Swept Frequency Type of Ultrasonic Inspection Method for Liner-Propellant Separations of the H-I Upper-Stage Motors

Morio Shimizu,* Katsuya Itoh,† and Tsutomu Fujiwara‡
National Aerospace Laboratory, Tokyo, Japan
Yukio Fukushima‡ and Michio Takahashi§
National Space Development Agency of Japan, Tokyo, Japan
and
Takao Maniwa¶
Nissan Motor Company, Tokyo, Japan

This paper describes the swept frequency type of ultrasonic inspection method that is usable for inspecting not only case-liner separations, but liner-propellant separations of solid motors and successful application of the method to the H-I upper-stage motors. Unfortunately, over the past quarter of a century, the liner-propellant separations have never been inspected practically with usual ultrasonic inspection methods. The new method has been developed at the National Aerospace Laboratory (NAL) since 1968, and the inspection technique is based on the one-dimensional quarter-wavelength resonance principle for the liner thickness under one free and the other fixed end-face boundary condition, which is considered the liner-propellant separation boundary condition of the liner. Since the motor cases have curved (spherical or cylindrical) surfaces, some curved contact surface probes were developed. This method was successfully applied to the apogee and third motor of the H-I rocket at the manufactory and then at the launching site. This inspection has contributed to the successful launchings of the H-I rocket since the first launching in August 1987.

Nomenclature

d_g = distance from probe to case due to liner thickness gradient
d_r = distance from probe to case due to liner thickness roughness
L = liner thickness
n = odd number
λ = ultrasonic wavelength
ϕ = diameter

I. Introduction

THE multiple-reflection technique in the ultrasonic inspection method has generally been applied to solid rocket motors. The pulse transmitted into the case is reflected at the case-liner and liner-propellant interface because of differences in their acoustic impedances. The reflection energy is about 86, 8.5, and 100% at the steel case-liner, liner-propellant, and any solid material-air interface, respectively. Then separation between the case and the liner can be detected with the multiple-reflection technique.[1,2] Unfortunately, it is extremely difficult to test the liner-propellant separations.[3] The fundamental obstacle is that relatively little energy is transmitted into the liner from the case because of the large impedance difference. Besides, rubber materials such as the liner have large coefficients of absorption. The pulse reflected from the liner-propellant interface is of such small energy that it is completely masked with strong multiple echoes in the case. Furthermore, the most important point is that the theory for the inspection of the liner-propellant separations has been based only on the reflection energy theory of the ultrasound, not including consideration of the relation between the liner thickness and the wavelength. For these reasons, the liner-propellant separations have not been inspected practically, over the past quarter of a century, with the multiple-reflection ultrasonic inspection methods in Europe[4] or in the United States.[5]

Recently we have found a paper with respect to the swept frequency ultrasonic inspection method for the liner-propellant separations.[6] The Acoustical Imaging System (AIS), a kind of swept frequency type of ultrasonic inspection system, was built and applied to small solid rocket motors. This paper may be the only one (besides ours) where a swept frequency ultrasonic inspection system was applied to the liner-propellant separations, however, the results were poor. Not only this paper but the continued AIS paper showed that the excellent ultrasonic system AIS could not detect liner-propellant separations.[7] The application was not based on the quarter-wavelength resonance principle mentioned later and we think this is the reason why the application failed.

On the other hand, our swept frequency type of ultrasonic inspection method, having been developed since 1968, can be used for inspecting the liner-propellant separations.[8] The inspection technique is based on the one-dimensional quarter-wavelength resonance principle for the liner thickness under the liner-propellant separation boundary condition of one free and the other fixed end-face of the separated liner. The resonance can be generated by adjusting an odd number times one-fourth wavelengths of the ultrasound to the liner thickness.[9] The present paper shows that the resonance can be easily detected with the swept frequency type of ultrasonic detectors using the multiple-reflection technique, as shown in the following reflectograms where the separation model of the H-I apogee motor is applied. This method was applied to the H-I upper-stage motors (the apogee and the third motor) since the first successful launching in August 1987.

