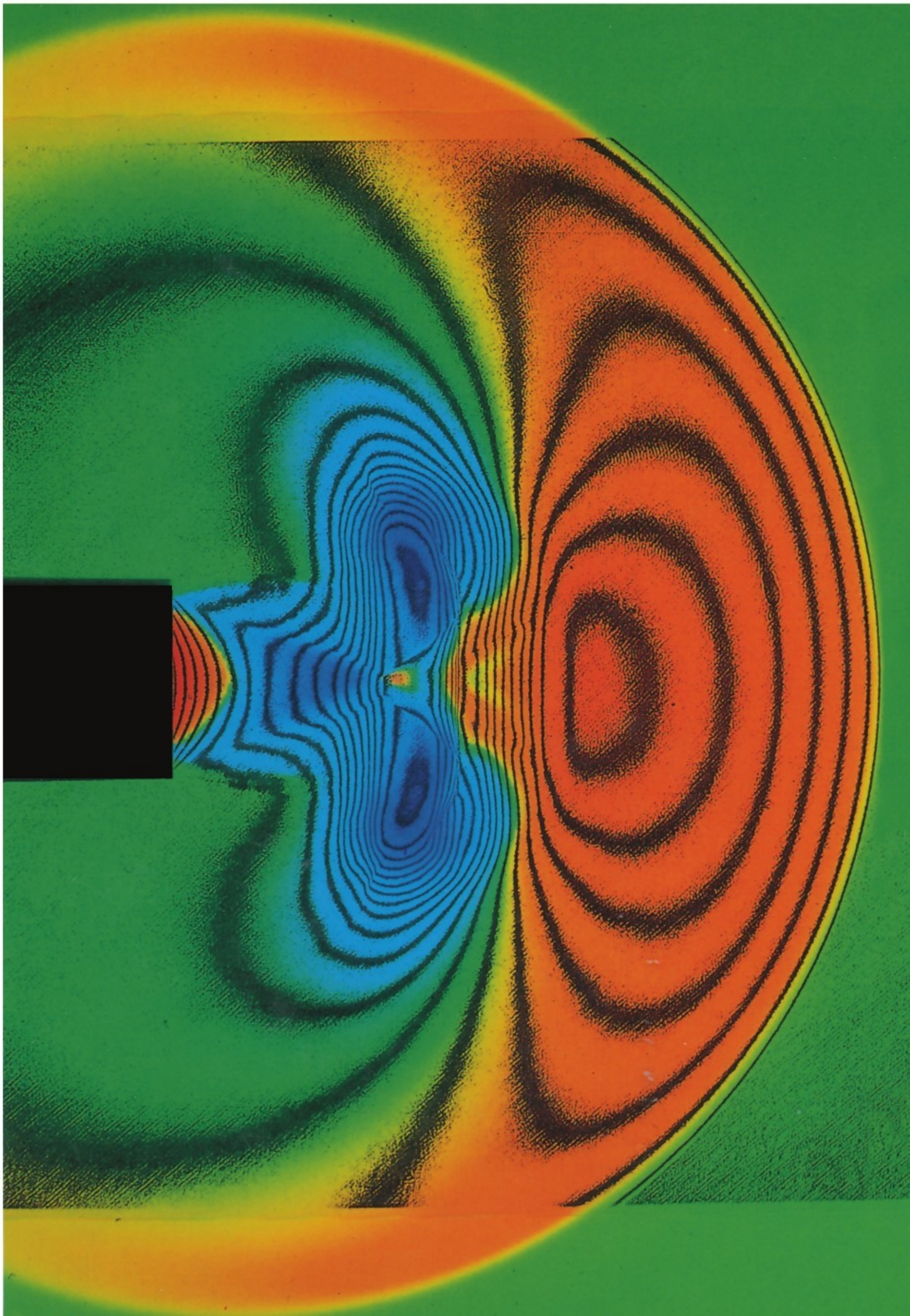
K. Takayama (Ed.)

