HIGHLY CITED LITERATURE OF HIGH SPEED COMPRESSIBLE FLOW RESEARCH

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ABSTRACT

High speed flow research has been sponsored and performed at differing levels of effort since the late 1800s. For example, hypersonic research has experienced numerous cycles since the 1950s, with various periods of high research activity, followed by equally long periods of very low activity. This lack of continuity in high speed flow research has led to a situation where researchers of one "generation" often do not know what the reseachers of previous "generations" have done, mainly due to large losses of institutional knowledge in government, industry, and academic organizations. Therefore, a chronically weak area in research papers, reports, and reviews is the complete identification of critical background documents that form the building blocks and intellectual heritage for modern compressible flow research. A method for systematically determining these critical references is presented in the context of its application to high speed flow using Citation-Assisted Background, which is based on the assumption that many critical documents tend to be highly cited within the literature. While Citation-Assisted Background is a highly systematic approach for identifying critical references, it is not a substitute for the judgement of the researchers, but rather complements their expertise. In this critical review of high speed compressible flow, important documents have been identified using Citation-Assisted Background, but other documents have been added by the authors to enhance the picture provided by the highly-cited documents.

KEYWORDS: Compressible Flow; High Speed; Hypersonic; Supersonic; Transonic; Ramjet; Scramjet; Computational Fluid Dynamics; Citation Analysis; Literature Survey; Literature Review

INTRODUCTION

High speed research (transonic, supersonic, and hypersonic flow) has been conducted for decades, if not centuries. A great deal of that research has taken place,

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however, in periods of intense interest, often followed by equally long periods of little or no interest. Because of this, the background literature available to researchers is very specialized and often not easily found.

When the situation is coupled with relatively recent advent of computer-based citation indexes, additional difficulties arise for the current researchers in the field. How many of the seminal works in high speed flow research are listed in various computer data base search engines; how easy are they to identify? Will current research students, who have a tendancy to rely heavily on computer and web-based searches, be able to find the critical research documents in their field of interest? Will the fact that a great majority of that research happened prior to the advent of computer data bases adversely impact the research that is currently being conducted? These are all questions hat have plagued researchers in a variety of fields, but perhaps one of the most difficult fields to obtain good background information for is high speed flow research.

The primary purpose of this work is to outline the critical mainly highly-cited literature for high speed research, going back over a century in time. The areas of high speed research that will be included in the description are aerothermodynamics, propulsion/combustion, and vehicle design. Numerous sub-topics will be considered for each of these areas, as appropriate, with the critical literature of these fields listed and discussed. The literature for each of these areas was located using a modern computer data base search approach known as Citation-Assisted Background (CAB). The details of how CAB is used for the search are outlined, and the results are discussed. Using such an approach for citation searching should greatly help in insuring that the future of high speed research will be solidly built upon the past, rather than missing critical and important previous work that would have been crucial to current and future research developments.

BACKGROUND

Research is a method of systematically exploring the *unknown*, or determining more about the *known*, in order to acquire knowledge and understanding. Efficient research requires awareness of all prior research and technology that could impact the research topic of interest, and builds upon these past advances to create discovery and new advances. The importance of this awareness of prior science and art is recognized throughout the research community in all fields of science and engineering. The need for exploring the past prior to exploring the future can be expressed in diverse ways, including requirements for Background sections in journal research articles, invited literature surveys in targeted research areas, and required descriptions of prior work in patent applications.

For the most part, development of Background material for any of the above applications is relatively slow, labor intensive, and limited in scope. Background material development usually involves some combination of manually sifting through outputs of massive computer searches, manually tracking references through multiple generations, and searching one's own records for personal references. The few studies that have been done on the adequacy of background material in documents show that only a modest fraction of relevant material is included.[1-3]

In a study that is highly relevant to the topic of this paper, two background surveys of the abrupt wing stall (AWS) literature (as a precursor to establishment of a government research program) by an AWS expert were compared to a text-mining based identification of relevant AWS documents from the SCI (ref. 4, Kostoff, R. N., Karpouzian, G., and Malpohl, G. "Text Mining the Global Abrupt Wing Stall Literature". Journal of Aircraft. 42:3. 661-664. 2005.). In the first expert-based AWS background survey (ref.5, Chambers, J. R., "Historical Review: Perspectives on Experiences with Uncommanded Lateral Motions at High-Subsonic and Transonic Speeds," Ball Aerospace and Technologies Corp., Aerospace Systems Div., Boulder, CO, Feb. 1999.), three of the expert's total of 37 references were in common with the 40245 references retrieved in the text mining-based study. In the second expert-based AWS background survey (ref. 6, Chambers, J. R., and Hall, R. M., "Historical Review of Uncommanded Lateral-Directional Motions at Transonic Conditions," AIAA Paper 20034-0590, Jan. 2003.), seven of the expert's total of 61 references were in common with the text mining study results.

For a relatively focused topic such as AWS, one would have expected a far more substantial overlap. Many of the expert's references appeared to be quite applied, with focus on tests of specific aircraft. In contrast, the text mining-based SCI papers tended to be more fundamental, concentrating on the analysis of basic flowfield phenomena and physics. In addition, authors tend to cite even more fundamental references, and so the combination of fundamental papers from the SCI retrieval coupled with their even more fundamental references identified a fundamental set of cited papers that complemented the more applied set in the expert's study. For the purpose of identifying gaps in the research literature to be addressed in a prospective AWS research program, a survey of the fundamental AWS research literature is essential.

This specific example shows perhaps the main value of the retrieval approach that underlies the CAB process; it allows the expert to go beyond his/her own experience to objectively access and retrieve literatures with which they may not be familiar. Had the objective of the AWS literature review been to identify seminal AWS papers, then the full CAB capabilities could have been exploited as well.

In another example of the inadequacy of background material, an analysis of Medline papers on the haemodynamic response to orotracheal intubation showed that recognized deficiencies in research method were not acknowledged. The authors of this study recommended that, when submitting work for publication, investigators should provide evidence of how they searched for previous relevant research work.[7]

Another specific example was provided by MacRoberts and MacRoberts.[8] Replicating their earlier work in a journal on genetics that indicated only 30% of influences evident in the text were reflected in a paper's references, the text of an issue of *Sida* (now called the *Journal of the Botanical Research Institute of Texas*) was studied to extract influences of previous work evident therein. Influences they judged to be present in the text appeared in the references only 29% of the time.

Typically missing from standard Background section or review article development, as well as in the specific examples cited above, is a systematic approach for identifying the key documents and events that provided the groundwork for the research topic of interest. In the field of hypersonic research, for example, the Air Force Scientific Advisory Board noted that, "hypersonics has always suffered from a pattern of cyclical fits and starts at roughly 15-year intervals."[9] This has led to a situation where entire generations of researchers and designers may be unaware of the programs or research which had previously been done, or the advances and concepts that those programs included. Programs like DYNASOAR, the X-15, the Space Shuttle, NASP, HOTOL, X-33, and Hyper-X were separated by fairly large periods of time, and often were performed by people who did not have the luxury of knowing the researchers or results of all the previous programs (in some cases because those results were not readily catalogued in modern data base systems; in other cases, such as AWS, because the vendors and sponsors did not want to over-advertise problems with their products). What impact has this cyclic nature of high speed research had on the current generation of people working on various concepts and designs? How many times have current researchers "missed" previous work because it was too old to find in modern databases, or because they did not have the appropriate search algorithms to identify the relevant research of interest? How much has this impacted the growth of science and engineering within high speed research? Finding a way to systematically (and to a lesser extent, permanently) solve this problem was a major motivation behind this work. The present paper presents such a systematic approach for identifying the key documents, called Citation-Assisted Background (CAB). The next section describes the CAB concept and provides an outline of how it is applied to the area of high speed flow research.

The CAB concept of Kostoff and Shlesinger[10] identifies the seminal and other critical background documents for a research area using citation analysis. CAB rests on the assumption that a significant building block document for a specific research area will typically have been referenced positively by a substantial number of people who are (or were) active researchers in that specific area. While the precise approach to applying CAB to high speed aerodynamics is outlined in the Appendix, Table 1 contains the twenty highest frequency (most cited) references extracted from the high speed flow database.