Received June 3, 1988; presented as Paper 88-3356 at the AIAA/ASME/SAE/ASEE 24th Joint Propulsion Conference, Boston, MA, July 11-15, 1988; revision received Feb. 3, 1989.

*The 13th Research Group Leader, Space Technology Research Group.
†Researcher, Space Technology Research Group.
‡Assistant Senior Engineer, Launch Vehicle Program Department.
§Assistant Senior Engineer, Satellite Development Department.
¶Senior Engineer, Quality Assurance Department, Aerospace Division.

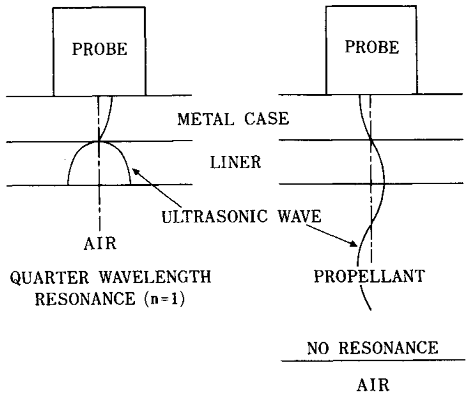


Fig. 1 System of swept frequency ultrasonic inspection method.

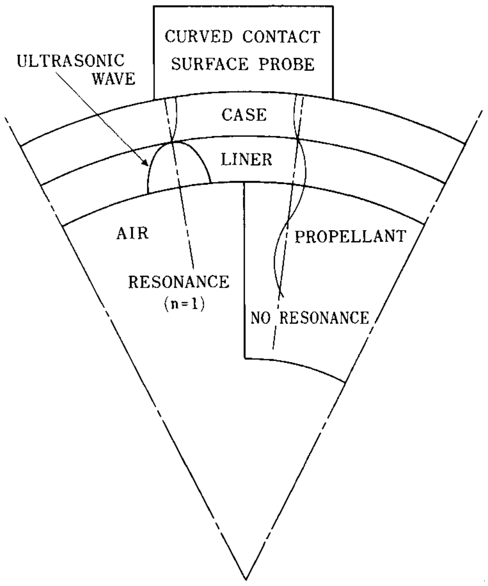


Fig. 2 Ultrasonic inspection of motors with a curved contact surface probe.

II. Swept Frequency Method

The single- or multiple-reflection technique has failed to be applied practically to the liner-propellant separations.[4,5] It is desirable to apply the inspection method for the liner-propellant separations to the case-liner separations as well. The multiple-reflection technique was adopted from many ultrasound inspection method techniques because it has most successfully been applied to the metal case-liner separations. The swept frequency technique combined with it was established in at the National Aerospace Laboratory (NAL) so that "... not only the reliability of the ultrasonic inspection at the steel case-liner interface gets higher, but also it may be possible to detect separations at the liner-propellant interface."[8]

Considering the vibrational boundary condition of the liner in Fig. 1, at the good bond regions the liner adheres on one side to the steel whose acoustic impedance is much higher than that of the liner, and on the other side to the dummy propellant whose acoustic impedance is almost the same as that of the liner, so that the liner-propellant boundary can hardly be recognized acoustically. At the liner-propellant separation regions, the liner comes in contact with air, whose acoustic impedance is much lower (practically zero) than that of the liner on the side opposite the case, so that the boundary condition of the liner is defined one-dimensionally as one fixed and the other free end-face. On this boundary condition, it is known that resonance happens when the liner thickness is equal to an odd number of quarter wavelengths [Eq. (1)].

$$L = \lambda n/4, \qquad n = 1,3,5,... \tag{1}$$

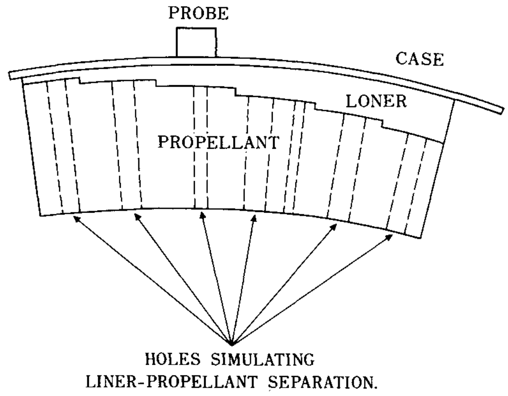


Fig. 3 Spherical model for the ultrasonic inspection test of the H-I apogee motor.

