

Manually operated piston-driven shock tube

K. P. J. Reddy and N. Sharath

A simple hand-operated shock tube capable of producing Mach 2 shock waves is described. Performance of this miniature shock tube using compressed high pressure air created by a manually operated piston in the driver section of the shock tube as driver gas with air at 1 atm pressure as the test gas in the driven tube is presented. The performance of the shock tube is found to match well with the theoretically estimated values using normal shock relations. Applications of this shock tube named Reddy tube, include study of blast-induced traumatic brain injuries and high temperature chemical kinetics.

In recent times applications of shock waves are extending into the fields of engineering, manufacturing, medical, biological and scientific research¹. Shock waves are produced by sudden release of energy like in explosions or volcanic eruptions, by bodies moving at supersonic speeds, by impact of high-speed projectiles and by laser ablation. In spite of such a wide range of applications and common occurrence of shock waves in daily life, the subject of shock waves has not been taught at the basic school and college levels. The primary reason for this is the safety issues involved with regard to the high pressure associated with the production and propagation of shock waves. This problem could be alleviated by developing systems for generating shock waves in the classrooms without the associated risks of high pressure.

Shock tube is the simple means of producing shock waves of required strength in the laboratory². The shock tube consisting of a simple tube separated into driver and driven sections by a metal diaphragm is commonly driven by compressed high pressure driver gas, created either by a compressor or by detonation of small amounts of explosive, in the driver side which ruptures the diaphragm creating a shock wave which travels into the driven section. Using these traditional shock tubes for classroom teaching or for medical and biological applications is inhibited by their large size. Recently, we have developed a simple hand-operated pressure-driven shock tube named 'Reddy tube'³ to overcome these limitations. The main aim of this note is to present the design and performance capabilities of this convenient to operate simple, mini shock tube which is more versatile than the traditional compression-driven and blast-driven shock tubes. The special feature of this shock tube is that it is a handheld, piston-

driven shock tube capable of operating in traditional compression-driven mode using manual energy. It is a common knowledge that except for producing weak shock waves⁴ there is no report of producing supersonic flows of sustained duration using human energy. Hence this is the first such devise capable of producing shock Mach numbers exceeding

1.5 by simple hand operation. The details of this hand-operated shock tube and calibration of its performance along with the Schlieren images of the flow exiting the open end of the Reddy tube are presented in this paper.

The Reddy tube essentially operates on the principle of free piston-driven shock tube (FPST) named after its developer

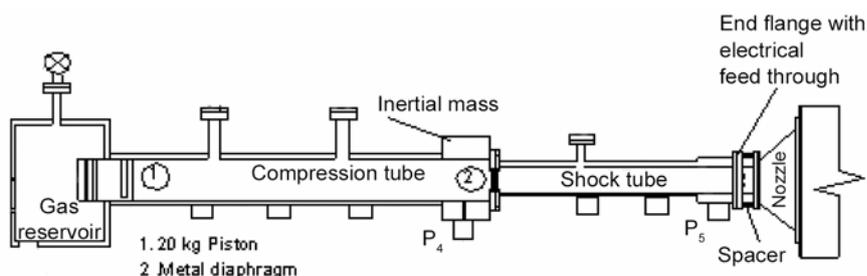


Figure 1. Schematic diagram of a fully instrumented free piston-driven shock tube.

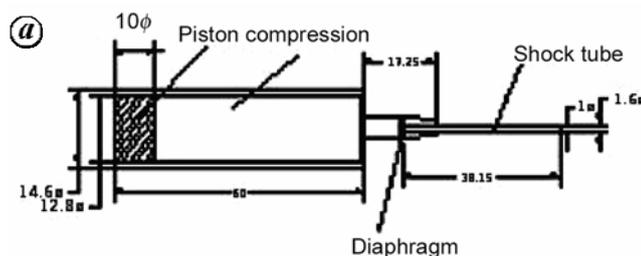


Figure 2. a, Schematic diagram of the Reddy tube. b, Photograph of a medical syringe converted into piston-driven mini shock tube.