Shock Waves

Proceedings, Sendai, Japan 1991/Volume I



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Proceedings
of the 18th International Symposium
on Shock Waves
Held at Sendai, Japan 21–26 July 1991

With 1268 Figures

Springer-Verlag
Berlin Heidelberg New York
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Hong Kong Barcelona
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ISBN-13: 978-3-642-77650-2 e-ISBN-13:978-3-642-77648-9
DOI: 10.1007/978-3-642-77648-9

Library of Congress Cataloging-in-Publication Data. International Symposium on Shock Waves (18th : 1991 : Sendai-han, Japan) Shock waves : proceedings of the 18th International Symposium on Shock Waves, held at Sendai, Japan, 21-26 July 1991 / K. Takayama, ed. p. cm. Includes bibliographical references and indes. ISBN 3-540-55686-9 (Berlin). – ISBN 0-387-55686-9 (New York) 1. Shock waves Congresses. 2. Shock waves–Industrial applications–Congresses. 3. Shock tubes–Congresses. 4. Fluid dynamics–Congresses. I. Takayama, K. (Kazuyoshi), 1940-. II. Title. QC168.85.S451578 1991 531'.1133–dc20 92-29581

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Softcover reprint of the hardcover 1st edition 1992

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Typesetting: Camera ready by author
55/3140 - 5 4 3 2 1 0 - Printed on acid-free paper

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PREFACE

The Eighteenth International Symposium on Shock Waves was held from 21 to 26 July 1991 in the Sendai Memorial Hall.

The First Shock Tube Symposium was held in 1957 at Albuquerque and from the Fifth Symposium in 1966 at Silver Spring through to the Tenth Symposium in 1975 at Kyoto, it became the International Shock Tube Symposium. From the Eleventh to the Fourteenth Symposium the name was modified to the International Symposium on Shock Tubes and Waves. Since 1985 a further modification to the name to the International Symposium on Shock Waves and Shock Tubes was adopted.

These changes of name suggest that the scope of the symposia has extended with time from the initial interest in shock tube research to include now, not only fundamental aspects of shock waves, but also an increasing number of applications in other research fields. Because it was intended to emphasise this trend and to embrace interdisciplinary topics on shock wave phenomena, the Eighteenth Symposium was named the International Symposium on Shock Waves. Some examples of such current interdisciplinary research are found in (i) the many intriguing medical applications of shock wave focusing; (ii) shock wave phenomena appearing in geoscience and astrophysics; and (iii) many unsolved gasdymanic problems in conjunction with shock waves in condensed matter.

Of over 400 abstracts submitted, 160 oral and 60 poster presentations were accepted for the symposium. These papers represent the position of the research frontier in shock wave phenomena. The proceedings contain 216 papers: 14 plenary lectures, 142 oral presentations, and 60 poster presentations.

The total number of participants who registered at the symposium was 437, from 23 countries: Japan 181, USA 70, Germany 34, CIS 28, France 23, Australia 22, Israel 17, China 16, UK 13, Canada 6, Taiwan 4, Italy 4, Sweden 4, Belgium 2, India 2, Korea 2, Netherlands 2, South Africa 2, Brazil 1, Czechoslovakia 1, Iran 1, Poland 1, and Romania 1.

As a symposium tradition, the first plenary presentation was the Paul Vielle Lecture, given on this occasion by Professor Hans Groenig of the Stosswellenlabor of RWTH Aachen. His paper summarizes hypersonic research facilities in Europe. The final plenary lecture was, again by tradition, the Otto Laporte Lecture, which was given by Professor Bradford Sturtevant of the California Institute of Technology. His topic was interdisciplinary research between volcanology and shock wave dynamics in connection with the eruption of Mount Bandai. This is an active volcano in Honshu, Japan, which, in 1883, suddenly exploded, blowing off its summit. His paper emphasizes that the enormous energy release of that eruption was associated with a water vapor explosion on a huge scale. This plenary lecture also became a memorial dedicated to co-author Professor Harry Glicken, who was killed a short time before the symposium by an eruption while investigating the active volcano at Mount Unzen of Kyushu in Japan. In addition to these established lecture series, the Eighteenth Symposium saw the inauguration of the Ernst Mach Memorial Lecture by Professor John M. Dewey of the University of Victoria. His paper reviews the state of the art of research in Mach reflection. Other plenary papers provide an overview of fundamental research topics of shock wave phenomena and their diverse applications to medicine, material science and industry.

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In 142 oral and 60 poster presentation papers of these proceedings, remarkable progress is to be seen in fundamental research, not only on gasdynamic shock wave phenomena, but also on shock waves in condensed matter and multi-phase media. Advances in experimental techniques and numerical simulation schemes are noticeable. Important applications of shock wave phenomena to hypersonic research and also in industry are reported. The investigation of the extension of extracorporeal shock wave lithotripsy to cancer therapy is another highlight of shock wave applications.

For the first time in this series of symposia, a poster session was organised. Sixty papers were on display and were formally open for discussion with their authors during the luncheon break on two of the days. All poster papers are included in these proceedings, each being allocated a maximum of four pages.