Therefore, if the resonance in the liner is generated strongly by adjusting an odd number of quarter wavelengths of the ultrasound to the liner thickness with a swept frequency type of ultrasonic flaw detector, and the resonance is hypersensitively detected with the detector, the liner-propellant separation can be inspected practically with this method. For the plane models that comprise a plane steel case, liner, and dummy propellant, the liner-propellant separations could easily be detected with this method.[9] Now, it should be confirmed that this method is useful for a curved model (being similar to real motors) with a curved metal case, liner, and dummy propellant. Theoretically speaking, if a curved probe fitting to the curved case is used, the phases of the ultrasound in the probe, case, and liner are the same as those of the plane model (Fig. 2). Hence, the aforementioned one-dimensional resonance principle holds also in the curved model. Otherwise (using a flat probe for the curved case), the resonance is weakly induced in the liner, because the phases vary (out of phase) according to the distance from the probe to the case in the coupler, and the waves somewhat cancel one another. When the difference in the distances is one-quarter wavelength, the waves are in antiphase, and the resonance is greatly weakened. Even if the resonance can be induced enough, it may be received only slightly because of the phase difference among the waves.

III. Experimental Method

A. Sample

The swept frequency ultrasonic inspection was successfully carried out in two kinds of plane samples consisting of a plane steel layer (case) of 1- or 3-mm thickness, liner layers of 1- and 2-mm thickness, and a thick dummy propellant layer.[9] Now, in order to apply the method to real motors, especially the H-I upper-stage motors, a curved sample (spherical model) is prepared, which comprises a spherical (378-mm radius of curvature) titanium alloy case with ethylene propylene dimethyl monomer (EPDM) liner (same as those of the H-I apogee motor) and dummy propellant. The liner thickness is changed in six steps, and various diameter holes are made in the dummy propellant, simulating the liner-propellant separations as in Fig. 3. These regions are named by three numbers respresenting thickness of the case, liner, and propellant, respectively. For example, (1-1.6-0) means a region where thickness of case, liner, and propellant are 1 mm, 1.6 mm, and 0 mm (no propellant), namely, liner-propellant separation; (1-1.6-20) corresponds to a good bond region.

