the cavitation parameter, as shown in Fig. 6.

Figure 7 is a waterfall diagram of the rotor vibration at the rotational speed of 42,500 rpm. In Fig. 7, the inlet pressure was varied from high to low with the passage of time at a constant shaft speed of 42,500 rpm. Rotor vibration with a large amplitude of around 350 Hz occurred in concurrence with the head drop mentioned earlier. In the hot-firing tests of the LE-7A engine, several bolts, which supported the aforementioned bearing housing and friction dampers, were broken by this large vibration. Because the original inducer is actually operated at a smaller flow rate ($Q/Q_d \fallingdotseq 0.94$) than the design flow rate in the LE-7A engine, great effort was made to determine the cause of this shaft vibration and sudden head degradation.

Oscillating pressures upstream, downstream, and in the middle section of the inducer were successfully measured using wide-band pressure sensors that were improved to be applicable to high-pressure liquid hydrogen.[7] When the phase difference between the pressure fluctuations at the two pressure measurement ports located in the periphery of the same section was analyzed, it was determined that the pressures rotated in the same direction as the inducer at a speed lower than that of inducer. Therefore, it was concluded that this phenomenon is not rotating cavitation, but a kind of rotating stall including cavitation.[9] The rotating speed of forward rotating cavitation is higher than that of the rotating blades. The phase difference between pressure fluctuations and rotor vibrations was also analyzed using fast Fourier transform, which identified the rotating pressure as the cause of the rotor vibration of 350 Hz. It was also clarified that the sudden inducer head degradation was caused by rotating-stall-type phenomenon at the inducer inlet, which might be closely related to the strong backflow cavitation that will be mentioned later. Shaft vibration of around 250 Hz is also observed in Fig. 7 and is considered to be a kind of self-excited vibration related to the frequency of the first critical speed. The cause of this vibration has not been clarified.

III. LE-7A FTP with Alternate Inducer

Design of Alternate Inducer

As already mentioned, the original inducer showed unstable operation that was caused by the strong backflow of the inducer inlet at the low NPSH, which resulted in a severe shaft vibration. Therefore, a program to develop an alternate inducer to suppress the backflow

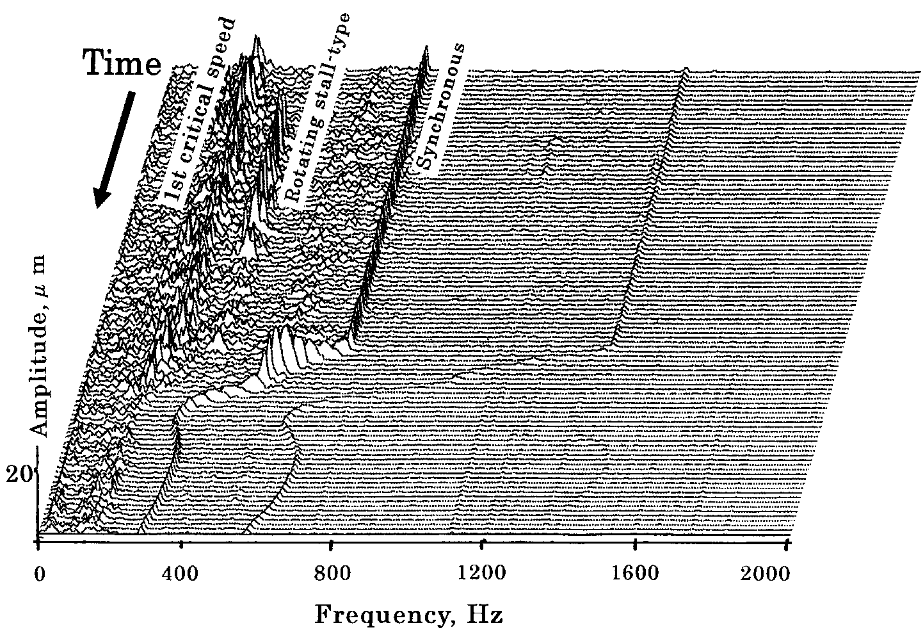


Fig. 7 Spectrum analysis of shaft vibration (original inducer).