Ray Stalker⁵, shown schematically in Figure 1. It consists of a primary reservoir containing high pressure air driving a piston into the compression tube filled with helium gas at 1 atm pressure. The other end of the compression tube is connected to the driven portion of the shock tube through a metallic diaphragm. At the end of the stroke the piston moving at high speed compresses the helium gas while heating it simultaneously due to adiabatic compression. The metallic diaphragm ruptures due to the high pressure heated helium gas resulting in creating and driving a strong shock wave into the driven portion of the shock tube containing the test gas. The other end of the driven tube can be connected to the wind tunnel portion to operate the facility as a free piston-driven hypersonic shock tunnel or closed with a flange to reflect the shock wave to produce shocked test gas with pressures exceeding a few hundreds of atmosphere and temperatures exceeding 10,000 K, which can be used for material processing and also to synthesize new materials⁶.

The first version of the proposed manually operated, piston-driven mini shock tube shown schematically in Figure 2, is the simplified and miniature version of the FPST. In this, typically the compression tube is a 60 mm long cylindrical tube of 12.8 mm internal diameter and 1 mm wall thickness. A plastic piston of 12.8 mm outer diameter fitted with a plunger for manual operation is closely fitted inside the compression tube. The piston head is provided with a couple of O-rings to prevent the compressed gas ahead leaking to the other side. The driven tube is a 30 mm long SS tube of 1 mm internal diameter and wall thickness of 0.8 mm. The compression tube and the shock tube are separated by a 50 μm thick plastic diaphragm and the other end of the shock tube is open to the atmosphere. In the initial trials we have made use of a medical syringe with a detachable hypodermic needle for this

purpose, in which the syringe acts as the compression tube with the plunger acting as the piston, while the hypodermic needle acts as the shock tube and these two are separated by a plastic diaphragm³. We have utilized thin plastic membrane typically used for food wrapping in the kitchen as the diaphragm. The open end of the hypodermic needle is made circular by grinding the sharp elliptic tip and the typical dimensions of the mini shock tube along with a photograph are given in Figure 2.

For operation of the shock tube, the plunger attached to the piston is withdrawn to the extreme end of the compression tube before attaching the hypodermic needle with a separating diaphragm such that the compression tube is filled with ambient air at atmospheric pressure and the other end of the needle is open to the atmosphere, and hence driver and driven gases are the atmospheric air. The piston travels through the compression tube as the plunger is pressed forward using right-hand thumb and the pressure ahead of the piston in-

creases rapidly which can be estimated using the equation $p = p_0(X/L)^{-\gamma}$, where p is the pressure in the compression tube ahead of the piston, p_0 the initial pressure in the compression tube, X the distance along the compression tube decreasing towards the end, L the full length of the compression tube and γ the specific heat ratio of the driver gas. The computations indicate that pressure as high as 25 and 45 bar can be generated by pushing the piston close to the end of the compression tube with air or helium as the driver gas respectively. Thus these pressure values are high enough to generate moderate strength shock Mach numbers by operating the shock tube in the pressure bursting mode. The estimated performance parameters of the shock tube driven by the pressures estimated using above equation are presented in Table 1, which also shows the expected shock Mach numbers in the driven tube filled with air at atmospheric pressure if the diaphragm ruptures when the piston is at positions indicated in the first column. It is seen that shock Mach number close to

Table 1. The estimated performance parameters of the Reddy tube

X/L	P_4/P_1	M_5	P_2/P_1	P_5/P_1	T_5/T_1
0.1	25.12	1.90	4.05	12.67	2.32
0.2	9.52	1.59	2.79	6.77	1.81
0.3	5.40	1.42	2.20	4.45	1.57
0.4	3.61	1.31	1.84	3.22	1.41
0.5	2.64	1.23	1.60	2.47	1.30