B. Detector

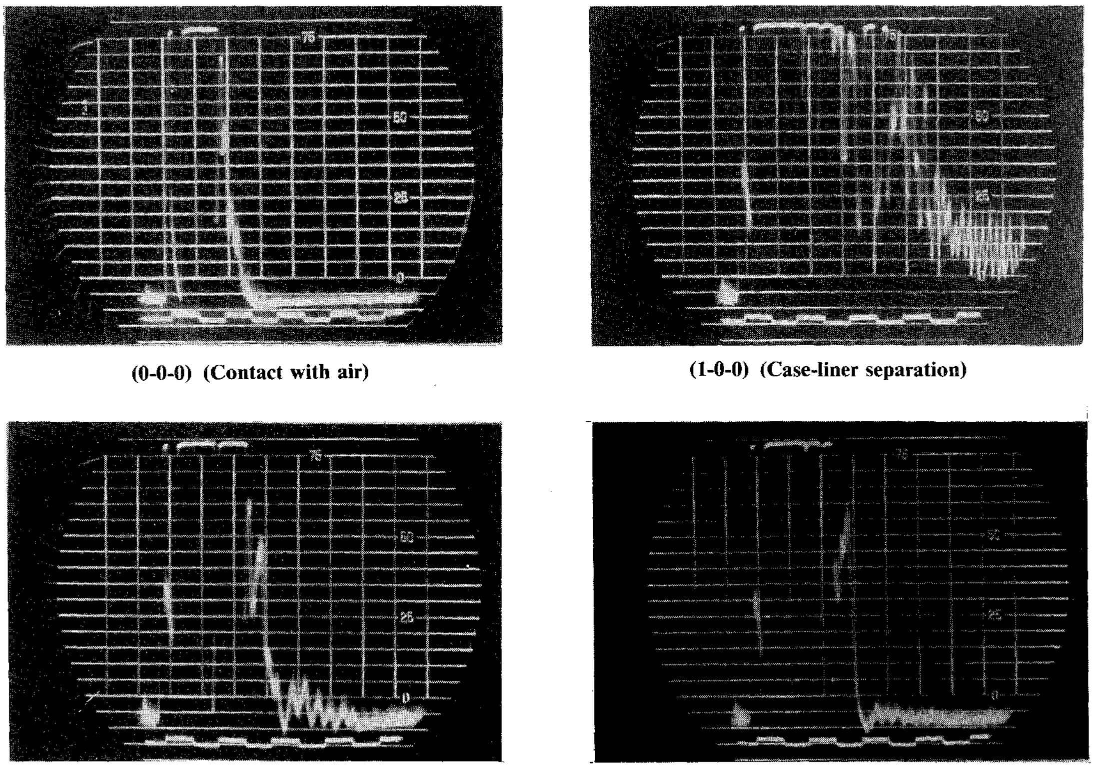
According to the theory mentioned previously, a swept frequency type of ultrasonic flaw detector is necessary. Recently, a few swept frequency ultrasonic detectors came to market. These are adopted, and their specifications are shown in Table 1.

Table 1 Performance of ultrasonic flaw detectors

Item	Swept frequency type I	Swept frequency type II	Discrete frequency type
Type	Stationary	Stationary	Portable
Frequency range	0.05–10 MHz	0.01–10 MHz	1, 2.25, 5 MHz
Modulation mode	3 kinds	6 kinds	—

Table 2. Specifications of flat, spherical and cylindrical probes

		Spherical probes			Cylindrical probes	
Item	Flat probe	S-1	S-2	S-3	C-1	C-2
Peak frequency, MHz	5	0.2	0.5	0.2	0.2	0.2
Radius of curvature, mm	infinite	378	378	646	378	646
Diameter of shape, mm	25	25	25	25	25	25



(0-0-0) (Contact with air)

(1-0-0) (Case-liner separation)

(1-3.1-0) (Liner-propellant separation)

(1-3.1-20) (Good bond)

Fig. 4 Discrete frequency ultrasonic inspection test for spherical model using the discrete frequency type of flaw detector and the flat probe (frequency: 5 MHz).

For the inspection test of the spherical model, usually flat contact probes were scarcely useful because area contact between the probe and the case cannot be expected, adding the theoretical reason with respect to the phases as previously mentioned. For this reason, spherical and cylindrical contact surface types of probes are prepared, whose radius of curvature is 378 or 646 mm (same as the spherical model or the H-I upper-stage motors). The peak frequency is 200 or 500 kHz (as tabulated in Table 2).

IV. Experimental Results

In order to confirm the applicability of the swept frequency ultrasonic inspection method for real motors, the spherical model is tested with the two kinds of detectors shown in Table 1. Using the discrete frequency type of detector and a flat probe (5 MHz) as usual, reflectograms are taken and shown in Fig. 4. It has been expected from the conventional multiple-reflection theory that the decay of the signal amplitudes is minimal for the case-liner separations, and this theory holds in Fig. 4. The reflectogram corresponding to the case-liner separation (1-0-0) is easily distinguished from the other reflectograms by comparing the decay of the signal amplitudes of the ultrasound during the multiple-reflection process. In this case, the decay of (1-0-0) is much less than the others in spite of using the flat probe. The theory also suggests that the decay of the signal amplitudes of the liner-propellant separation is less than that of the good bond[4,5] (although the suggestion had been denied theoretically and experimentally in our previous papers[8,9]). However, it is extremely difficult to find any difference between the reflectogram for the liner-propellant separation (1-3.1-0) and the good bond (1-3.1-20). Therefore, it is reconfirmed that the case-liner separations are detectable but the liner-propellant separations are undetectable with the discrete frequency type of detector.