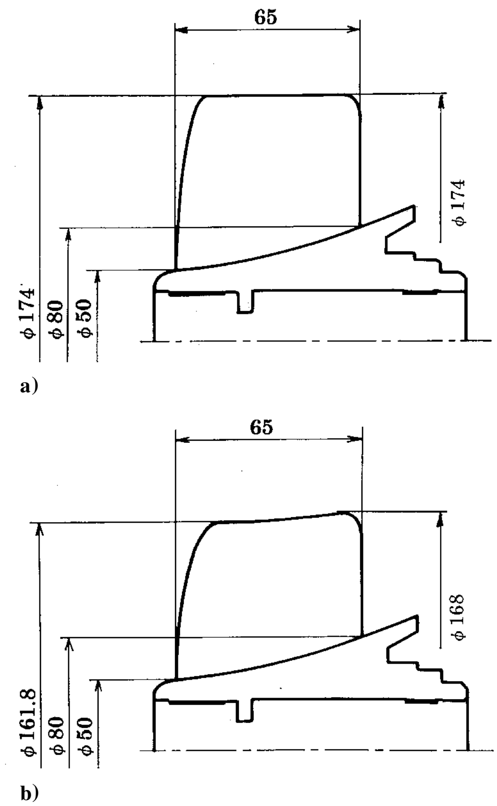


Fig. 8 Comparison of main geometries of a) original inducer and b) alternate inducer.

cavitation was undertaken to solve this problem. In this program, an effort was also made to suppress rotating cavitation.

Major design parameters of the alternate inducer are shown in Table 2. With regard to the design of the alternate inducer, the inlet tip diameter was decreased, and its outlet tip diameter was kept almost the same to increase the inlet flow coefficient and to keep the head rise coefficient almost intact compared with the original inducer. The design and nominal flow rate of this inducer are completely coincident. This corrective design was considered to be reasonable because the specific speed of this inducer is around 700 (m, m^3/min, rpm), which rather encourages a type of mixed flow inducer, when judged from the empirical relationship between the specific speed and pump geometry.[10] Figure 8 shows a comparison of the main geometries of the original and alternate induces.

To minimize blade blockage, the flow incidence angle α of the alternate inducer was reduced so as to about 10% below that of the original inducer at the design point. Because this change, the value of α/β_{1t} is 20% less than that of the original inducer. This means that the backflow of the inducer inlet will be greatly weakened, and the region of occurrence of the aforementioned rotating-stall-type phenomenon is considered to be kept away from the present operating region.

The hub configuration of the alternate inducer is exactly the same as that of the original inducer to allow replacement of the original inducer. The curvature of the camber line also changes linearly from inlet to outlet, the same as in the original inducer. The sweepback angle of the alternate inducer was increased to 90 deg, which is about 30 deg larger than that of the original inducer to decrease the load and the bending stress of the blades near the hub.

The wedge angle of the blade's leading edge and the blade thickness of the alternate inducer were determined taking both hydrodynamic and structural points of view into consideration. The blade surface finish of the alternate inducer was fairly enhanced by hydrodynamic polishing after machining and fine path processing to decrease the threshold stress related to fatigue failure, which also enhanced hydraulic efficiency.