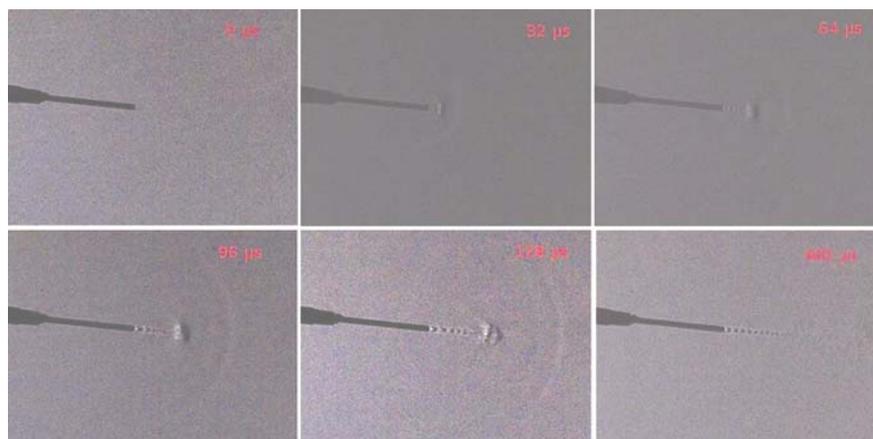


Figure 3. Schlieren images of the flow at the exit of the Reddy tube at different time intervals.

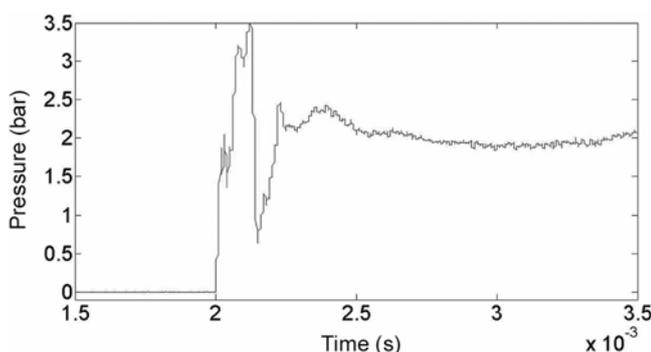


Figure 4. Total pressure signal measured at the exit of the 1 mm diameter Reddy tube.

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2 can be generated by choosing a diaphragm thickness such that it ruptures when the piston is at the position $X/L = 0.1$. Corresponding estimated shock tube performance parameters are estimated using one-dimensional normal shock relations.

The flow emerging from the open end of the 1 mm diameter shock tube visualized using the Schlieren technique⁷ with a high-speed camera (Phantom, M/s Vision Res. Inc.) is shown in Figure 3. The diffracting spherical shock wave followed by a strong vortex ring and an underexpanded jet emanating from the open end of the Reddy tube are clearly seen in these time-resolved images. It is seen that the flow dies down after about $400 \mu\text{s}$. The speed of the spherical shock wave in the free space measured from these images is $338 \pm 20 \text{ m/s}$. Because of the small size of the driven tube, the speed of the shock wave could not be measured inside the shock tube. However, the total pressure due to the flow outside the shock tube is measured using a Kulite pressure transducer and the measured typical pressure signal is shown in Figure 4. It is seen that the signal resembles the over pressure produced by a typical blast wave and the peak over pressure generated by this simple hand operated shock tube is about 3.5 bar. From the nature of the overpressure produced in the Reddy tube, we feel that it is ideally suited for investigating the blast-induced traumatic brain injuries in small-sized laboratory animals^{4,8}.

For many applications of the shock tube it is essential to characterize the flow properties inside the shock by calibrating its performance. However, the miniature shock tube described above is unsuitable for carrying out measurements of the flow fields inside the driven tube due to its small diameter. Hence we developed a scaled-up version of the Reddy tube, as shown in Figure 5. The modified Reddy tube consists of a 29 mm diameter stainless steel shock tube divided into a 490 mm long driver tube and 500 mm long driven tube separated by a 0.1 mm thick aluminium or Mylar diaphragm. The diaphragm rupture pressure in the driver section is generated manually by pushing a 29 mm diameter piston used in the veterinary syringe. The inner wall of the shock tube is finished to less than $10 \mu\text{m}$ smoothness by honing operation. A longer driver tube ensures late arrival of the expansion fan, which enables

achieving test times longer than $500 \mu\text{s}$. The diaphragm rupture pressure is monitored using a digital pressure gauge (M/s IRA Ltd, India) mounted close to the diaphragm station. The speed of the shock wave inside the driven tube and the pressure jump across the primary and reflected shock waves are measured using two piezoelectric pressure gauges (M/s PCB Electronics) mounted 70 mm apart toward the end portion of the shock tube. A port is provided at the closed end of the driven tube to connect a vacuum pump to vary the driven pressure or to fill up a required test gas. A fully instrumented 29 mm diameter Reddy tube is shown in Figure 5 b.