Table 1. Top Twenty Most Highly Cited Documents

#REC	FIRST AUTHOR	YEAR	SOURCE	VOL	PAGE
361	ROE[11]	1981	J COMPUT PHYS	43	357
350	BALDWIN[12]	1978	AIAA PAPER 78-0257		
241	JAMESON[13]	1981	AIAA PAPER 81-1259		
168	PAPAMOSCHOU[14]	1988	J FLUID MECH	197	453
145	MURMAN[15]	1971	AIAA J	9	114
142	HAYES[16]	1959	HYPERSONIC FLOW THEORY*		
136	STEGER[17]	1981	J COMPUT PHYS	40	263
127	COURANT[18]	1948	SUPERSONIC FLOW . . . *		
126	HARTEN[19]	1983	J COMPUT PHYS	49	357
118	BEAM[20]	1978	AIAA J	16	393
110	BROWN[21]	1974	J FLUID MECH	64	775
107	ANDERSON[22]	1989	HYPERSONIC HIGH TEMP. . . *		
103	VAN LEER[23]	1979	J COMPUT PHYS	32	101
100	FAY[24]	1958	J AERONAUT SCI	25	73
92	MACCORMACK[25]	1969	AIAA PAPER 69-0354		
90	BIRD[26]	1994	MOL. GAS DYNAMICS*		
87	STEWARTSON[27]	1969	PROC R SOC LON A	312	181
86	SPALART[28]	1992	AIAA PAPER 92-0439		
84	JONES[29]	1972	INT J HEAT MASS TRAN	15	301
84	BOGDANOFF[30]	1983	AIAA J	21	926

* book

Two frequencies are computed for each reference, but only the first is shown in Table 1. The frequency shown in the left-most column is the number of times each reference was cited by the 10556 records in the retrieved database only. This number reflects the importance of a given reference to the specific discipline of high speed compressible flow. The second frequency number (not shown) is the total number of citations the reference received from all sources, and reflects the importance of a given reference to all the fields of science that cited the reference. This number is obtained from the citation field or citation window in the SCI. In CAB, only the first frequency is used, since it is topic-specific. Using the first discipline-specific frequency number obviates the need to normalize citation frequencies for different disciplines (due to different levels of activity in different disciplines), as would be the case if total citation frequencies were used to determine the ordering of the references. References that have high values of the second frequency and low values of the first frequency are typically (but not always) of peripheral relevance to the discipline of interest.

A few observations about the twenty articles listed in Table 1 are in order before proceeding with more details about the search. The topics of the articles are dominated by presentations of numerical algorithms appropriate for compressible flow (a total of eight articles), as well as turbulence models (three articles). These results show how important computational fluid dynamics (CFD) has been in recent decades in compressible flow research, but also shows how more recent citations dominate the list of top cited articles. Four of the citations are books that present a wealth of information and cover a great deal of the research conducted prior to their publication. Finally, three of the articles present important experimental results and two of the articles show theoretical developments. As would be expected for seminal works in a field of engineering, most of these articles are more than twenty years old, but very few of them are from the 1940s through 1960s (five articles are from these three decades), with the majority being from the 1970s and 1980s (thirteen total citations from these two decades). A great deal of compressible flow research was done during the period of the 1940s and 1950s, much of it of very high importance. The relatively low number of citations for works from these decades points to a possible lack of knowledge about the older work within the field by more modern researchers, as well as the tendency to cite more recent work. Finally, the number of citations for each article or book in Table 1 is relatively high, ranging from 361 to 83 (The number of citations which would be considered "high" in any field is determined by the amount of the literature available, the number of researchers in the field, and the funding available for research). The fact that there may be a great number of articles with significant numbers of citations (but less than 83) implies that a great number of very important and highly cited articles fall outside of the twenty presented here.

HIGH SPEED FLOW SEARCH IMPLEMENTATION

To identify the total candidate references for a Background section, a table similar in structure to Table 1, but containing all the references from the retrieved records, is constructed. A threshold frequency for selection can be determined by arbitrary inspection (e.g., a Background section consisting of 150 key references is arbitrarily selected in this case). The first author has found a dynamic selection process more useful. In this dynamic process, references are selected, analyzed, and grouped based on their order in the citation frequency table until the resulting Background is judged sufficiently complete by the Background developers.

To insure that the influential documents at the wings of the temporal distribution are included, the following total process is used. The reference frequency table is ordered by inverse frequency, as above, and a high value of the selection frequency threshold is selected initially. Then, the table is re-ordered chronologically. The early historical documents with ***citation frequencies substantially larger than those of their contemporaries*** are selected, as are the ***extremely recent documents with citation frequencies substantially larger than those of their contemporaries***. By contemporaries, it is meant documents published in the same time frame, not limited to the same year. Then, the dynamic selection process defined above is applied to the early historical references, the intermediate time references (those falling under the high frequency threshold), and the extremely recent references.

Table 2 contains the final references selected for the high speed flow Background survey using the approach described above. The second reference listed, Molenbroek's 1890 paper, had many more citations (7) than any paper published in the 1800s, up to Prandtl's paper in 1904. In turn, Prandtl's paper had more citations (22) than any paper published previously, or those published until Von Karman's paper in 1932. This is a graphic example of how we interpret that a paper has substantially more citations than its contemporaries.

Table 2. Chronological List of Seminal Documents Selected for Inclusion in Background

#CIT	FIRST AUTHOR	YEAR	SOURCE	VOL	PAGE
4	MACH[41]	1875	SITZUNGSBER AKAD WIS	72	44
7	MOLENBROEK[42]	1890	ARCH MATH PHYS	9	157
22	PRANDTL[43]	1904	PHYS Z	5	599
10	HADAMARD[44]	1923	LECTURES CAUCHY'S PROB*		
13	GOLDSTEIN[45]	1930	PROC CAMB PHILOS SOC	26	1
22	VON KARMAN[46]	1932	T ASME	54	303
39	TAYLOR[47]	1933	PROC ROY SOC LON A	139	278
23	LANDAU[48]	1936	PHYS Z SOWJETUNION	10	34
20	TSIEN[49]	1938	J AERONAUT SCI	5	480
60	LEES[50]	1946	NACA TN 1115		
30	LIEPMANN[51]	1946	J AERONAUT SCI	13	623
29	PUCKETT[52]	1946	J AERONAUT SCI	13	475
23	TSIEN[53]	1946	J MATH PHYS	25	247
39	ACKERET[54]	1947	NACA TM 1113		
32	HAYES[55]	1947	Q APPL MATH	5	105
127	COURANT[18]	1948	SUPERSONIC FLOW SHOCK		
38	KOVASZNAY[56]	1950	J AERONAUT SCI	17	565
36	PACK[57]	1950	Q J MECH APP MATH	3	173
67	WILKE[58]	1950	J CHEM PHYS	18	517
82	VAN DRIEST[59]	1951	J AERONAUT SCI	18	145
48	CROCCO[60]	1952	J AERONAUT SCI	19	649
68	LIGHTHILL[61]	1952	PROC ROY SOC LON A	211	564
53	KOVASZNAY[62]	1953	J AERONAUT SCI	20	657
69	LIGHTHILL[63]	1953	PROC ROY SOC LON A	217	478
69	POWELL[64]	1953	P PHYSICAL SOCIETY B	66	1039
82	SHAPIRO[65]	1953	DYNAMICS THERMODYNAM	1	
34	HIRSCHFELDER[66]	1954	MOL THEORY GASES LIQ		
37	LAX[67]	1954	COMMUNS PURE APPL MA	7	159
42	ECKERT[68]	1955	J AERONAUT SCI	22	585
56	ASHLEY[69]	1956	J AERONAUT SCI	23	1109
51	KORST[70]	1956	J APPL MECH	23	593

72	LEES[71]	1956	JET PROPULSION	26	259
39	CHAPMAN[72]	1957	NACA TN 3869		
80	LIEPMANN[73]	1957	ELEMENTS GASDYNAMICS		
51	LIGHTHILL[74]	1957	J FLUID MECH	2	1
73	CHAPMAN[75]	1958	NACA R 1356		
100	FAY[24]	1958	J AERONAUT SCI	25	73
78	GODUNOV[76]	1959	MAT SBORNIK	47	271
142	HAYES[16]	1959	HYPERSONIC FLOW THEO		
42	LAX[77]	1960	COMMUN PUR APPL MATH	13	217
46	CHENG[78]	1961	J AEROSPACE SCI	28	353
76	MILLIKAN[79]	1963	J CHEM PHYS	39	3209
46	LEES[80]	1964	AIAA J	2	1907
48	SPALDING[81]	1964	J FLUID MECH	18	117
50	STEWARTSON[82]	1964	THEORY LAMINAR BOUND		
53	VINCENTI[83]	1965	INTRO PHYSICAL GAS DYN.		
43	DOWELL[84]	1966	AIAA J	4	1267
92	MACCORMACK[25]	1969	AIAA PAPER 69-0354		
87	STEWARTSON[27]	1969	PROC R SOC LON SER-A	312	181
51	DAVIS[85]	1970	AIAA J	8	843
54	GREEN[86]	1970	PROGR AEROSPACE SCI	11	235
145	MURMAN[15]	1971	AIAA J	9	114
84	JONES[29]	1972	INT J HEAT MASS TRAN	15	301
110	BROWN[21]	1974	J FLUID MECH	64	775
69	CEBECI[87]	1974	ANAL TURBULENT BOUND		
69	JAMESON[88]	1974	COM PA MATH	27	283
49	LAUNDER[89]	1974	LETT HEAT MASS TRANS	1	131
56	WHITE[90]	1974	VISCOUS FLUID FLOW		
59	WHITHAM[91]	1974	LINEAR NONLINEAR WAV		
63	BEAM[92]	1976	J COMPUT PHYS	22	87
350	BALDWIN[12]	1978	AIAA Paper 78-0257		
118	BEAM[20]	1978	AIAA J	16	393
51	STEGER[17]	1978	AIAA J	16	679
43	SCHLICHTING[93]	1979	BOUNDARY LAYER THEORY		
103	VAN LEER[23]	1979	J COMPUT PHYS	32	101