On the other hand, using the swept frequency type of flaw detectors and the curved probes, things are quite different. Adjusting the ultrasonic frequency of the detector (type I) so as to make an odd number of quarter wavelengths equal to

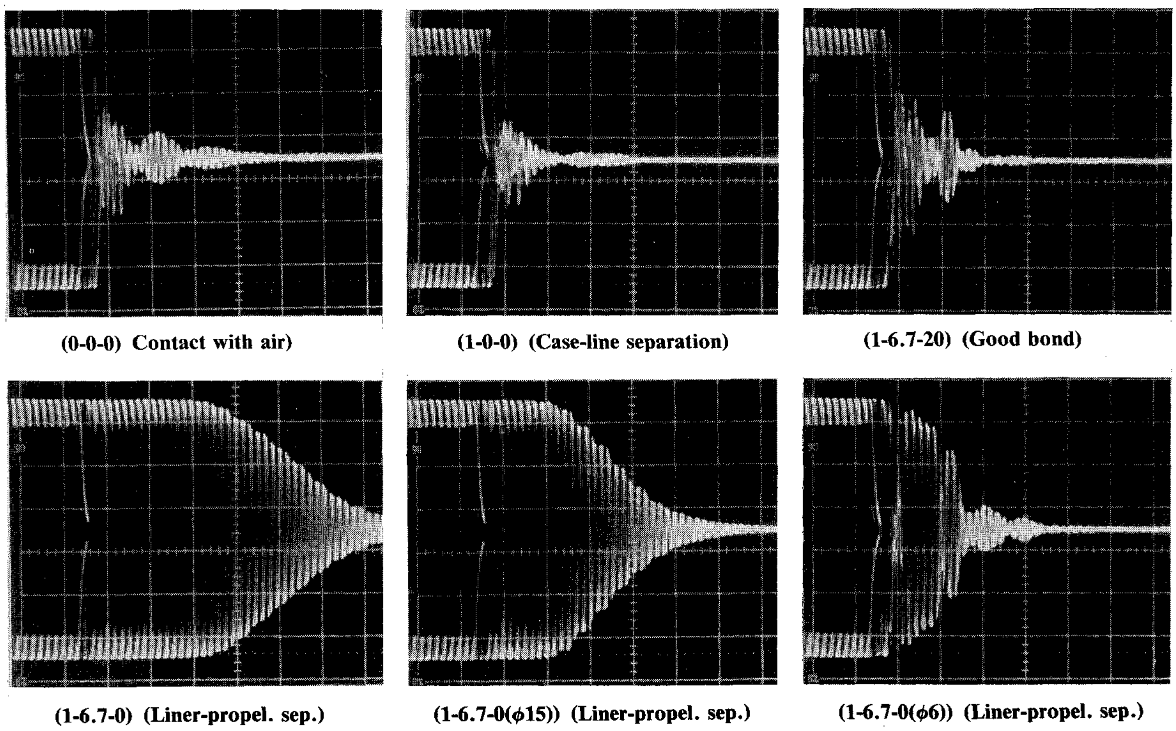


Fig. 5 Reflectograms of swept frequency ultrasonic inspection for the medium liner thickness part of spherical model obtained with the swept frequency flaw detector (type I) and the spherical probe S-2 (frequency: 286 kHz).