As they were received, manuscripts for inclusion in the proceedings were reviewed and retyped. In order to be a reliable data base for shock wave research, references in all manuscripts were cross-checked for uniformity and completeness of citations. Where needed, units were adapted to the SI system. Greater clarity was sought in some papers by modification of text and by redrawing of figures.

A special poster display comparing various methods of computation and experiment for the diffraction of a shock wave over a 90 degree corner was open continuously for three days during the symposium. The 19 contributions have already been published in Shock Waves, An International Journal, Vol.1, No.4, 1991.

Four international workshops were organized before and after the symposium. These were planned to promote informal exchange of ideas on a specified research topic, the opportunity for which might have been missed in the tight schedule of the symposium itself. These workshops each had a tutorial character which was intended to brief those who may wish to work in the particular area.

During the Eighteenth Symposium, the International Advisory Committee met and determined that the Nineteenth Symposium would be held in Marseille in 1993 and chaired by Professor Raymond Brun of the University of Provence, Marseille.

Finally, on behalf of the Organization Committee of the 18th ISSW, I would like to express my gratitude to Professor Hans Groenig of the Stosswellenlabor of RWTH Aachen and Professor Douglas Archer of the University of New South Wales for their help in reviewing the manuscripts for the proceedings. I would like to thank Director Hiroshi Miyajima of the National Aerospace Laboratory, Kakuda Branch Institute (NAL Kakuda), Professor Takashi Niioka of the Institute of Fluid Science, Tohoku University (IFS), and Dr. Jun Ikeuchi of the Government Industrial Research Institute of Tohoku (GIRIT) for their help in supporting the organization of the symposium. Enthusiastic assistance offered by the following is acknowledged with thanks: Professor Robert Casey (IFS), Professor Akihiro Sasoh (IFS), Dr. Tsutomu Saito (Cray Research Japan), Professor Masaaki Kuwahara (School of Medicine, Tohoku University), Mr. Norio Sanada (GIRIT), Professor Osamu Inoue (IFS), Mr. Osamu Onodera (IFS), Dr. Shigeru Sato (NAL Kakuda), Dr. Katsuhiro Itoh (NAL Kakuda), Mrs. Humiko Yoshida (IFS), Mr. HIdenori Ojima (IFS), Mr. Kikuo Takahashi (IFS), Mr. Shinji Kitajima (Chugoku Kayaku Co. Ltd.), Dr. Masud Behnia (University of New South Wales), Professor Shigenobu Maruyama (IFS), Professor Ozer Igra (Ben-Gurion University), and Mr. Hiroshi Doi (Senseki Hospital). I wish to thank the students of IFS and the local Executive Committee members for their help in organization of the symposium, and Mrs. Chieko Takayama, Miss Penelope Henderson, Mrs. Louise Casey, Mr. Toshio Okawa, and Mr. Kiichiro Takayama for their arrangment and management of the social programs and related activities. I am very grateful to Dr. Hideo Ise, Dr. Osamu Kitayama and Dr. Yu Abe of the School of Medicine of Tohoku University for their cooperation in serving as members of the medical care team.

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For editorial assistance and retyping and camera-ready preparation of manuscripts, I wish to thank Professor Akihiro Sasoh and Mr. Masato Watanabe, Mr. Tomoji Matsumura, Mr. Kiyoshi Yamada, Mr. Hong-Hui Shi, Mr. Satoru Itaka, Mr. Toshio Ohta, Mr. Kiyotaka Suzuki, Mr. Shigehisa Hunabashi, Mr. Hironobu Ohuchi, and Mr. Hajime Nagoya, students at the Shock Wave Research Center (IFS) of the Institute of Fluid Science, Tohoku University for their efforts in retyping the manuscripts and preparing the camera ready manuscripts. The special support offered by Mr. Toshio Sekine (Otowa Printing Co. Ltd.) for preparing half-tones from original manuscript photographs is acknowledged with thanks. Finally, may I express my appreciation to Professor W. Beigelböck (Springer-Verlag, Heidelberg) for his kind cooperation in publishing these proceedings.

March 1992 Kazuyoshi Takayama

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Anomalous refraction of shock waves

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Abstract. We present the results of our numerical work on anomalous shock refraction at air/CO_2 and air/SF_6 interfaces. The numerical method was a second-order multi-fluid Godunov code. The results indicate that anomalous refraction is not one phenomena but a group of them, and their natures depend on whether the wave impedance increases or decreases during refraction.