62	PULLIAM[94]	1980	AIAA J	18	159
241	JAMESON[13]	1981	AIAA PAPER 81-1259		
361	ROE[11]	1981	J COMPUT PHYS	43	357
136	STEGER[17]	1981	J COMPUT PHYS	40	263
61	CHIEN[95]	1982	AIAA J	20	33
57	NI[96]	1982	AIAA J	20	1565
69	VAN LEER[97]	1982	LECTURE NOTES PHYS	170	507
84	BOGDANOFF[30]	1983	AIAA J	21	926
126	HARTEN[19]	1983	J COMPUT PHYS	49	357
54	ANDERSON[98]	1984	COMPUTATIONAL FLUID		
47	TAM[99]	1984	J FLUID MECH	138	273
41	TAM[100]	1984	J FLUID MECH	138	249
49	COLE[101]	1986	TRANSONIC AERODYNAMICS		
57	ROE[102]	1986	ANNU REV FLUID MECH	18	337
168	PAPAMOSCHOU[14]	1988	J FLUID MECH	197	453
63	WILCOX[103]	1988	AIAA J	26	1299
107	ANDERSON[22]	1989	HYPERSONIC HIGH TEMP		
58	PARK[104]	1990	NONEQUILIBRIUM HYPER		
52	GOEBEL[105]	1991	AIAA J	29	538
56	SARKAR[106]	1991	J FLUID MECH	227	473
71	LELE[107]	1992	J COMPUT PHYS	103	16
86	SPALART[28]	1992	AIAA PAPER 92-0439		
90	BIRD[26]	1994	MOL GAS DYNAMICS DIR		
61	MENTER[108]	1994	AIAA J	32	1598
51	TAM[109]	1995	ANNU REV FLUID MECH	27	17
47	CANIC[110]	2000	COMMUN PUR APPL MATH	53	484
30	CANIC[111]	2002	COMMUN PUR APPL MATH	55	71
42	CHEN[112]	2003	J AM MATH SOC	16	461
25	CHEN[113]	2004	COMMUN PUR APPL MATH	57	310
26	XIN[114]	2005	COMMUN PUR APPL MATH	58	999

These search results were examined by the authors; all papers in the table were judged to be relevant for a Background section, or review paper, on high speed flow. Other observations about the results of Table 2 include the distribution of articles by publication date. While there are relatively few articles from the 1930s (5) and 1940s (7), a large jump in the number of publications takes place in the 1950s (23), as would be expected (in contrast to the results of Table 1). To place these numbers in context, there were e.g. 272 articles in the database for the 1930s, of which five stood out as seminal based on their relative numbers of citations. The 1960s, however, saw a large decrease in publications (10), with a significant increase during the 1970s (16) and 1980s (17), largely due to numerical simulations being conducted at the time. There is also a fairly large number of first authors with two publications on the list, but only three authors have three citations where they are first authors: Lees, Lighthill, and Tam. There is also a distinct change in the types of articles, where articles from the 1950s are largely theoretical or experimental in nature, the articles from the 1970s and 1980s are largely computational.

The analysis and discussion above have focused on the contents of the Background; i.e., which documents should be included. In some cases, the Abstracts of the seminal or other critical references have been retrieved and clustered, to produce a structure for the Background. Thus, the CAB approach can be used to determine both the content and structure of the Background section. Again, CAB does not exclude content and structure determinations by the experts. CAB can be viewed as the starting point for content and structure determination, upon which the experts can build with their own insights and experience.

While the CAB approach is systematic, it is not automatic. Judgement is required to determine when an adequate number of references has been selected for the Background, and further judgement is required to analyze, group, and link the references to form a cohesive Background section. Additionally, the highly influential references that were not highly cited due to insufficient dissemination should be included by the Background developers, if they know of such documents. CAB is not meant to replace individual judgement or specification of Background material. Rather, CAB is meant to augment individual judgement and reference selection, as reflected in its name of Citation-Assisted. Therefore, CAB should be viewed as a starting point in the background literature selection process. For this review in particular, there are many pioneering niche area documents that required inclusion based on the authors' personal knowledge.

HIGH SPEED FLOW BACKGROUND RESULTS

A Background section documents the intellectual heritage of a discipline by identifying, and relating, the significant documents, people, and events that have had major influences on the development of the discipline. Some influences can be quantified; others are evaluated more subjectively. One of the metrics used as a proxy for influence is the number (and quality) of citations to particular documents and/ or events. This section identifies the key documents that have had significant influence on the development of high speed compressible flow. Most of these documents were identified as highly-cited from the documents in the retrieved database only. In future literature surveys for Background, or for stand-alone reviews, the authors strongly recommend that a systematic approach to defining seminal and other critical papers be used, such as the method presented here.

There have been three focal areas in high speed compressible flow, and they have been pursued in parallel since the dawn of high speed flight. They are all aimed at supporting the integrity of a body traveling at high speeds through a fluid mixture. One focal area is the aerothermodynamics of the flow field surrounding the body, including the computational schemes used to predict and understand the details and integral effects of the flow field. A second focal area includes the propulsion system required to accelerate the body to, maintain its speed at, and decelerate from, the high speeds, as well as the underlying combustion phenomena required. The third focal area is the overall vehicle design required to maintain the structural and dynamic integrity of the body, as well as minimize the negative impacts of the vehicle’s interaction with the environment. The background for each of these areas is summarized, with emphasis on the seminal papers and books in those areas. Typically, a seminal paper or book will be a highly cited document, at least relative to other documents with similar topical material.

AEROTHERMODYNAMICS

The modern starting point for the development of high speed compressible flow theories and concepts was the already existing field of low speed subsonic flow theory. Incompressible results had been extended to compressible flow cases using similarity concepts and the ability to solve the inviscid equations for subsonic and supersonic flows. The subsonic and supersonic theories, in turn, could be related to other flow regimes in certain cases. For example, hypersonic flow theories and concepts were initially based on the already developed field of supersonic flow. Researchers such as Busemann, Ackeret, von Kármán, Lees, and Jones had developed a multitude of closed form expressions and approximations for subsonic and supersonic flight, including methods for predicting the inviscid flowfield pressure and forces, as well as approximations for the viscous effects on a vehicle. Many of these theoretical developments had focused on the concept of flowfield similitude, which related the aerodynamics of a vehicle flying at a given Mach number to the aerodynamics of a different sized vehicle flying at some other Mach number. This allowed for using already available wind tunnel data to inform the design of other vehicles and concepts for use at higher speeds. Once the theoretical results had been established and verified, then computational simulations slowly became possible, which added another dimension to the high speed flow prediction capability (theoretical, experimental, and computational capabilities then existed).

Aerothermodynamics Research Origins

Historically, the first published works to be applied to high speed flow were Newton's writings on the fluid resistance of flat plates.[115] Newton's concept of momentum transfer did not work well for ship hulls (the state-of-the-art application of his time). Centuries later, in 1875, Mach performed his historical mechanical shock wave reflection and interaction experiments with soot covered glass plates.[41] The Mach triple points sharply erase the soot which results in a residual picture of funnel-shaped V-formations. The head-on collision of two shock waves is marked as a narrow line of piled-up soot. A decade later, this was followed by Molenbroek's important observation that the differential equations governing the steady two dimensional potential flow of a compressible fluid are non-linear, but become linear in the hodograph plane.[42] In 1904, Prandtl reasoned that relative motion between a fluid and a streamlined boundary could be analyzed in two parts: a thin layer at the boundary providing the viscous resistance to motion, and the fluid outside the boundary layer providing, in accordance with the principles of irrotational flow, the normal forces producing lift.[116] At the same time, Prandtl also described stationary waves in gas radiation.[43] Forty-five years later, Pack showed that, for small fluctuations of a uniform supersonic gas jet about the state in which it enters a medium with zero excess-pressure it is possible to express the 'wave-length' in terms of the mean velocity of the jet.[57] The mean velocity is that on the bounding stream-lines and not the velocity of efflux as assumed by Prandtl in an earlier investigation. With this correction, better agreement was obtained between theoretical and experimental values for the wave-length of cylindrical jets. Hadamard's early work on Cauchy's problem in linearized partial differential equations provided the mathematical foundations for much later work on supersonic flows past thin wings.[44] A decade later saw an important paper by Von Kármán and Moore on resistance of slender bodies moving with supersonic velocities,[46] and complete solutions to high speed flow past cones with attached shock waves.[47] This was followed by Tsien's paper on supersonic flow over an inclined body of revolution.[49] All of these theories were important in and of themselves, but also due to how they influenced other research that followed.