Table 3. Detectablity of the method for circular liner-propellant separation regions

	A	B	C	D	E	F
Separation region						
Liner thickness, mm	1.6	3.1	5.2	6.7	8.3	12.8
Resonance frequency, kHz	236	118	220	286	226	208
Odd number	1	1	3	5	5	7
Detectability						
25-mm-diam separation	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
15-mm-diam separation	Good	Good	Good	Excellent	Fair	Fair
6-mm-diam separation	Poor	Poor	Poor	Good	Fair	Fair

the liner thickness, resonance reflectograms in the 25-mm-diam liner-propellant separations are obtained and easily distinguished from the good bond reflectograms, where the liner thickness varies from 1.6–12.8 mm. For example, Fig. 5 shows the case of 6.7 mm liner thickness. The reflectogram [1-6.7-0(ϕ25)] of the 25-mm-diam liner-propellant separation can easily be distinguished from the reflectogram (1-6.7-20) of the good bond. This difference seems to be rather wider than that between the good bond (1-3.1-20) and the case-liner separation (1-0-0) in Fig. 4. Namely, the inspectability of our method for the liner-propellant separations is in no way inferior to that of the practical method for the case-liner separations. Therefore, our method can be applied to the extremely difficult inspection of the liner-propellant separations as effectively as the method for the easy inspection of the case-liner separations. It is noteworthy that the reflectograms at the good bond regions are similar to these at (0-0-0) where the probe surface contacts not with the case but with air. The case-liner separation (1-0-0) reflectograms are also similar to these. The case is considered too thin for the long-wavelength ultrasound to form multiple echoes in the case, and only the resonance in the liner can be received clearly. Now, how can small liner-propellant separation areas be detected with our method? It has been practically impossible to detect any liner-propellant separation with usual ultrasonic reflection methods, no matter how large the separation. Our method is useful, but it is only natural that as the area is smaller, it is harder to detect it. The experimental conditions and results are tabulated in Table 3. For the 15-mm-diam separation regions {e.g., [1-6.7-0(ϕ15)]}, this method is still useful, and even the 6-mm-diam separations {e.g., [1-6.7-0(ϕ6)]} can also be detected in some cases, especially in Fig. 5. The detection of such small liner- propellant separations indicates the excellence of our method. Hence, it is confirmed that this method is very useful for real (curved-case) motors as predicted.

V. Application of the H-I Upper-Stage Motors

Our method was applied to the H-I upper-stage motors (the apogee and third motor) for the first Japanese 550-kg-class synchronous satellite ETS-V, launched from the Tanegashima Space Center (TNSC) in August 1987. The ultrasonic inspection was performed at the solid-motor manufactory at the motor completion and then at TNSC just before the rocket assembly. The specifications of the detector (type II) are shown in Table 1, and the spherical and cylindrical probes used are listed in Table 2. The apogee motor is of extended spherical type and has the extended (cylindrical) part at the center of the motor as shown in Fig. 6. Then, not only spherical but also cylindrical contact surface type of probes