Key words: Shock refraction, CFD, Shock impedance

1. Introduction

Refraction is expected whenever a shock passes from one material to another. Formally, it appears when the relative refractive index n is different from unity (n $\neq$ 1) during propagation, where

$$n \equiv \mid U_i \mid / \mid U_t \mid = \sin \alpha_i / \sin \alpha_t \quad . \tag{1}$$

Here U_i, U_t are the velocities of the shock in the incident and transimitting (receiving) material, and α_i, α_t are the wave angles of the shock in these materials. Nearly all refractions are accompanied by a wave that is transmitted back into the initial material. This will be a compression if the wave impedance Z increases during refraction $Z_t > Z_i$, but an expansion if Z the decreases ($Z_t < Z_i$). The wave impedance is the vector mass flux,

$$Z_i \equiv \rho_i U_i \quad ; \quad Z_t \equiv \rho_i U_t \quad , \tag{2}$$

where ρ is the material density. An alternative and equivalent definition makes use of the momentum equation,

$$Z_i = \frac{P_i - P_o}{\mid U_{Pi} \mid} n_i \tag{3}$$

where P_i-P_o is the pressure jump across i, U_{Pi} is the particle (piston) velocity, and n_i is a unit vector in the direction of propagation.

It is convenient to classify refracting systems as regular or irregular, analogous to the classificaiton of shock reflection as regular or Mach (irregular). Regular sytems have uniform flow fields between the waves but irregular sytems have at least one non-uniform region.

2. Anomalous refraction

This is an irregular system first detected during the experiments of Jahn (1956). One necessary condition for its onset is that the refraction should be fast-slow $n > 1$,e.g. when a shock passes from air into CO_2 (Jahn) or from air into SF_6(Abdel-Fattah and Henderson 1978). A second condition is that the wave angle α_i of the incident shock i exceeds the condition where there is sonic flow downstream of, and relative to, i (M_1=1). This critical condition $\alpha_i = \alpha_i^*$ say is easily

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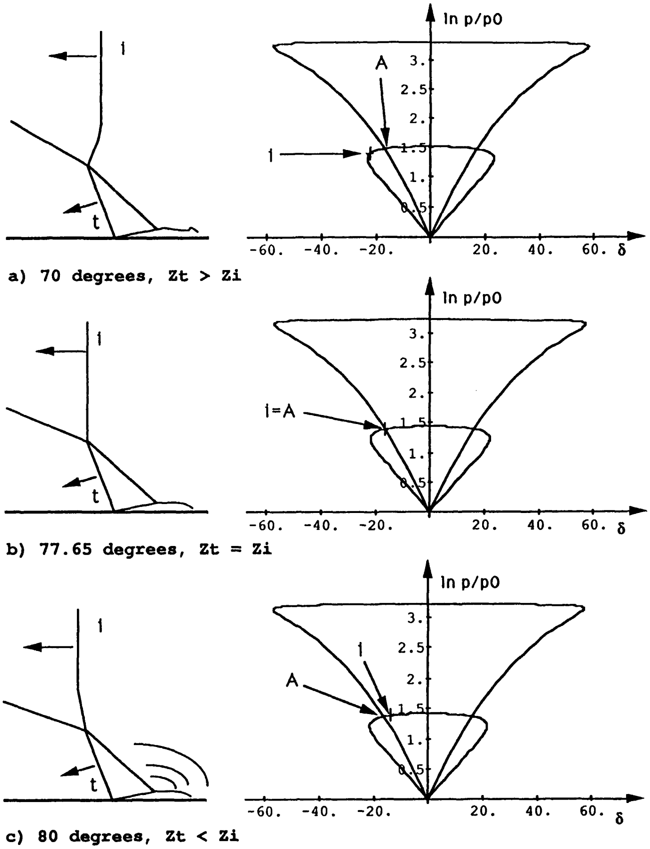

Fig. 1. Wave and polar sequence with changing wave impedance for Air/ SF_6 shock refraction ($n > 1$)

calculated from a wave diagram. The result for an arbitrary material is (Kamegai 1986; Grove and Menikoff 1989).

$$\tan^2 \alpha_i^* = \frac{U_i^2}{a_1^2 - (U_i - U_{pi})^2} \quad , \tag{4}$$

where a_1 is the speed of sound in the undisturbed incident material. For the special case of a perfect gas Eq. (4) can be more conveniently written in terms of the shock Mach number M_i and the ratio of specific heats γ

$$\tan^2 \alpha_i^* = \frac{(\gamma + 1)M_i^2}{(M_i^2 - 1)[(\gamma - 1)M_i^2 + 2]} \quad . \tag{5}$$