Early in World War II, Theodore von Kármán resurrected Newton's work and showed its applicability to hypersonic flow—this is the well known Newtonian flow theory that is still in use today.[117] The first paper to "knowingly" address hypersonic flow was titled, "Superaerodynamics," which described aerodynamics at very high speeds.[118] The article dealt primarily with the difficulties that would be encountered in the hypersonic flow regime and did not develop theories. It was perhaps von Kármán who first realized that hypersonic flow required new and unique theoretical developments,[117] and encouraged Tsien to extend transonic and supersonic similarity to hypersonic flow. Therefore, the first highly-cited work in the field is Tsien's exposition of the similarity laws of hypersonic flow.[53] In fact, it was in this paper where the term "hypersonic" was first coined. This seminal work, published at a time of expanding interest in high speed missiles, seemed to open the floodgates for other researchers, who followed with extensions and modifications to Tsien's work. Hayes' work on hypersonic similitude was based on the equivalence principle that a hypersonic flow is simulated by the unsteady motion of a gas in a space with the number of dimensions reduced by one.[55] The resulting simpler unsteady Euler equations admit an extended group of affine transformations. At about the same time, a classical paper on supersonic wave drag of thin airfoils was published.[52]

Similarity Laws

A great deal of research took place which was completely based on the concept of similarity. These approaches were valuable since they allowed for already existing results or experimental data to be used to find out what would happen in new flow regimes, such as hypersonic flow. Research such as Van Dyke's combined hypersonic-supersonic similarity rule[119] and Lees' hypersonic similarity law for an unyawed cone[120] allowed for the use of already existing supersonic flow theories for hypersonic flow by determining the limitations on applicability (both in Mach number and vehicle shape). For example, Lees' research showed that the tangent-wedge and tangent-cone supersonic theories could be applied to hypersonic flow under appropriate conditions, creating useful and accurate prediction methods which required modest time expenditures. In parallel, Hayes and Probstein made advances in similarity theory, culminating in their classic work on hypersonic flow theory,[16] which contained in part the Hayes similitude principle. Other important books on hypersonic flow theory include those by Anderson,[22] Park,[104] and Bertin.[121]

The 1960s saw more emphasis given to similarity laws in viscous regions, such as Dewey's use of local similarity concepts in hypersonic viscous interaction problems,[122] Kao's test of local similarity in hypersonic viscous flow near the stagnation line of a blunt body,[123] and Bush's strong interaction similarity solutions for flat plate flow.[124] While studies were published on similarity laws in the 1970s and 1980s, they appeared to have negligible impact from a citation perspective. In the early 1990s, when modeling extra-galactic radio sources, Falle showed that flow caused by a supersonic gas jet is self-similar under certain conditions,[125] but this case has marginally peripheral relation to the body of flowfield similarity studies referenced above. Thus, the hypersonic-supersonic similarity studies appeared to have peaked in terms of influence in the 1950s and 1960s, although many of those results are still in use today for practical applications.

Wave Motion and Propagation Theory

At the same time that the similarity studies were being pursued, parallel efforts focused on the theory of wave motions and propagation, as were newly possible computations to identify shock position and structure more accurately. The classic text of Courant and Friedrichs reflected the great deal of work on wave propagation that had taken place during World War II, and focused on a systematic theory of nonlinear wave propagation within the framework of compressible fluid dynamics.[18] Concurrently, Lin addressed the flow behind curved shocks,[126] an important concept for hypersonic flow. Soon after, Whitham addressed the flow pattern of a supersonic projectile.[127] Shapiro's classical work presented a comprehensive view of the flowfield physics, focusing on the dynamics and thermodynamics of compressible flow.[65] Liepmann and Roshko's book on gas dynamics included a wealth of information on theoretical developments in all high speed regimes,[73] Whitham's book on non-linear wave motion is frequently cited,[91] Schlichting's book on boundary layers includes chapters on compressibility effects,[93] and Cole and Cook's book on transonic aerodynamics covered many of the advances for theoretical descriptions of transonic flow.[101] More recent work by Canic et al. addressed free boundary problems and reflection of weak shocks; in particular, they developed a new use of inviscid perturbation techniques to demonstrate the stability of transonic shock waves.[110,111] Chen and Feldman also examined multidimensional transonic shocks and free boundary problems for nonlinear equations of mixed type.[112,113]

Numerical Methods

While it was very important to continue developing theoretical concepts applicable to high speed flow, the advent of the modern digital computer at the same time was certain to have an impact on high speed flow prediction. A major advance occurred in the computation of wave motions with Lax's paper on weak solutions of nonlinear hyperbolic equations.[67] This provided a method for first-order accurate computation of the shock structure and trajectory using what is now known as the "shock capturing" method. The Lax-Wendroff paper on conservation laws provided the basis for second-order accurate computational schemes,[77] as did MacCormack's explicit two-step method.[25] Godunov's paper represented a major step forward in the proper treatment of artificial viscosity to stabilize numerical oscillations in strong gradient regions.[76] Rusanov provided a third-order accurate scheme,[128] and Turkel et al. provided a fourth-order accurate scheme,[129] although second-order accurate schemes have dominated research over the past thirty years. Moretti presented another shock prediction approach called the "shock fitting" method, which led to a great deal of controversy about the theoretically appropriate way to numerically predict shock waves.[130,131]

The late 1970s saw the emergence of improved computers and powerful implicit schemes for more accurate and rapid solutions of the Navier-Stokes equations (such as those by Briley and McDonald[132] and Beam and Warming[20,92]), as well as implicit schemes for the Euler equations.[133] White's book on viscous fluid flow overviewed a number of these numerical techniques.[90] The important advances in numerical solutions of the gas dynamic equations may be broken into a number of categories, including methods for improving computational speed, methods aimed at providing upwind differencing, and methods for improved accuracy in shock regions.

Methods aimed at improving the computational speed of these schemes include an iterative solution to transonic flows over airfoils and wings,[88] an implicit finite-difference simulation of three-dimensional compressible flows by Pulliam and Steger,[94] Pulliam and Chausee's diagonalization procedure,[134] the implicit schemes of Yee,[135] and the implicit multigrid schemes of Jameson.[136] An explicit numerical scheme for solving the unsteady Euler flow equations to obtain steady solutions was constructed by combining the multigrid technique with a new second-order accurate finite volume integration method, which was developed by Ni in 1982.[96] Other important advances quickly followed, including Roe's highly-cited paper on approximate Riemann solvers, parameter vectors, and difference-schemes,[11] Roe's approximate Riemann solver for reduced running time,[102] and Jamesons' implicit lower-upper multigrid scheme.[137] A strong conservation form of the governing equations with primitive variables was used in these studies for accurate solutions over a wide range of Mach numbers, as shown by Vinokur[138] and

Chen et al.[139] Bell et al. wrote a paper in 1994 which presented a local adaptive mesh refinement algorithm for solving hyperbolic systems of conservation laws in three space dimensions, based on the use of local grid patches superimposed on a coarse grid to achieve sufficient resolution in the solution.[140]

A number of numerical methods have been developed over the years for providing upwind differencing, an essential feature for mixed hyperbolic/elliptic partial differential equation solutions. Most of these methods are formed on the early work of Murman and Cole,[15] who realized the importance of changing differencing schemes in the vicinity of shocks. However, the Cole-Murman approach may allow entropy violating expansion shocks as solutions, which led others to expand on their ideas. Engquist and Osher developed a scheme guaranteeing that these potentially non-physical shocks would not occur.[140a] Improvements have also been made by Steger and Warming's flux vector splitting approach for the Euler equations,[17] Van Leer's paper on flux vector splitting,[97] Osher and Solomon's study on upwind difference schemes for hyperbolic systems of conservation laws,[141] Mulder's implicit upwind scheme,[142] Anderson's comparison of finite volume flux vector splitting for the Euler equations,[143] the characteristics-based schemes for the Euler equation,[144] and Liou's advection upstream splitting method.[145]

Other important numerical improvements include Van Leer's second-order extension to Godunov's method,[23] the use of finite volume methods,[13] Harten's high resolution schemes for hyperbolic conservation laws,[19] the comprehensive book on foundations of finite difference schemes and numerical methods and principles of grid generation by Anderson et al,[98] Colella's piecewise parabolic method for gas dynamic simulations,[146] Thompson's study on time-dependent boundary conditions for hyperbolic systems,[147] Lele's compact finite difference schemes,[107] and Xin's establishment of the existence and uniqueness of a transonic shock for the steady flow through a general two-dimensional nozzle with variable sections.[114] These rapid advances in computational algorithms, coupled with the parallel development of computer processor speeds (doubling approximately every eighteen months), have led to major improvements in the computational prediction of high speed flows.

Shock Structure/Position

In addition to the basic high speed theory development and rapid advances in computational capabilities, there was a large body of work devoted to direct applications of high speed vehicles and design concepts. Belotserkovsky's 1957,[148] and Garabedian's 1958,[149] computations of detached bow shock waves in hypersonic flow were some of the first studies to provide accurate descriptions of shock structure and position in regions of mixed hyperbolic-elliptic flowfields, integrating the advancing numerical techniques with improved understanding of the flowfield physics. These studies were stimulated by the spacecraft and missile atmospheric re-entry problem, including work by Van Dyke on the supersonic blunt body problem,[150,151] the development of Modified Newtonian theory by Lees,[71] Vagliolaurin's theoretical studies on the flowfield about blunt-nosed bodies in supersonic flight,[152] Nonweiler's description of the aerodynamic problems of manned space vehicles,[153] Probstein's study of shock wave and flow field development in hypersonic re-entry,[154] and Traugott's research on high speed flows about blunted cones.[155] Time asymptotic methods to solve the flowfields included Bohachevsky's time dependent conservation variables-based papers on flows about blunt bodies with detached shock waves,[156,157] followed by Bohachevsky and Kostoff's computation of high Mach Number flowfields with radiation and oscillating cavity shocks.[158]

Subsequent shock structure/position computations included Davis' numerical solutions of hypersonic viscous shock-layer equations,[85] Woodward's numerical simulation of fluid flow with strong shocks,[159] Zoby and Simmonds' engineering methods for vehicles at high angles of attack,[160] viscous optimized waverider work by Bowcutt, et al,[161] jet interaction in hypersonic flow by Shang et al,[162] and Blottner's computational simulations of hypersonic flow over spherical nosetips.[163] Finally, a good assessment of numerical approaches for compressible flow prediction was written by Shang.[164] These theoretical and computational applications were essential to the development of launch and re-entry vehicles, and showed the importance of the foundational work that had gone on in the 1940s and 1950s.