Figure 9 shows the configuration of the assembled alternate inducer and its liner, which were newly produced. The blade tip

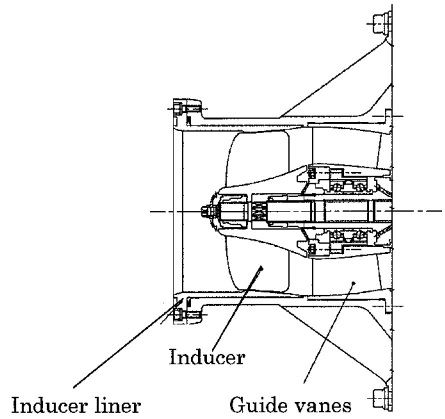


Fig. 9 Assembled configuration of alternate inducer and its liner.

clearance is 0.5 mm in operating conditions, which is exactly the same as that of the original inducer. The inducer liner has an oblique step at the inducer inlet to suppress the rotating cavitation.[11,12] Several types of step configurations were investigated in both the water and hydrogen tests. Both supersynchronous and synchronous rotating cavitations cause very large oscillatory stress, which should be considered in relation to fatigue fracture of the inducer blades. Furthermore, synchronous rotating cavitation (steady asymmetric cavitation) causes rotor vibration with large amplitude by hydraulic unbalance.

Test Results and Discussion

Detailed data on the alternate inducer were obtained during the tests of the LE-7A liquid hydrogen turbopump alone. In these tests, the turbopump was connected with the hydrogen feed line, which has the same configuration as that used in an actual flight. The tests were conducted under various conditions, including flow rate Q/Q_d, rotational speed, and inducer inlet pressure, with the flight operating conditions taken into consideration.

Besides the measurement of the hydraulic and mechanical performance in the steady state, various dynamic properties, including pressure fluctuations just around the inducer, shaft vibrations, and accelerations, were measured. Pressure fluctuations were measured upstream, just around the blade tip and downstream of the inducer, by quartz-type wideband oscillating pressure sensors, mentioned in the discussion of test facility and procedures in Sec. II. Shaft vibration data were obtained by measuring the radial displacement of the rotor at the backshroud of the second impeller.

As of April 2002, seven liquid hydrogen turbopumps with an alternate inducer were demonstrated to operate successfully at the low NPSH. In hot-firing tests of the LE-7A engines, the hydrogen turbopumps were verified to have sufficient durability and suction performance. Typical suction performance curves of the alternate inducers are shown in Fig. 10. The sudden head drop that appeared in the original inducer near the required NPSH did not appear at all, even when the inlet flow coefficient $\phi_1 = 0.076$ was less than the design flow coefficient $\phi_{1d} = 0.08$. Because the minimum cavitation parameter of the alternate inducer in the actual flight of the H-2A rocket is around 0.042, it will be possible for the inducer to be operated with a sufficient margin of suction pressure. In the present case, rotating cavitation was also perfectly suppressed by the installation of an oblique step under all operating conditions in the hydrogen tests, but could not be completely suppressed in the water test even using the same oblique step at the same flow coefficient, mentioned later. It is believed that hydrogen is more effective than any other fluid in suppressing rotating cavitation due to its thermodynamic properties and its large compressibility, which has the same effect as cavitation compliance on suppression of rotating cavitation.[9,13]

The alternate inducer was also tested at a rotational speed of 7500 rpm using a closed-loop inducer test facility at the KRC of the National Aerospace Laboratory.[8,14] The working fluid was degasified water at room temperature and visual observations were performed using a casing made of a transparent plastic. From visual observations of the water tests, it was verified that the backflow cavitation of the inducer inlet with the alternate inducer was greatly weakened compared with that of the original inducer when both the inducers were compared at the nominal flow coefficient, as shown in Fig. 11. The minimum cavitation numbers of the original and alternate inducer in actual flights of the H-2A rockets are 0.032 and 0.035, respectively. Taking into consideration the difference of thermodynamic effect of cavitation between water and liquid hydrogen, Fig. 11 is considered to simulate the operation in the low NPSH of liquid hydrogen.

Rotating cavitation was not completely suppressed in these water tests. Data on static and dynamic strain of the inducer blades and pressure fluctuations were also acquired in the water tests. An evaluation of the structural design of the alternate inducer was performed by finite element method analysis of a three-dimensional solid model using pressure profiles obtained by computational fluid dynamics. Evaluation of fatigue of the alternate inducer was also conducted using the stress, which was estimated from the results of water tests.

