

**BROADBAND SCATTERING FROM SHEAR FLOWS AND THE NON-DOPPLER REMOTE SENSING OF VELOCITY PROFILES**

Dan Censor  
Department of Electrical and Computer Engineering  
Ben-Gurion University of the Negev  
Beer Sheva, Israel 84105

**ABSTRACT**

The present study investigates an alternative method to the celebrated Doppler technique. Remote sensing of motion based on the Doppler effect of frequency shifted scattered waves is a well understood and established technique. The prospects of dramatical improvements beyond the present state of the art are not promising. It is therefore worthwhile to investigate alternative and complementary methods. A theoretical discussion of such a non-Doppler method is given here. The first order velocity effects in the acoustical wave equation are treated as inhomogeneous (source) terms and the solution is represented in terms of a Green function integral. Hence this solution is the first order of the Born approximation. For simple cases such as channel flows, the integral can be evaluated, directly or by means of the stationary phase approximation method. It is then shown that a broadband interrogating pulse (which would be quite useless for Doppler type remote sensing) produces a scattered signal whose pulse shape is directly related to the velocity profile. The extraction of the velocity profile involves time integration, hence the present method has a feature of noise reduction built into it. However, there are still many open questions regarding the implementation of the present method in the presence of spurious effects, such as turbulence, pressure and temperature gradients etc. These problems are briefly discussed. Here, only a summary is presented. The full length version will be given elsewhere.

**MOTIVATION AND INTRODUCTION**

Remote sensing of flow velocity is usually based on the Doppler effect of frequency shifted scattered waves. This is a subject area which is particularly of interest in ultrasound systems for biomedical applications<sup>1</sup>. Although theoretical controversies still exist<sup>2-5</sup>, clearly the method provides a practical diagnostic tool. Since this method has reached a high degree of maturity, it is questionable whether radical improvements and breakthroughs can be expected in the near future. Therefore the investigation of new methods for flow diagnostics for various applications is timely. Such an alternative method is considered here, based on the concept of propagation and scattering in moving media.

Essentially, this means propagation and scattering in the presence of flow shear which exists at the interface between the two relatively moving regions. Morse and Ingard<sup>6</sup> devote a chapter to this subject. The literature on the subject is overwhelming and a representative, rather than an exhaustive list of references is given here<sup>7-22</sup>. These studies, including their cited references, provide a good coverage of the existing literature.

The present study is similar to most existing models in that it investigates the solutions of the wave equation in moving media. In the formalism developed below the velocity dependent terms are considered to be the sources of the field, i.e., they are treated as the inhomogeneous term of the differential equation. A Green function integral representation of the solution i.e., a first order Born approximation, is constructed. This approximation is valid for first order effects in the Mach number. Higher order effects are neglected. A similar formalism has been previously used by Censor and LeVine<sup>23</sup>. The interesting aspect, and in that the present study is different from previous discussions, is that the solutions, when considered for a broadband incident wave, e.g., a sharp pulse, are related in a simple way to the velocity profile. This suggests a diagnostic tool for measuring velocities, which is not based on the Doppler method.

The new non-Doppler method has certain advantages and disadvantages, compared to the Doppler method of flow velocity remote sensing. The new method requires specular aspect angles, i.e., a bistatic arrangement, as opposed to backscattering often used in the Doppler method. The Doppler effect method requires long pulses which contain many cycles of the R.F. signal (i.e., the carrier frequency). It works best with a time harmonic signal i.e., CW wave. On the other hand, the present non-Doppler method operates best with a broad spectrum, ideally a  $\delta$ -function, which of course cannot be achieved in a real system. The Doppler effect diagnosis of velocities requires a focused and range gated beam, in order to know from where the signal arrives and what the velocity at that location is. If the beam is not focused or the range gate too wide, many frequency shifts will be created<sup>24, 25</sup>, i.e., we will measure a Doppler spectrum. On the other hand, the non-Doppler method described here requires a divergent beam and wide range gate to operate properly. It is therefore possible that the new method will prove to be complementary to the Doppler method, in the sense that one will operate better in a case where the other's performance is poor.