Laminar Boundary Layers

Two central motivations driving these flow field computations were the need to predict surface forces for vehicle control purposes and the need to alleviate surface heating at high speeds. Much of the focus on surface heating was on the physiochemical and thermodynamic processes occurring in the boundary and shear layers, and simultaneous efforts were applied to modeling laminar and turbulent boundary layers, and the conditions for the transition from laminar to turbulent flow. Without understanding these viscous-dominated flow phenomena, practical vehicle design would not be possible. A very early study on low-speed flow boundary layers was Goldstein's paper on solutions of the boundary layer equations in hydrodynamics.[45] Some of the earlier post-war high speed laminar boundary layer studies included Lees' study on stability of laminar boundary layer in a compressible fluid,[50] the study by Cope et al. on compressible laminar boundary layers,[165] Chapman and Rubesin's classical study on compressible laminar boundary layers with arbitrary surface temperature distributions,[166] Lighthill's classic on heat transfer through a laminar boundary layer,[167] as well as his paper on the reflection of a weak disturbance from a laminar boundary layer,[168] Emmons' important study on laminar-turbulent transition,[169] Moore's study including laminar boundary layer dissociation,[170] VanDriest's study on boundary layer stability,[171] and Lighthill's discussion of the two independent mechanisms by which boundary layers transmit the influence of disturbances upstream.[172]

Because of the complexity of the governing differential equations, integral or moment methods were predominant in attacking the viscous layer at this time, especially the Karman-Pohlhausen momentum integral method.[173] However, this approach suffers from the defect that the velocity profile is uniquely determined by a single pressure gradient parameter. In an attempt to eliminate the shortcomings of the Karman-Pohlhausen method Crocco and Lees introduced a semi-emperical "mixing theory", in which the velocity profile was specified in terms of a single shape parameter not directly related to the local static pressure gradient.[60] Soon after, Eckert used engineering relations for friction and heat transfer to surfaces in high velocity flow, assuming constant property fluids at an appropriate reference temperature.[68] A decade later came Stewartson's seminal volume on the theory of laminar boundary layers in compressible fluids.[82] Decades later, Drela and Giles used simultaneous algorithms (simultaneously solving the external and viscous regions) for two- and three-dimensional transonic flows around airfoils and wing.[174]

Compressible Boundary Layers and Heating

An early study by Ackeret et al. investigated compression shocks and boundary layers in high speed gases.[54] In the mid-1950s, added attention was focused on compressed boundary layers. These included Dunn's study on compressible boundary layer stability[175] and Probstein's study on compressible boundary layer curvature.[176] Additionally, heating, especially stagnation region heating, became a focal point. Research included Fay and Riddell's important article on heating in the stagnation point region,[24] Allen and Eggers' study of heating during atmospheric re-entry,[177] Cheng's article on hypersonic stagnation region flow,[78] Patankar's book on numerical heat transfer prediction,[178] and the development by Zoby et al., of convective heating equations for hypersonic flow.[179] Increased emphasis on boundary layer separation and re-attachment led to the Lees and Reshotko paper on compressible boundary layer stability[180] followed by Lees' paper on supersonic separated and re-attaching laminar flows ,[80] Schlichting's classic treatise on boundary layer theory,[93] and Stewartson's seminal effort on self-induced separation.[27]

Laminar/Turbulent Transition

While heating was an essential property for understanding high speed flight, the heating predictions can be in error by an order of magnitude without knowing when and where transition takes place. This led to a great deal of work on analytic methods that could predict transition. Papers that focused on transition in compressible boundary layers included Lees' early study of laminar boundary layer stability in a compressible fluid,[181] Low's study of boundary layer transition at supersonic speeds,[182] Chapman's work on separated flows in supersonic and subsonic streams with emphasis on the effect of transition,[72,75] Dhawan's study of boundary layer transition,[183] Laufer's insulated flat plate study,[184] Pate's studies of radiated noise effects on boundary layer transition,[185] Kendall's wind-tunnel experiments on transition,[186] Mack's study of linear stability of supersonic boundary layer transition,[187] Reshotko's review of boundary layer stability and transition,[188] the article by Beckwith and Miller on transition in high-speed wind tunnel testing,[189] and the article by Blackaby et al., on hypersonic stability theory.[190]

Schneider has updated much of the earlier work and collated flight test data results on transition, showing that a great deal of work still needs to be done in this area in order to obtain quality experimental data.[191,192,193] A good review of the field of high speed transition has also recently been written by Federov.[194]

Turbulent Boundary Layers

Turbulent boundary layers were also vitally important to understand in high speed flight, especially since most high speed flight includes laminar, transitional, and turbulent flow in varying measures. In analyzing turbulence measurements in supersonic flow performed prior to 1950, Kovasznay showed that there were three major problems to be solved before credible turbulence measurements could be obtained in supersonic flow: extend the response of the hot-wire probe and its associated equipment to much higher frequencies; determine whether King’s law for the heat loss from a wire, applicable to incompressible flow, may be applied to compressible flow computations; interpret the measurements obtained in a compressible flow, where there are three parameters of the flow instead of the velocity alone, as in the low speed case. Kovasznay addressed the determination of the laws of heat loss from wires and wire sensitivity in supersonic flow in his 1950 paper.[56]

Turbulent compressible boundary layer and shear layer studies included Wilson’s supersonic study,[195] Van Driest’s classic study on turbulent boundary layers in compressible fluids,[59] Dorrance’s mass transfer study,[196] and Bogdonoff’s study on turbulent boundary layer separation.[197] In a comprehensive study on turbulence in supersonic flow, Kovasznay showed that each of the freestream turbulence modes (acoustic, vorticity, entropy, chemical) is capable, upon shock interaction, of generating all four modes behind the shock.[62] Fifty years ago, Korst proposed a criterion that the total pressure on the reattaching streamline which is embedded in the shear layer must be equal to the downstream pressure to ensure that the streamlines have sufficient energy to reach the downstream pressure without flow reversal.[70]

Later studies on turbulent boundary layers include Kistler’s study on supersonic turbulent boundary layer fluctuations,[198] Spalding and Chi’s practical study on compressible turbulent boundary layer drag estimation,[81] Jones and Launder’s prediction of laminarization with a two-equation turbulence model,[29] Waltrup and Schetz's study of turbulent boundary layers subject to adverse pressure gradients,[199] Brown and Roshko's study of structures in turbulent mixing layers,[21] Cebeci and Smith's classic book on turbulent boundary layer analysis,[87] Launder and Spalding's study on numerically computing turbulent flows,[89] Baldwin and Lomax's classical study on the thin-layer approximation and an algebraic turbulence model for turbulent separated flows.[12] Other important papers include Chien's predictions of boundary layer flows with low Reynolds Number turbulence models,[95] Bogdanoff's examination of compressibility effects in turbulent shear layers,[30] Chinzei's studies on spreading of two-stream supersonic turbulent mixing layers,[200] Papamoschou's experimental study on compressible turbulent shear layers,[14] Wilcox's assessment of the scale determining equation for advanced turbulence models,[103] Ragab's studies of linear instabilities in compressible mixing layers,[201] Tam's examination of the modes of instability waves in high speed jets[202] and in supersonic mixing layers,[203] Samimy's study on compressibility effects on free shear layers,[204] Zeman's dilatation dissipation concept,[205] and Elliott's study of compressibility effects in free shear layers.[206] These studies were quickly followed by Sandham's investigation of the effect of Mach number on the evolution of instabilities in the compressible mixing layer,[207] Goebel's experimental study of compressible turbulent mixing layers,[105] and Sarkar's modeling of dilatational terms in compressible turbulence.[106] In 1992, new subgrid-scale models for the large-eddy simulation of compressible turbulent flows were developed and tested based on the Favre-filtered equations of motion for an ideal gas.[208] This was followed by further turbulence modeling studies, including the Spalart and Allmaras one-equation turbulence model for aerodynamic flows,[28] Clemens' study on multi-dimensional effects in turbulent mixing layers[209] and later studies on large scale structure and entrainment in supersonic mixing layers,[210] Lele's analysis on the compressibility effects of turbulence,[211] the article by Dutton et al. on separated base flows,[212] and Menter's paper on two-equation eddy-viscosity turbulence models for engineering applications.[108] Without these developments, especially the research that led to practical engineering methods for estimating skin friction and heat transfer, modern high speed vehicle design would not have been possible.

Shock Interactions

Since one of the most serious problems facing designers of high-speed vehicles is the occurrence of shock/boundary layer interactions or shock/shock interactions, there are numerous important papers in this field. As Bertin and Cummings noted, "The designers of vehicles that are to fly at hypersonic speeds have long recognized that the locally severe heating rates produced by viscous interactions and by shock/shock interactions can cause catastrophic failures . . . One of the first in-flight confirmations of the severity of shock-impingement heating occurred in October 1967, when the X-15A-2 suffered severe damage to its ventral fin (pylon) during a high altitude flight at Mach 6.7."[213] Unfortunately, the demise of the Space Shuttle Columbia brings the importance of these concepts into very clear focus.