Figure 12 presents a spectrum analysis of the radial shaft displacement of the liquid hydrogen turbopump with the alternate inducer. The large radial displacements with a frequency of around 350 Hz, which appeared in the turbopump with the original inducer, were completely suppressed in the turbopump with the alternate inducer. As shown in Figs. 10 and 12, the rotating-stall-type phenomenon that occurred in the original inducer was completely suppressed in the alternate inducer. Therefore, it can be concluded that the design of the alternate inducer is appropriate. Table 3 shows the hydrogen and water test results of both the original and alternate inducers with the rotating-stall-type phenomenon and rotating cavitation.

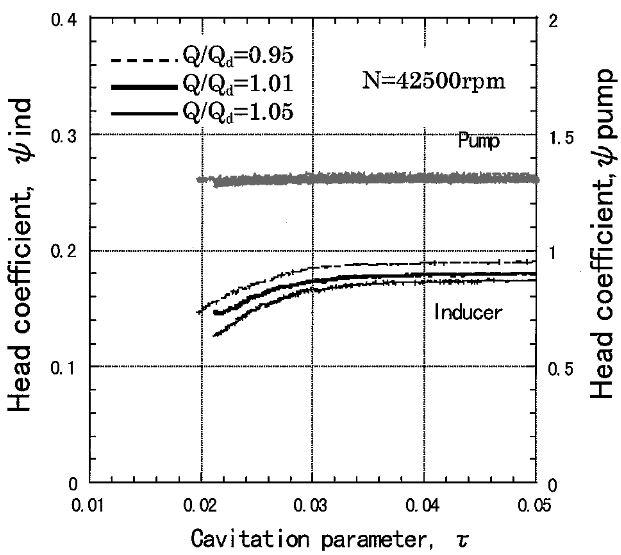


Fig. 10 Suction performance curves of alternate inducer.

We cannot fully explain the detailed mechanism of the relationship between the sudden head drop and the strong backflow in the inlet of the original inducer. In water tests, the original inducer did not show the sudden head degradation that produced the rotating-stall-type phenomenon that was observed in the liquid hydrogen tests.

Figure 13 shows spectrum analyses of pressure fluctuations measured upstream, around the blade tip, and downstream of the alternate inducer in the liquid hydrogen tests. A, B, and C in Fig. 13 indicate the locations of the sensor ports, upstream of the inducer, just around the blade tip of the inducer, and downstream of the inducer, respectively.

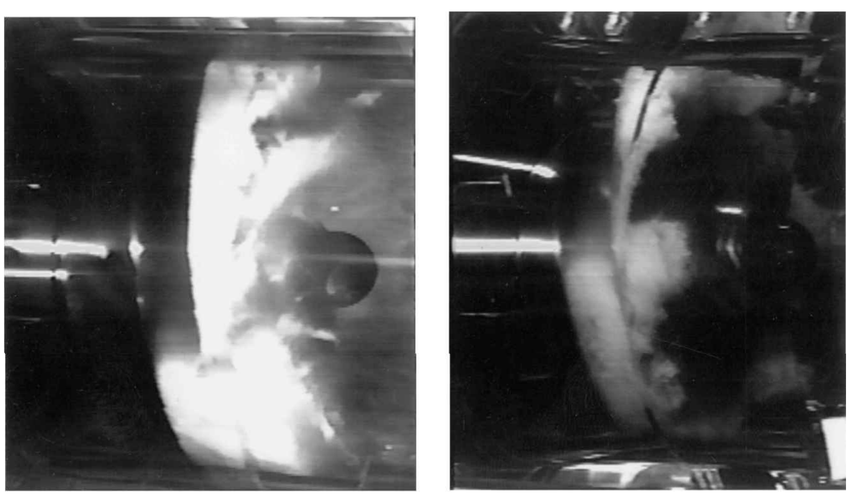
With regard to dynamic pressure within the inducer (Fig. 13b), pressure fluctuation with a frequency of around 2100 Hz due to blade passing is the most outstanding, which suggests that the dynamic pressure was measured with fairly high accuracy. Upstream of the inducer (Fig. 13a), pressure fluctuations with frequencies of between 800 and 1000 Hz are the most remarkable. However, no countermeasures were taken to suppress these pressure fluctuations because their amplitude, which decreases with the decrease of the inlet pressure, is not too large and their frequency is much less than the resonant frequency of the blades of the inducer.