The Reddy tube is operated by pushing the plunger in the driver section manu-

ally and the diaphragm rupture pressure p_4 is recorded on the digital pressure gauge at the end of the driver section. The shock arrival time and the pressure rise behind the primary and the reflected shock waves are recorded from the outputs of the piezoelectric gauges connected to a digital CRO. Typical signals recorded for a paper diaphragm are shown in Figure 6, in which the blue signal is from the first pressure gauge and the red signal is from the second gauge closer to the shock tube end. These signals clearly indicate the shock wave arrival time, pressure rise due to the primary shock wave travelling from the diaphragm station towards the end of the shock tube and the reflected shock wave travelling in the opposite direction after

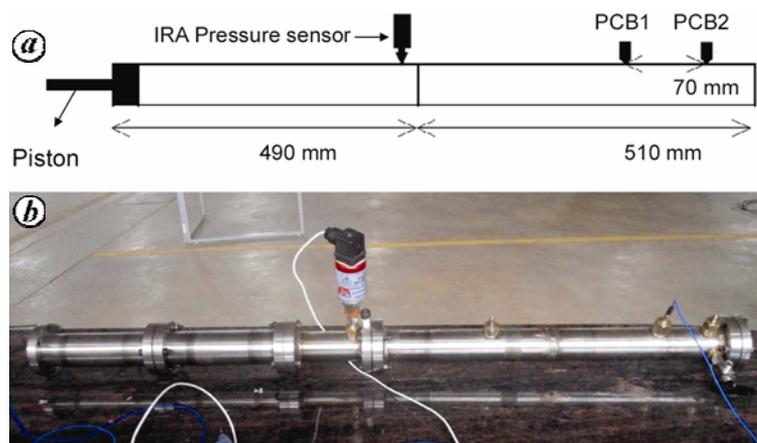


Figure 5. a, Schematic diagram of the 29 mm diameter Reddy tube indicating the location of the pressure sensors. b, Photograph of fully assembled, modified Reddy tube with pressure gauges mounted for measuring the shock speed and diaphragm rupture pressure.

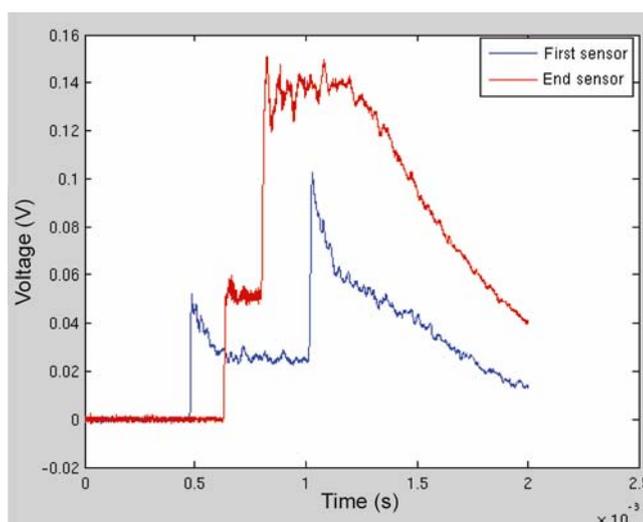


Figure 6. Typical pressure signals from one of the runs of the Reddy tube. The flat region in the time interval of 0.75×10^{-3} and 1.4×10^{-3} s in the signal from the end sensor indicates the test time which is long enough to study the chemical reactions.

reflection at the closed end of the shock tube. It is found that the typical rupture pressure varies in the range 3–7 bar depending on the strength of the person pushing the piston and also due to the variation of the thickness of the diaphragm. The speed of the shock wave is calculated by using the relation $U_s = \Delta x / \Delta t$, where Δx is the distance between the gauges and Δt is the time taken for the shock wave to travel between the two gauges. Corresponding shock Mach number is calculated using the relation $M_s = U_s / a$, where $a = (\gamma_1 RT)^{1/2}$ is the speed of sound in the test gas air, γ_1 (= 1.4) the specific heat ratio, R (= 287 J/kg) the specific gas constant and T (= 300 K) is the gas temperature. The experimental values of the pressure jump p_2/p_1 and p_5/p_1 across the primary shock and the reflected shock waves respectively, are measured from the typical pressure signals shown in Figure 6, where the initial pressure p_1 in the driven section is 0.91 bar for all the runs reported here.