Finally, it must be stressed that the present study is theoretical. It is not fully clear how spurious effects such as turbulence, pressure and temperature gradients will affect the practical measurements. A brief discussion of such effects is given below

**REFERENCES**

1. M. Azimi and A.C. Kak, "An analytical study of Doppler ultrasound systems", *Ultrasonic Imaging*, **7**, 1-48, 1985.
2. D. Censor, "Harmonic and transient scattering from time varying obstacles", *J. of the Acoustical Society of America*, **76**, 1527-1534, 1984.
3. J.C. Piquette and A.L. Van Buren, "Comments on Harmonic and transient scattering by time varying obstacles [J. Acoust. Soc. Am., **76**, 1527-1534 (1984)]", *Journal of the Acoustical Society of America*, **79**, 179-180, 1986.
4. D. Censor, "Reply to 'Comments on 'Harmonic and transient scattering by time varying obstacles'" [J. Acoust. Soc. Am., **76**, 1527-1534(1984)]", *J. of the Acoustical Society of America*, **79**, 181-182, 1986.
5. D. Censor, "Acoustical Doppler effect analysis - is it a valid method?", *J. of the Acoustical Society of America*, **83**, 1223-1230, 1988.
6. P.M. Morse and K.U. Ingard, *Theoretical Acoustics*, McGraw-Hill, 1968. See Chapter 11.
7. D. Censor and J. Aboudi, "Scattering of Sound waves by rotating cylinders and spheres", *J. of Sound and Vibration*, **19**, 437-444, 1971.
8. G.G. Steinmetz and J.J. Singh, "Reflection and transmission of acoustical waves from a layer with space-dependent velocity", *The J. of the Acoustical Society of America*, **51**, 218-222, 1972.
9. L.A. Stallworth and M.J. Jacobson, "Sound transmission in an isospeed ocean channel with depth-dependent current", *The J. of the Acoustical Society of America*, **51**, 1738-1750, 1972.
10. J. Aboudi and D. Censor, "Scattering of elastic waves by moving objects", *The J. of the Acoustical Society of America*, **52**, 203-209, 1972.
11. D. Censor, J. Aboudi and D. Newlander, "Reflection and transmission of elastic waves by a moving slab", *Applied Scientific Research*, **25**, 313-326, 1972.
12. U. Ingard and V.K. Singhal, "Upstream and downstream sound radiation into a moving fluid", *The J. of the Acoustical Society of America*, **54**, 1343-1346, 1973.
13. M. Schoenberg and D. Censor, "Velocity-dependent reflection, refraction, and scattering of elastic shear waves in the presence of a lubricating layer", *The J. of the Acoustical Society of America*, **53**, 508-513, 1973.
14. S.D. Savkar, "Radiation of cylindrical duct acoustic modes with flow mismatch", *J. of Sound and Vibration*, **42**, 363-386, 1975.
15. R. Dash, "Point source radiation through a composite medium", *J. of Sound and Vibration*, **49**, 365-377, 1976.
16. R. Dash, "Reflection and radiation due to a quadrupole near a fluid interface", *J. of the Acoustical Society of America*, **62**, 835-846, 1977.
17. R.K. Amiet, "Refraction of sound by a shear layer", *J. of Sound and Vibration*, **58**, 467-482, 1978.
18. J.N. Scott, "Propagation of sound waves through a linear shear layer", *American Institute of Aeronautics and Astronautics Journal*, **17**, 237-244, 1979.
19. S.P. Koutsoyannis, "Characterization of acoustic disturbances in linearly sheared flows", *Journal of Sound and Vibration*, **68**, 187-202, 1980.
20. S.P. Koutsoyannis, K. Karamcheti and D.C. Galant, "Acoustic resonances and sound scattering by a shear layer", *American Institute of Aeronautics and Astronautics Journal*, **18**, 1446-1454, 1980.
21. L.M. Lyamshev, "Theory of sound propagation in a moving layered inhomogeneous medium", *Soviet Physics, Acoustics*, **28**, 217-221, 1982.
22. S.M. Candel, "Sound source radiation in two-dimensional shear flow", *American Institute of Aeronautics and Astronautics Journal*, **21**, 221-227, 1983.
23. D. Censor and D.M. LeVine, "The Doppler effect: Now you see it, now you don't", *J. of Mathematical Physics*, **25**, 309-316, 1984.
24. V.L. Newhouse, D. Censor, T. Vontz, J.A. Cisneros and B.B. Goldberg, "Ultrasound Doppler probing of flows transverse with respect to beam axis", *IEEE Transactions on Biomedical Engineering*, **BME-34**, 779-789, 1987.
25. D. Censor, V.L. Newhouse, T. Vontz and H.V. Ortega, "Theory of ultrasound Doppler-spectra velocimetry for arbitrary beam and flow configurations", *IEEE Transactions on Biomedical Engineering*, **BME-35**, 740-751, 1988.