With regard to observations downstream of the inducer (Fig. 13c), pressure fluctuations with extremely high frequencies of around 8 kHz appeared, and these frequences did not change with the decrease of the inlet pressure. It was concluded that the cause of the frequency of 8 kHz was due to the resonance frequency of the sense-port dynamics inasmuch as the frequency changed when the length of the sensor port was changed. This resonant frequency was almost coincident with the quarter-wave frequency of this sensorport calculated using physical properties of liquid hydrogen that were obtained using measured temperature and pressure.

In the final phase of the development of the alternate inducer, the battleship firing test of H-IIA was performed to confirm the

Table 3 Summary of test results of original and alternate inducers

Inducer	Rotating stall-type	Rotating cavitation
	Liquid hydrogen test	
Original	Appearance	Appearance
Alternate	Disappearance	Disappearance
	Water test	
Original	Disappearance	Appearance
Alternate	Disappearance	Appearance



a) b)

Fig. 11 Comparison of backflow cavitation at inducer inlet with nominal flow coefficients (water test): a) original inducer, $\phi = 0.064$, and $\sigma = 0.043$ and b) alternate inducer, $\phi = 0.079$, and $\sigma = 0.044$.

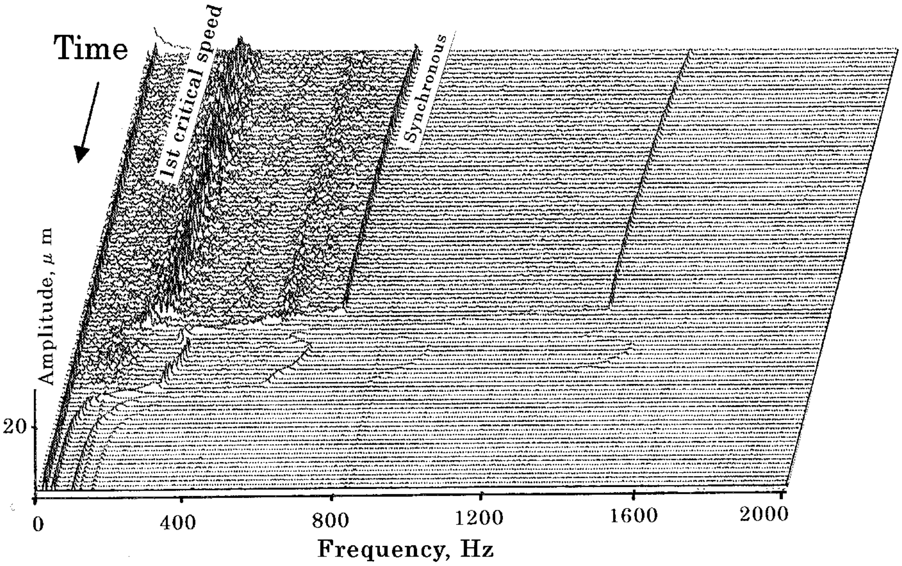


Fig. 12 Spectrum analysis of shaft vibration (alternate inducer).