For the measured values of the ratio of rupture pressure p_4 to the initial driven section pressure p_1 , the estimated value of the shock Mach number is calculated using the nonlinear equation

$$\frac{p_4}{p_1} = \left[\frac{2\gamma_1 M_s^2 - (\gamma_1 - 1)}{(\gamma_1 + 1)} \right] \times \left[1 - \left(\frac{\gamma_4 - 1}{\gamma_1 + 1} \right) \left(\frac{a_1}{a_4} \right) \right]^{(-2\gamma_4/\gamma_4 - 1)} \times \left[M_s - \frac{1}{M_s} \right] \quad (1)$$

where γ_4 and a_4 are the specific heat ratio of the driver gas and the speed of sound in the driver gas respectively. In the experiments reported here we have assumed air as the driver gas and the driven gas and hence $\gamma_4 = \gamma_1$ and $a_4 = a_1$.

For the shock Mach number estimated from the above equation, the pressure jump across the primary and reflected shock waves is estimated using the following Rankine–Hugoniot (R–H) normal shock relations²

$$\frac{p_2}{p_1} = \left(\frac{2\gamma_1 M_s^2 - (\gamma_1 - 1)}{(\gamma_1 + 1)} \right), \quad (2)$$

and

$$\frac{p_5}{p_1} = \left[\frac{2\gamma_1 M_s^2 - (\gamma_1 - 1)}{(\gamma_1 + 1)} \right] \times \left[\frac{(3\gamma_1 - 1)M_s^2 - 2(\gamma_1 - 1)}{(\gamma_1 - 1)M_s^2 + 2} \right]. \quad (3)$$

The measured values from the signals shown in Figure 6 and the corresponding theoretical values estimated using the eqs (1)–(3) are shown in Figures 7–9. From these figures it is seen that the experimental values match well with the theoretically estimated values. This essentially indicates that the performance of the shock tube is good. However, from Figure 7 it is seen that the matching of the measured shock Mach number with the theoretical values is not as good as the other performance parameters

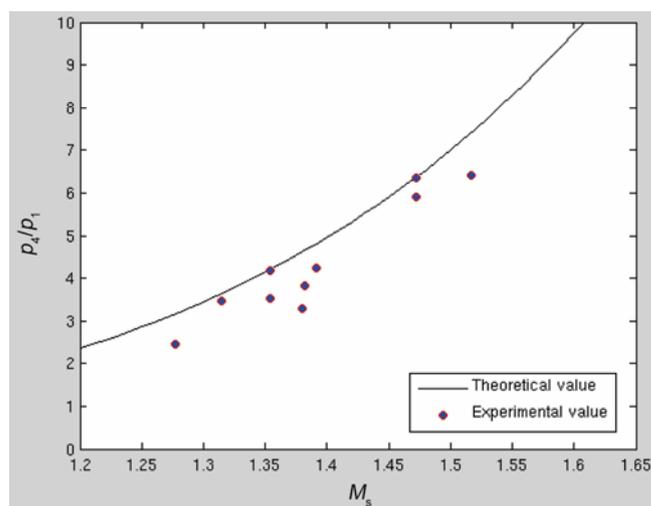


Figure 7. Comparison of the theoretically predicted values of the shock Mach number with the measured values of the ratio of diaphragm rupture pressure to the shock tube initial pressure.

shown in Figures 8 and 9. This deviation is found to be due to the inaccuracy in measuring the diaphragm rupture pressure. Currently, efforts are being made to improve these measurements using a digital pressure gauge of improved least count.

The good performance of the Reddy tube makes it a versatile tool for many scientific and biological applications. For example, the 29 mm Reddy tube can be used for chemical kinetics studies. The temperatures needed to undertake these studies can be estimated using the following R–H relations,

$$\frac{T_2}{T_1} = \frac{\left[\left(2\gamma_1 M_s^2 - \left(\frac{\gamma_1 - 1}{2} \right) \right) \times \left(M_s^2 \left(\frac{\gamma_1 - 1}{2} \right) + 1 \right) \right]}{M_s^2 \left(\frac{\gamma_1 - 1}{2} \right)^2}. \quad (4)$$

and

$$\frac{T_5}{T_1} = \frac{\left\{ [2\gamma_1 M_s^2 (\gamma_1 - 1) + (3 - \gamma_1)] \times [M_s^2 (3\gamma_1 - 1) - 2(\gamma_1 - 1)] \right\}}{[M_s^2 (\gamma_1 + 1)^2]}. \quad (5)$$