Papers that integrate laminar/turbulent boundary layer studies and shock motion studies to examine shock-wave boundary layer effects include Liepmann's historic paper on transonic shock-wave boundary layer interactions,[51] Fage's early flat surface studies,[214] Bardsley's early study on the interaction between an oblique shock wave and a turbulent boundary layer,[215] Barry's early study on flat plate boundary layer shock wave interaction,[216] Mark's study on shock-wave reflection from a shock tube boundary layer,[217] Kistler's study of fluctuating wall pressure under separated supersonic flow,[218] McCabe's three dimensional analysis of shock wave interaction with a turbulent boundary layer,[219] Edney's important description of the various types of shock/shock interactions,[220] Green's comprehensive analysis of the interaction between shock waves and turbulent boundary layers,[86] Korkegi's survey of high Mach number viscous interactions,[221] and Settles' study of attached and separated compression corner flowfields in supersonic flow.[222] Adamson's review of two-dimensional shock-boundary layer interactions[223] emphasized that when interaction occurs between the shock wave and the boundary layer, the velocity profile in the boundary layer is thereby altered, as is the wave pattern in the external flow. The changes can be local if the shock wave is very weak but are observed on a larger scale if the shock is strong enough to cause separation. The interaction can occur in the presence of an incident oblique or normal shock wave or can be caused by an irregularity in wall shape, such as a corner or a step.

Following studies included Delery's experimental investigation of turbulence properties in shock-boundary layer interactions,[224] Dolling's study on unsteadiness of separated shock wave structure,[225] Cheng's review of hypersonic viscous flow research,[226] Speziale's review of turbulence modeling for RANS and VLES,[227] Andreopoulos' review of shock/boundary layer interation,[228] and Dolling's review of shock wave boundary layer research.[229] Many future problems on high speed vehicles will most likely be directly linked to unknown shock/boundary-layer or shock/shock interactions, so the importance of conducting research in this field will continue well into the future.

Chemically Reacting Flows

While most of the preceding research was conducted for supersonic or hypersonic flows, few of the articles dealt with chemically reacting or rarefied flows. Chemically reacting flows take place when the flowfield temperature reaches a level that causes the constitutive parts of the atmosphere to start reacting and changing their basic molecular state. For example, as the temperature reaches 2000K O_2 begins to dissociate, at 4000K O_2 dissociation is complete and N_2 dissociation begins, and at 9000K N_2 dissociation is complete and O and N begin to ionize.[22] Taking these chemical reactions into account is essential to fully analyzing the viscous and heating affects of the flow.

An important reference for articles that involved real-gas effects on high speed flow and/or kinetic theory approaches was the classic text by Hirschfelder, Curtiss, and Bird.[66] A 1957 study by Lighthill addressed equilibrium flow dynamics of dissociating gases.[74] Important articles in the field of chemically reacting flows include Wilke's article on viscosity in gas mixtures,[58] Schwartz's two articles on vibrational relaxation in gases,[230,231] Treanor and Marrone's article on dissociation,[232] Marrone and Treanor's article on chemical relaxtation,[233] the oft-cited article by Millikan and White on molecular vibrational relaxation,[79] Keck and Carrier's article on diffusion theory of non-equilibrium dissociation,[234] the review article on molecular gas dynamics,[235] and Bird's book on molecular gas dynamics.[236] Other articles include the description by Maus et al. of real gas effects on the Space Shuttle,[237] a review article on the numerical solution of the Boltzmann equation,[238] Stalker's review article on chemical nonequilibrium in hypervelocity aerodynamics,[239] the book by Park on non-equilibrium hypersonic flow,[104] Tirsky's review article on gas dynamic models for real gas hypersonic flows,[240] Bird's book on the direct simulation of gas flows,[26] and a review article by Cheng and Emanuel on non-equilibrium flow.[241] As numerical simulations of real-gas flow become more and more sophisticated, and as the models for real-gas effects also improve, the inclusion of real-gas effects in certain simulations will become essential for obtaining realistic results.

Jet Noise

While jet noise only represents a small percentage of the literature in high speed compressible flow, it is very important for a variety of reasons, especially related to aircraft noise pollution. A number of the most important article on jet noise include the examination of acoustic noise from supersonic gas jets in Powell's early studies on two dimensional jet noise,[64] Troutt's experiments on the acoustic properties of a supersonic jet,[242] Norum's study on screech suppression in supersonic jets,[243] Tam's papers on sound generated by instability waves in supersonic flow,[99,100] Tam's paper on screech tones of non-axisymmetric jets,[244] and Tam's review of supersonic jet noise.[109] As the production of "green aircraft" becomes more important in the future, it will be interesting to see new and important research in this field.

Rarefied Gas Dynamics

Rarefied gas dynamics is important for re-entry aerodynamics, satellite lifetime predictions, and momentum control in post-atmospheric flight. While research into rarefied gas dynamics is not as common as continuum flow research, there are still important works in the field. These include the book by Kennard,[245] Vincenti and Krueger's book on rarefied gas dynamics,[83] Kogan's book on rarefied gas dynamics,[246] and Sherman's review article on rarefied gas dynamics.[247] Computations for rarefied gas dynamics have also been completed by Zhong et al,[248] although difficulties exist in correctly stating boundary conditions.[226] A good review article on the computational difficulties in rarefied flows was written by Ivanov and Gimelshein.[249] Finally, a statistically based approach for predicting rarefied flows, the Direct Simulation Monte Carlo method, was initially proposed by Bird,[26] and is a relatively fast way to numerically simulate these flows, as shown by Boyd.[250] It is safe to say, however, that a great deal is left to be learned about predicting and understanding rarefied gas dynamics.

PROPULSION/COMBUSTION

While manned hypersonic flight has been achievable since the 1960s, and rocket-powered launch vehicles achieved hypersonic speeds even earlier than that, the desire to design workable air-breathing high speed engines continues to be at the forefront of hypersonic technology development. Although turbojets provide good performance up to M ~ 3, and ramjets can operate from M ~ 2 to M ~ 6, propulsion systems that can operate at higher Mach numbers (such as scramjets) have only recently had limited success during experimental testing. Even if scramjets become usable, the problem of requiring multiple propulsion systems on the same vehicle (one for takeoff and another for cruise) severely limits the design and usability of such systems. Curran, et al, noted that, “Obviously it is desirable to extend the performance of a scramjet over the widest possible range of Mach numbers to reduce the complexity of the lower-speed propulsion system.”[251] In addition to the aerodynamic and materials issues related to high-speed propulsion systems, supersonic combustion is also extremely challenging. The recent combustion challenges of the X-51 flight test vehicle have often been compared to lighting a match in a hurricane and keeping it burning, which is due to the high speeds of the flow through the engine coupled with ability to extract energy in such a short period of time. To this end, a fairly significant amount of research has been conducted into high speed combustion and propulsion systems.

High speed combustion started to become of increasing interest in the late 1950s, although non-seminal studies of scramjets appeared in the literature in about the mid-1950s. Gross performed a comprehensive study of supersonic combustion,[252] followed by Libby’s seminal study on turbulent mixing of reactive gases,[253] and Lehr’s examination of shock-induced combustion.[254] A great deal of the early research work centered on the mixing of fuel and air in order to perform efficient combustion, beginning with Schetz and Billig's work on gaseous jets injected into a supersonic flow,[255] the work of Schetz et al., on under-expanded transverse jets,[256] Ferri’s writing of a comprehensive review of mixing-controlled supersonic combustion,[257] which was followed by Brown and Roshko's examination of large structures in turbulent mixing layers,[21] Evans work on the influence of chemical kinetics and unmixedness on burning in supersonic hydrogen flames,[258] and the use of a plasma jet for flame stabilization to promote supersonic combustion.[259] Other studies include the examination of combustion-related shear flow dynamics in supersonic jets by Schadow et al.,[260] Tillman's work on the mixing of supersonic jets,[261] Darabiha's examination of the extinction and ignition limits of strained hydrogen air diffusion flames[262] as well as transient behavior,[263] a study by Lee, et al, on a transverse jet in a supersonic crossflow.[264] Billig reviewed the research on supersonic combustion in 1993,[265] Yang examined shock-induced mixing for supersonic combustion,[266] Linan and Williams book on combustion,[267] Baurle's work on supersonic turbulent combustion,[268] Gruber's work on mixing in supersonic jets,[269] and the review of Gutmark et al on mixing enhancement in supersonic free shear flows.[270]

Work that has concentrated on the development of high-speed propulsion systems include the predictions by Waltrup and Billig of pre-combustion wall pressure distributions in scramjets,[271] Linan's article on combustion technology,[272] a valuable collection of articles on the aerodynamics of base combustion,[273] procedures for designing optimized scramjets,[274] the work of Billig, et al, on dual-combustion ramjets,[274] the flow in supersonic nozzle throats,[275] a study of swirling supersonic nozzle flow,[276] a research overview for liquid-fueled ramjets,[277] McDaniel and Grave's study of injection in non-reacting supersonic combustors,[278] and Hertzberg's ram accelerator for projectile acceleration.[279] These studies were followed by an investigation of shock/boundary-layer interactions in ducts in 1990 by Carroll and Dutton,[280] a study of standing oblique detonation waves by Pratt et al,[281] Murthy and Curran's books on high-speed propulsion systems,[282,283] the work on parallel injectors by Northam et al,[284] a study on the effects of injector geometry on scramjet combustor performance,[285] work on injection and mixing techniques for scramjet combustors,[286] and the work of Hartfield, et al, on ramp injectors.[287] Heiser, Pratt, and Daly's book on hypersonic airbreathing propulsion contains a good overview of many propulsion concepts,[288] which was followed by the study of injection strategies for ramjets by Riggins, et al,[289] a study of kerosene fuel combustion in supersonic flow,[290] Billig's work on supersonic combustion ramjets,[291] the study of scramjet combustors by Masuya et al,[292] scramjet engine design for spaceplanes,[293] the work of Mitani, et al, on scramjet performance,[294] and Gutmark' and Grinstein's work on flow control with noncircular jets.[295] Obviously, continued research into ramjets and scramjets (and newer technologies) will continue to pace the development of high speed vehicles in the future.