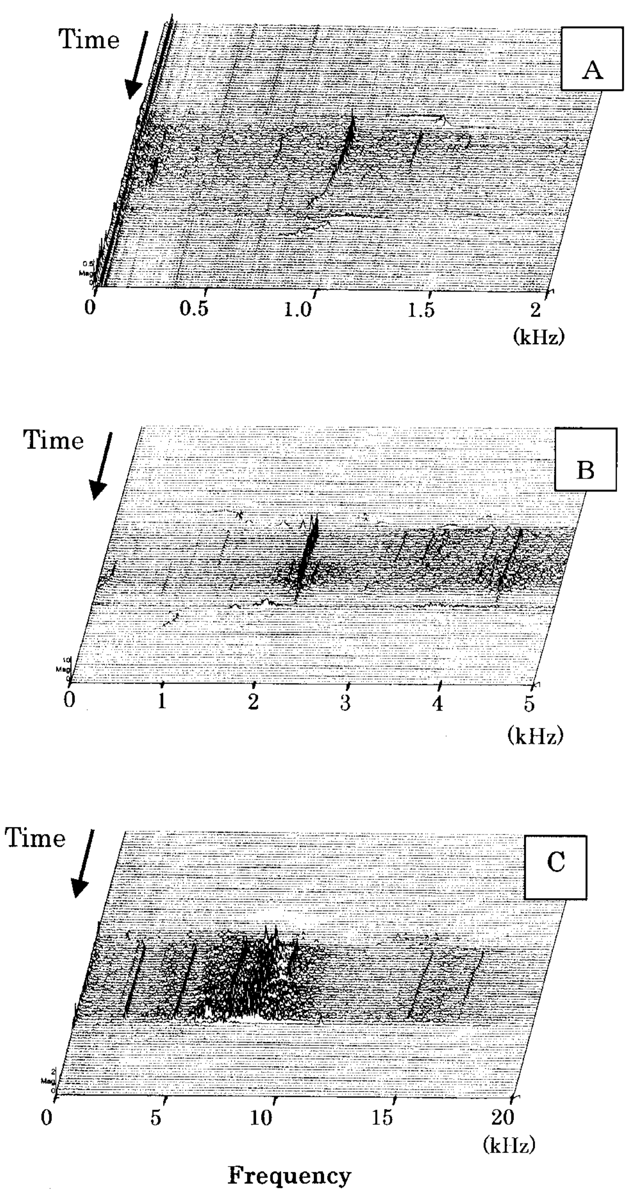


Fig. 13 Spectrum analysis of pressure fluctuations of alternate inducer: a) upstream, b) around blade tip, and c) downstream.

effect of the alternate inducer on overall system performance of the H-IIA first stage. Pressure of the liquid hydrogen propellant tank and temperature of hydrogen were changed to simulate the actual flight pattern. The LE-7A FTP with the alternate inducer operated satisfactorily under conditions similar to an actual flight. The alternate inducer operated successfully in the feed line, which was distorted by the gimbals of the LE-7A engine.

The second H-2A test flight vehicle, in which the LE-7A FTP with the alternate inducer was installed, was successfully launched in February 2002 from the National Space Development Agency Tanegashima Space Center, and the LE-7A engine operated perfectly.

IV. Conclusions

The original inducer of a liquid hydrogen turbopump of the LE-7A engine caused sudden head degradation and a rotating-stall-type phenomenon that brought about severe shaft vibrations near the required NPSH. A program to develop an alternate inducer was commenced in October 2000 to suppress these undesirable phenomena of the liquid hydrogen turbopump.

With the alternate inducer, the inlet tip diameter was decreased and its outlet diameter was kept almost unchanged to increase the inlet flow coefficient to decrease the backflow at the inducer inlet and to keep the head rise coefficient almost intact compared with the original inducer.

To date, seven alternate inducers have been investigated in tests of the liquid hydrogen turbopump alone. The alternate inducer completely eliminated sudden head degradation, the rotating-stall-type phenomenon, and severe shaft vibrations.

Acknowledgment

The authors would like to express their sincere thanks to the researchers and engineers involved in this joint development work.

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