Chemical kinetics studies using shock tubes are usually carried out by taking the thin mixture of chemical under investigation in gaseous form mixed with an inert gas such as argon, which acts as a buffer gas, as test gas in the driven section of the shock tube. The test gas is subjected to the elevated temperature and the pressure behind the reflected shock wave for a millisecond duration. The equilibrated gas after the reaction is analysed for determining the reaction rates⁹. From the R–H relations it is seen that temperatures exceeding 900 K can be easily obtained in the Reddy tube by considering helium as the driver gas and argon as the driven gas. This temperature is adequate to carry out the ignition delay and chemical kinetics studies of many chemicals of interest¹⁰.

We have presented here the design and operation details of the hand-operated shock tube called Reddy tube. The calibration of the Reddy tube is presented to demonstrate the performance capabilities of this new miniature shock tube. Shock Mach numbers exceeding 1.5 are easily produced in the Reddy tube by manual operation. This is the first report of the production of such a strong shock wave

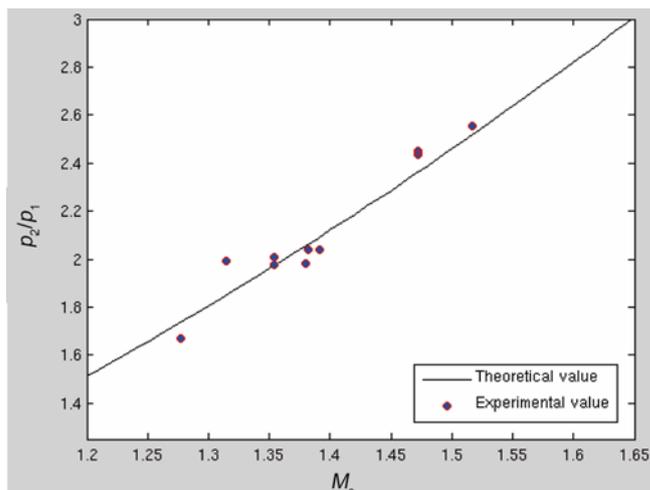


Figure 8. Comparison of the measured pressure jump across the primary shock wave with the theoretically estimated values for different shock Mach numbers.

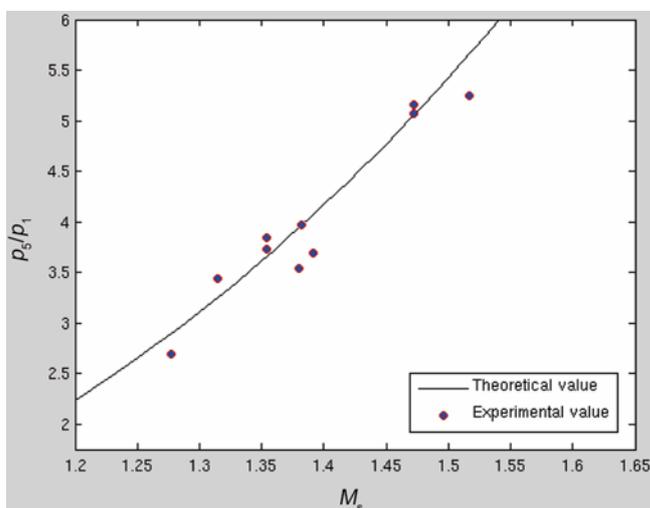


Figure 9. Comparison of the measured pressure jump across the reflected shock wave with the theoretically estimated values for different shock Mach numbers.

manually. The shock Mach numbers can be further enhanced to 2 using helium as the driver gas. The temperature and pressure conditions behind the reflected shock wave in the Reddy tube are suitable for chemical kinetics studies and the overpressures produced at the open end

of the 1 mm diameter shock tube are suitable for studying the blast-induced traumatic brain injuries.

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K. P. J. Reddy and N. Sharath are in the Laboratory for Hypersonic and Shock Wave Research, Department of Aerospace Engineering, Indian Institute of Science, Bangalore 560 012, India.
e-mail: laser@aero.iisc.ernet.in