Jahn (1956) experimented with the air/CO_2 interface for $\alpha_i > \alpha_i^*$ and obtained the type of anomalous refraction sketched in Fig.1c. The incident shock i weakens as it approaches the interface, and curves in the rearward (downstream) direction. This fact indicates that $Z_t < Z_i$. The polar diagram supports this conclusion since the pressure ratio $P_i/\ P_0$ associated with i exceeds that associated with the equality of impedance condition ($Z_t = Z_i$) at the polar intersection A. In Fig.1b the polar map of i coincides with A, (i≡A) and the wave impedances of i and t are

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equal. Physically i is now a plane wave all the way to the inter-face. In Fig.1a, $Z_t > Z_i$ and i strengthens as it approaches the interface, and curves forward.

In Jahn's experiments it was always true that $Z_t < Z_i$ so the anomalous refraction was as illustrated in Fig.1c, but in the experiments of Abdel-Fattah and Henderson (1978) $Z_t > Z_i$ and the anomality was as in Fig.1a. When i was sufficiently strong, there was a Mach reflection in air.

3. Numerical work

We assumed that all the gases were perfect and that the flows were two-dimensional, compressible, unsteady and non-viscous. Consequently we numerically integrated the continuity and Euler equations in association with the perfect gas equations of state. The code has been described in some detail elsewhere (Colella et al. 1989; Henderson et al. 1991). Briefly it was a second order finit difference solution on a rectangular grid with reflecting boundary conditions on three sides and an inflow condition on the fourth. A second order Godunov method with operator splitting was chosen (Van Lear 1979; Colella and Woodward 1984). There was automatic refinement of the grid in regions of special interest or excessive error. This provided us with an economic method for resolving important regions of flow.

4. Results and discussion

We have computed examples of anomalous refractions at air/CO_2 and air/SF_6 interfaces. A sequence for the latter with a varying impedance relation is shown in Fig.2. In Fig.2c, $Z_t < Z_i$ and as expected, i weakens and curves in the downstream direction as it approaches the interface. In Fig.2b, $Z_t = Z_i$ and i remains everywhere a plane shock, while in Fig.2a, $Z_t > Z_i$, and i curves forward. There are some other interesting results. The t shock reflects off a rigid wall and intersects the gas mixing layer. In Fig.2c, the intersectin is a source of acoustic radiation, and this was also detected in the experiments of Abdel-Fattah and Henderson (1978). In Fig.2a, the layer shows marked instabilities, which appear to be successively linear, Kelvin-Helmholz, and chaotic.

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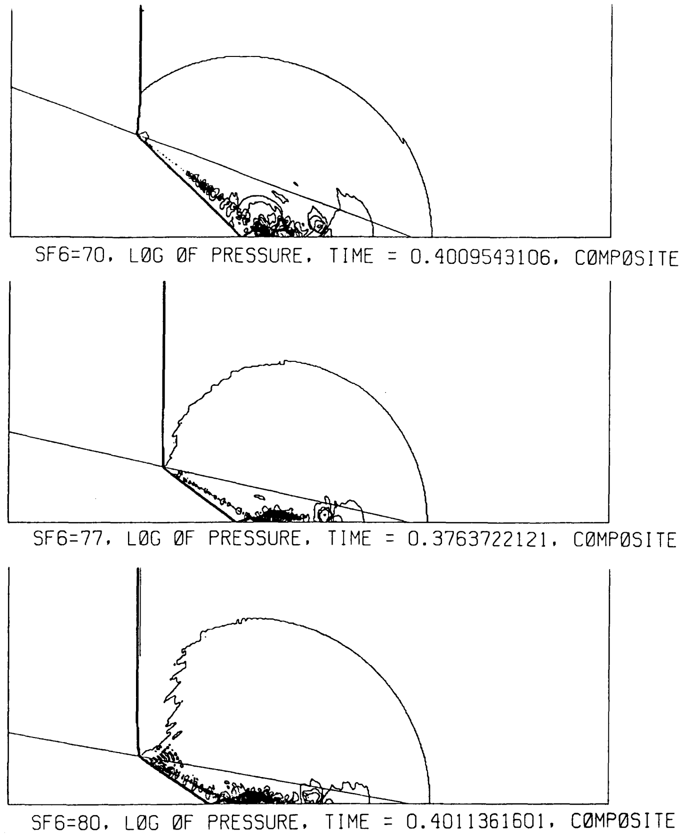

Fig. 2. Numerical contour plots for Air/SF_6 shock refraction ($n > 1$). a) $Z_t > Z_i$, b) $Z_t = Z_i$, c) $Z_t < Z_i$

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