VEHICLE DESIGN

If vehicles are to fly at high speeds, a large number of difficult design challenges must be examined and solved. To make matters more difficult, these challenges must be met in such a way as to allow the molding of a comprehensive vehicle system. Townend noted that there are three types of hypersonic vehicles that are typically envisioned: reusable aerospace planes (to replace expendable launch vehicles), hypersonic airliners, and orbital transfer vehicles.[296] These vehicle types all require similar effort in design, as noted by Blankson; "The technical problems are multi-disciplinary to first order. Proper resolution of these problems requires the ability to integrate highly-coupled and interacting elements in a fundamental and optimal fashion to achieve the desired system performance."[297] Clearly, high speed vehicle design calls for state-of-the-art technology and cutting-edge multidisciplinary design methods. Among the difficult design challenges facing the development of hypersonic vehicles (in addition to those already mentioned in the previous sections) are: fuels, structures, materials, noise, propellant tanks, and thermal protection systems.[213] In addition to the design challenges listed, a great deal of design method enhancement needs to take place, often without significant ways to validate results prior to flight testing.

A great deal of work has been done over the years on vehicle design for re-entry, and more recently for powered hypersonic flight. Re-entry vehicles were first designed in the 1940s and 1950s, and a great deal of the ground-breaking work for these vehicles was done at that time. A variety of technical difficulties face those who design re-entry vehicles, including high heating rates and large decelerations, both of which lead to challenges for aerodynamics, structures, materials, and thermal protection systems. Allen and Eggers noted that convective heat transfer problems could be alleviated for low ballistic coefficient vehicles (the ballistic coefficient is essentially the ratio of the vehicle weight to its drag) with high pressure drag shapes,[177] which is evident in the early manned re-entry systems such as Mercury, Gemini, and Apollo. They also stated that high ballistic coefficient vehicles (such as ballistic missiles) required minimizing viscous forces on the vehicle and the use of small cone angle configurations. Continuing advances in aerothermodynamic design have been made by a variety of researchers, including Eggers' work on hypersonic vehicles,[298] aerodynamic heating for missile configurations,[299] the hypersonic environment for Hermes,[300] the aerothermodynamics of transatmospheric vehicle,[301,302] advances in hypersonic design in Germany,[303-305] and concepts for advanced manned launch systems.[306] More details on the challenges facing hypersonic vehicles can be found in the review article by Bertin and Cummings.[307]

One of the most interesting high-speed design concepts is the "waverider" vehicle, a concept first put forward by Nonweiler.[308,309] Waveriders take advantage of the known shape of shock waves to create three dimensional configurations that utilize the high pressures created behind shocks to produce lift on the vehicle. Others who have become proponents of the waverider concept include Küchemann[310] and Anderson et al., who sponsored a symposium on waveriders in 1990.[311] A good review of waverider configurations was performed by Eggers et al.[312] Another important contribution is the development of the "viscous optimized" waverider, which has been shown to change the vehicle configuration when viscous effects are included in the waverider theory. Work by Bowcutt et al[161] and Corda and Anderson[313] have been important to the development of these more advanced waveriders.

Another common vehicle concept has been the National Aerospace Plane (NASP) and various follow-on vehicles, which has led to a great deal of research and technology development for hypersonic flight. Works by researchers in the U.S. and abroad, including concepts by Williams,[314] Burns,[315] Lozino-Lozinsky and Neiland,[316] and Koelle[304] have done a great deal to re-energize the spaceplane concept. Newer concepts and programs are described in Cummings and Bertin.[317]

FLUTTER

The prediction of aeroelastic phenomenon such as flutter forms a critical capability for high speed vehicles. The occurance of flutter on a high-speed aircraft can be catastrophic, but being able to predict the flutter envelope is quite challenging. Various theories and concepts have been used over the years, including piston theory, which was introduced into aeroelasticity in the linearized form by Ashley and Zartarian in 1956.[69] This theory furnishes an approximation for the aerodynamic pressure acting on a slightly deformed flat plate in a supersonic airstream. A decade later, more focused studies on aerodynamic flutter began to accelerate. These studies on structure flutter in high speed flow include Dowell's examination of nonlinear oscillations of a fluttering plate,[84] Durvasula's work on skewed panels in supersonic flow,[318] Dowell's panel flutter review of aeroelastic stability of plates and shells,[319] the work of Yates and Bennett on suppression of flutter at supersonic and hypersonic speeds,[320] the use of potential flow methods for flutter prediction,[321,322] supersonic finite-element analysis of flutter,[323] and Dowell's continuing work on non-linear aeroelasticity.[324] Work on flutter continued through the 1980s and 1990s with Oyibo's application of panel methods to flutter analysis,[325] the use of CFD to perform flutter analysis by Cunningham et al,[326] Guruswamy's numerical approach to coupling fluid/structural flow prediction,[327,328] Birman and Librescu's work on the flutter of laminate composites,[329] the use of finite-element methods to predict flutter at hypersonic speeds,[330,331] work on fluid-structure interaction for maneuvering aircraft,[332] supersonic flutter with thermal effects,[333] use of geometric conservation laws for flow problems with moving boundaries and deformable meshes, and their impact on aeroelastic computations,[334] and Morton's approach to coupled numerical prediction of flutter.[335]

NOISE

Noise studies have been of concern even before the start of the jet age, as evidenced by Landau and Teller's landmark paper[48] and Lighthill's article on aerodynamic sound generation.[61] While sound radiation papers started to appear in the literature in the late 1950s, such as the paper by Hammerling et al, on radiation from shock waves[336] and the paper by Phillips (driven by relevance to questions of structural fatigue and human discomfort in high-speed aerodynamics) on the generation of sound by supersonic turbulent shear layers,[337] the first paper of major importance appears to be Pierce's examination of spikes on sonic boom pressure waveforms.[338] It was followed by

Sears' paper on aerodynamic noise and sonic boom,[339] Crow's work on the effects of atmospheric turbulence on sonic booms,[340] Hayes' comprehensive evaluation of sonic boom phenomena,[341] Pierce's study on the effects of atmospheric irregularities on sonic boom propagation,[342] and Plotkin's work on the effect of boundary layers on shock oscillations.[343] In about the mid 1970s, a great deal of computational work on sonic boom noise prediction began, including Tannehill and Mugge's improved definition of thermodynamic properties,[344] the calculation of viscous flows for blunt bodies,[345] the application of shape optimization to flow calculations by Aly et al,[346] and Marconi's work on tailoring heating to sonic boom reduction.[347] A paper on the active control of sonic booms was written by Crow and Bergmeier[348] and Plotkin reviewed the state of the art for modeling sonic booms in 2002.[349] It should be clear from this summary that hypersonic vehicle design has progressed a long way in the past few decades, and that computational capabilities have made it possible to continue progressing for many decades to come.

CONCLUSIONS

High speed compressible flow literature has been evaluated using Citation-Assisted Background, including works as far back as an article by Mach in 1875. Relevance of the cited works was determined by finding the number of citations by other works in the field, and a detailed list of highly cited reference works was found. These works were placed into a broader context by discussing them relative to other important works in compressible flow research, including aerothermodynamics publications, as well as publications in propulsion and design.

Some limitations of the CAB approach as applied to this review are in order, and they are listed in detail in the appendix. One key limitation that deserves emphasis revolves around the limited choice of databases used for any study. There are many databases that contain important concepts in high speed compressible flow, such as the SCI for basic/applied research, the Engineering Compendex for technology development/engineering research, patent database, non-SCI journals, magazine articles, books, contractor reports/DTIC database, repots written in other countries, and the classified literature. Because of the citation capability of the SCI, only the SCI database was selected. In theory, documents from any of the above categories could have shown up in the SCI references, and been included in the final CAB selection. In practice, because of limited universal availability of many of these sources, the only non-journal documents to have appeared tended to be books, NASA TRs, and AIAA conference papers. In particular, many European reports, especially from Russia/Soviet Union and Germany, did not appear.

Additionally, the SCI is mainly a basic and applied research database. The highly-cited references will tend to be among the the most fundamental in the discipline. For vehicles that operate at high speeds, many of the critical advances came from engineering improvements. Other types of databases would be required to identify these more engineering-oriented critical items, such as the patent database. There are other engineering article databases available, such as the Engineering Compendex, but they do not have the readily available citation structure of the SCI.