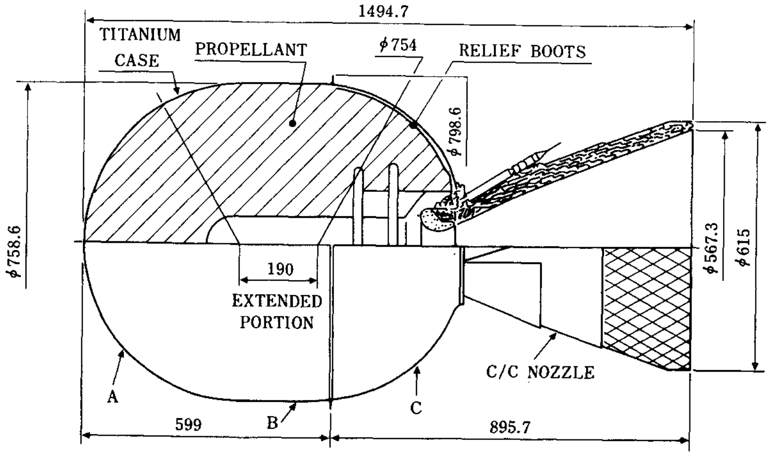
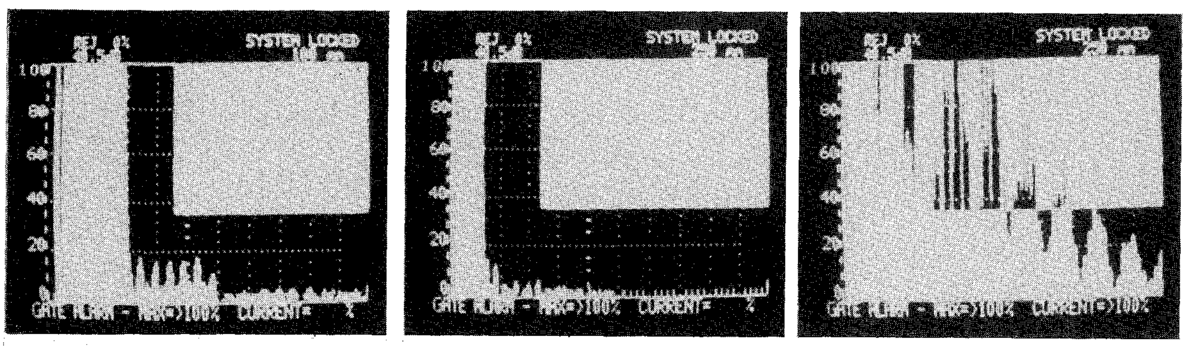


Fig. 6 Shape and dimensions of the H-I apogee motor and the places where reflectograms in Fig. 7 were taken.



Front (A) **Center (B)** **Back (C)**

Fig. 7 Reflectograms of swept frequency ultrasonic inspection for the H-I apogee motor, using the swept frequency flaw detector (type II) and the probes S-1 and C-1.

Table 4 Ultrasonic inspection conditions of the H-I upper-stage motors

Inspection place	Probe	Liner thickness, mm	Frequency, kHz	Odd number
Front A	S-1	1.6	650	3
Center B	C-1	5	230	3
Back C	S-1	6	330	5

are necessary to inspect the whole motor body (except for the nozzle) whose radius of curvature is 378 mm.

The inspection ultrasonic frequency was determined with the aforementioned theory and local thickness of the liner, and shown in Table 4. The whole motor body except for the nozzle was inspected, and no separation was detected. Here, three typical inspection regions of the motor (front A, central B, and back C region) are shown in Fig. 6. The resultant reflectograms are shown in Fig. 7. The front- and central-region reflectograms do not indicate any resonance, but the back-region reflectogram presents strong resonance resulting from the existence of the relief boots or flaps (artificial separation). Therefore, the usefulness of the swept frequency method for the real apogee motor is confirmed. Similar results were obtained with respect to the H-I third motor whose radius of curvature is 646 mm.

VI. Consideration

According to the theory, resonance is induced when the liner thickness is equal to an odd number of quarter wavelengths. Then, what value should be taken as the odd number? First, the strongest resonance is induced at the lowest resonance order. Second, the lower the resonance order (the longer the wavelength), the less sensitive the resonance condition is in respect to the liner-thickness variation. Namely, if the liner-separation surface is rough or the thickness is changed in the probe contact area, the resonance, depending on the liner-thickness variation compared with the wavelength (Fig. 8), becomes weaker at the shorter wavelength condition. Therefore, the lowest resonance-order value is desirable.

However, it is difficult to extend the good frequency characteristics range of the detector and the probe to a much lower frequency region. Usually, the range of good frequency characteristics is limited from 500–10 MHz, which is, unfortunately, rather higher than the desired range of 10–200 kHz at the lowest resonance order. Then, as shown in Table 3, the odd numbers take the tradeoff value from 1–7, corresponding to the frequency range from 100–500 kHz. In any case, it might be stressed that the swept frequency ultrasonic inspection method for the liner-propellant separations is very effective and is based on a surprisingly simple principle (one-dimensional quarter-wavelength resonance), leading to the solution of this difficult problem.