Finally, it should be emphasized that the CAB approach operates best when used to complement standard text searching by a topical expert(s). This combination exploits the strengths of each while eliminating the weaknesses. As the AWS example in the Background section showed clearly, both the retrieval upon which the CAB approach is based and the expert approach conducted independently overlooked important background material. Had the expert used CAB-based retrieval in conjunction with his standard approach, both the relevant data contained in the contractor report data base and in the SCI database would have been extracted for maximum synergy. A review of the broader high speed compressible flow literature would show even greater benefit from the synergy of CAB and expert-based retrieval, where the seminal studies that shaped the literature are of highest interest.

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APPENDIX

Implementation of the Citation-Assisted Background concept requires the following steps:

- The research area of interest must be defined clearly
- The documents that define the area of interest must be identified and retrieved
- The references most frequently used in these documents must be identified and selected
- These critical references must be analyzed, and integrated in a cohesive narrative manner to form a comprehensive Background section or separate literature survey

These required steps are achieved in the following manner:

1. The research topic of interest is defined clearly by the researchers who are documenting their study results. For example, consider the topic of high speed compressible flow (HSC). In the present text mining study of high speed flow, the topical area was defined as gas dynamic flows in the transonic range ($0.8 < M < 1.3$), fully developed supersonic range ($1.3 < M < 5.0$), and hypersonic range ($M > 5.0$).

2. The topical definition is sharpened further by the development of a literature retrieval query. In the present text mining study above, the literature retrieval query, developed using an iterative relevance feeedback approach, was:

   Topic=((Hypersonic* OR Supersonic* OR Transonic* OR Shock-Induced-Combustion OR Shock-Layer OR (Shock* SAME Boundary-Layer*) OR (Reentry SAME Vehicle*) OR Scramjet* OR Shock-Tunnel* OR Reentry-Trajectory OR Shock-Induced-Separation OR Entropy-Layer* OR (Ablation SAME Heat-Shield*) OR Aerodynamic-Heating)) AND Document Type=(Article OR Review) Refined by: Subject Areas=(ENGINEERING, AEROSPACE OR MECHANICS OR PHYSICS, FLUIDS & PLASMAS OR ENGINEERING, MECHANICAL OR MATHEMATICS, APPLIED OR THERMODYNAMICS OR ENGINEERING, MULTIDISCIPLINARY OR COMPUTER SCIENCE, INTERDISCIPLINARY APPLICATIONS OR PHYSICS, MATHEMATICAL OR MATHEMATICS, INTERDISCIPLINARY APPLICATIONS OR ENERGY & FUELS OR MATHEMATICS) AND [excluding] Source Titles=(PHYSICS OF PLASMAS OR PHYSICAL REVIEW E OR IEEE TRANSACTIONS ON PLASMA SCIENCE OR JOURNAL OF PLASMA PHYSICS OR PLASMA SOURCES SCIENCE & TECHNOLOGY OR JOURNAL OF THE MECHANICS AND PHYSICS OF SOLIDS OR PLASMA CHEMISTRY AND PLASMA PROCESSING OR PLASMA PHYSICS AND CONTROLLED FUSION OR CONTRIBUTIONS TO PLASMA PHYSICS OR NUCLEAR FUSION OR PLASMA PHYSICS REPORTS OR PLASMA SCIENCE & TECHNOLOGY OR PHYSICS OF FLUIDS B-PLASMA PHYSICS OR COSMIC RESEARCH)

3. The query is entered into a database search engine, and documents relevant to the topic are retrieved. In the current high speed flow text mining study, 10556 documents were retrieved from the Web version of the Science Citation Index (SCI) in the time period from 1900 until early 2010. The SCI was used because it is the only major research database to contain references in a readily extractable format.

4. These documents are combined to create a separate database, and all the references contained in these documents are extracted. Identical references are combined, the number of occurrences of each reference is tabulated, and a table of references and their occurrence frequencies is constructed.

Important caveats about the overall approach include:

1. Listing and selection of the most highly cited references are dependent on the comprehensiveness and balance of the total records retrieved. Any imbalances (from skewed databases or incorrect queries) can influence the weightings of particular references, and result in some references exceeding the selection threshold where not warranted, and others falling below the threshold where not warranted.
2. The query used for record retrieval should be extensive (as discussed by Khan and Khor,[31] Harter and Hert,[32] and Kantor[33]). The query needs to be checked for precision and recall, which becomes complicated when assumptions of binary relevance and binary retrieval are relaxed.[34] There are myriad issues to be considered when evaluating queries and their impact on precision and recall. For example, a systems analytic approach to analyzing the information retrieval process concluded that, for completeness, the interaction of the environment and the information retrieval system must be considered in query development.[35] The first author's experiences with the studies done so far with CAB (on diverse topics such as nonlinear dynamics,[36] nanotechnology,[37,38] anthrax,[39] and SARS[40]) have shown that modest query changes may substitute some papers at the citation selection threshold, but the truly seminal papers have citations of such magnitude that they are invulnerable to modest query changes. For this reason, the cutoff threshold for citations has been, and should be, set slightly lower, to compensate for query uncertainties.
3. There may be situations where at least minimal citation representation is desired from each of the major technical thrust areas in the documents retrieved. In this case, the retrieved documents could be clustered into the major technical thrust areas, and the CAB process could be performed additionally on the documents for each cluster. The additional references identified with the cluster-level CAB process, albeit with lower citations than from the aggregated non-clustered CAB process, would then be added to the list obtained with the aggregated CAB process. The first author has not found this cluster-level CAB process necessary for any of the disciplines studied with CAB so far.
4. There may be errors in citation counts due to referencing errors, and the subsequent fragmenting of a reference's occurrence frequency metric into smaller

metric values. Care needs to be taken in insuring that a given reference is not fissioned into multiple large fragments that are not subsequently combined.

5. The CAB approach is most accurate for recent references, and its accuracy drops as the references recede into the distant past. This results from the tendency of authors to reference more recent documents and, given the restricted real estate in journals, not reference the original documents. To get better representation, and more accurate citation numbers, for early historical documents, the more recent references need to be retrieved, collected into a database, and have their references analyzed in a similar manner (essentially examining generations of citations).
6. High citation frequencies are not unique to seminal and other critical documents only; different types of references can have high citation frequencies. Documents that contain critical research advances, and were readily accessible in the open literature, tend to be cited highly, and represent the foundation of the CAB approach. Application of CAB to the technical research areas so far shows that this type of document is predominant in the highly cited references list. Books or review articles also appear on the highly cited references list. These documents do not usually represent new advances, but rather are summaries of the state of the art (and its Background) at the time the document was written. These types of documents are still quite useful as Background material. Finally, documents that receive large numbers of citations highly critical of the document could be included in the list of highly cited documents. In the CAB studies so far, the first author has not identified such papers in the detailed development of the Background.
7. 7.. In order for an important and/or seminal concept to appear in a CAB retrieval, it had to have been published and to have appeared in the database(s) selected. There are many databases that contain important concepts in high speed compressible flow, such as the SCI for basic/applied research, the Engineering Compendex for technology development/engineering research, patent database, non-SCI journals, magazine articles, books, contractor reports/DTIC database, repots written in other countries, and the classified literature. Because of the citation capability of the SCI, only the SCI database was selected. In theory, documents from any of the above categories could have shown up in the SCI references, and been included in the final CAB selection. In practice, because of limited universal availability of many of these sources, the only non-journal documents to have appeared tended to be books, NASA TRs, and AIAA conference papers. In particular, many European reports, especially from Russia/Soviet Union and Germany, did not appear.
8. Further, the decision to publish a concept/document in the open literature is influenced by many considerations. Positive results tend to receive higher publication priority than negative results, both by editors/reviewers and by sponsors/performer organizations, even though negative results may be very important for efficient use of research resources in future studies. Important research results that might provide competitors an advantage, whether from a national security perspective or a business competitive perspective, may not get

published in the open literature. Some of this research may appear eventually in the patent literature.

Additionally, the present study concerns high speed compressible flow, a discipline in which the first author worked decades ago. Using the CAB approach, the first author found that all the key historical documents with which he was familiar were identified, and all the historical documents identified appeared to be important. Thus, for the present data point at least, the weaknesses identified above (imbalances, undervaluing early historical references, unwanted highly cited documents) did not materialize. To insure that any critical documents were not missed because of imbalance problems, the threshold was set somewhat lower to be more inclusive.

The converse problem to multiple types of highly cited references, some of which may not be the seminal or other critical documents desired, is influential references that do not have substantial citation frequencies. If the authors of these references did not publish them in widely and readily accessible forums, or if they do not contain appropriate verbiage for optimal query accessibility, then they might not have received large numbers of citations. Additionally, journal or book space tends to be limited, with limited space for references. In this zero-sum game for space, research authors tend to cite relatively recent records at the expense of the earlier historical records. Also, extremely recent but influential references have not had the time to accumulate sufficient citations to be listed above the selection threshold on the citation frequency table. Methods of including these influential records located at the wings of the temporal distribution were described in the methodology section of the main body of the text. Inclusion of the references that were not widely available when published is more problematical, and tends to rely on the Background developers' personal knowledge of these documents, and their influence.