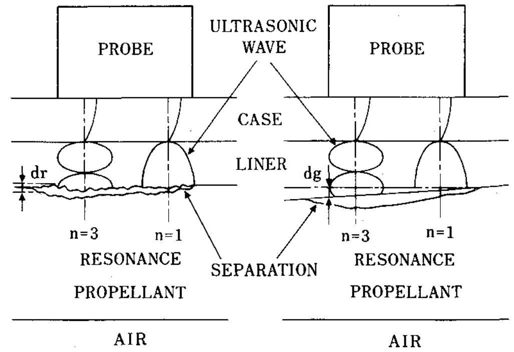


Fig. 8 Separation surface condition of liner-propellant interface and ultrasonic wavelength of inspection.

VII. Conclusion

The swept frequency ultrasonic inspection method can be used for inspecting the liner-propellant separations of real motors that cannot usually be inspected with the discrete frequency type of ultrasonic flaw detectors. The inspection method is based on the one-dimensional quarter-wavelength resonance principle for the liner thickness under the boundary condition that is defined as one fixed surface and the other free surface. The resonance can easily be generated by adjusting an odd number times one-fourth wavelengths of the ultrasound to the liner thickness, and also can easily be detected with the swept frequency type of ultrasonic flaw detectors, using the multiple-reflection technique with spherical and cylindrical contact surface probes developed for the real motors. This method has contributed to the successful launchings of the upper-stage motors of the H-I rocket since the first successful launching in August 1987.

References

[1]Harris-Maddox B., "The Ultrasonic Testing of Solid Propellant Rocket Motors," *Materials Evaluation*, Vol. 24, Feb. 1966, pp. 101–104.

[2]Stinebring, R. C. and Harrison, R. H., "Nondestructive Testing of Rocket Components Using Microwaves and Low-Frequency Ultrasonics," *Materials Evaluation*, Vol. 23, Jan. 1965, pp. 17–23.

[3]Amaral, J. M. and Lamb, B. L., "Development of Nondestructive Test Technique for Large Solid Propellant Grains," NASA CR-72840, N71-20477, March 1971.

[4]Zwijnenburg, A., Korting, P. A. O. G., and Reitsma, H. J., "On the Possibility of Detecting Case/Liner and Liner/Propellant Debonds in a Rocket Motor by Means of the Ultrasonic Multiple Reflection Pulse Echo Technique," *Propellants, Explosives, Pyrotechnics*, Vol. 8, April 1983, pp. 40–45.

[5]Rogovsky, A. J., "Ultrasonic and Thermographic Methods for NDE of Composite Tubular Parts," *Materials Evaluation*, Vol. 43, April 1985, pp. 547–555.

[6]Busse, L. J., Collins, H. D., Eick, J. L., Gribble, R. P., and Sperline, P. D., "An Acoustical Imaging System for the Inspection of Solid Rocket Motors," Air Force Rocket Propulsion Lab., Edwards AFB, CA, AFRPL-TR-84-002, AD-A139482, Jan. 1984.

[7]Foley, M., "Acoustical Imaging System Evaluation," Air Force Rocket Propulsion Lab., Edwards AFB, CA, AFRPL-TR-85-057, AD-A159425, Sept. 1985.

[8]Shimizu, M., Noguchi, Y., and Tanemura, T., "On the Ultrasonic Inspection of Separation in Solid Propellant Rocket Motors," *Proceedings of the 17th Japan Congress on Materials Research*, Society of Materials Science, Kyoto, Japan, 1973, pp. 271–275.

[9]Shimizu, M., et al., "Reliability Technique for Solid Motors (II), Swept Frequency Type of Ultrasonic Inspection Method for Liner-Propellant Separations," *Proceedings of the 15th International Symposium on Space Technology and Science (ISTS)*, AGNE Pub., Tokyo, Japan, 1986, p. 295–302.