HYDROMAGNETIC FLOW DUE TO NON-TORSIONAL OSCILLATIONS OF A DISC IN A ROTATING FLUID

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Received on December 24, 1974 and in revised form on June 2, 1975

ABSTRACT

The viscous flow due to non-torsional oscillations of a disc in a rotating system is studied when a uniform magnetic field is applied along the axis of rotation. The solution in the resonant case is obtained by using the initial value formulation. The solution for the steady motion due to uniform impulsive motion of the disc is discussed. The expression for the depth of penetration of vorticity is obtained and the effect of magnetic field on it is also discussed.

Keywords: Non-torsional oscillations, Penetration of vorticity, Hydromagnetic flow.

1. INTRODUCTION

Hydromagnetic flows in rotating fluids have considerable applications in geophysics and astrophysics wherein ordinary hydrodynamics is usually inapplicable, since almost all phenomena of astrophysics occur where there are magnetic fields associated with materials of large conductivity and hence a strong coupling results between the motion of the matter and the magnetic field. It is generally accepted that hydromagnetic flow in the earth's liquid core is responsible for the main geomagnetic field and the theory of earth's magnetism is based on the dynamics of the core motions. A detailed account of these types of geophysical problems is given by Hide [1] and Hide and Roberts [2]. The interaction of the Coriolis force on the plane hydromagnetic waves is discussed by Lehnert [3].

Hide and Roberts [4] have investigated the hydromagnetic flow due to an oscillatory disc in the presence of a uniform magnetic field in a rotating system and various limiting cases of electrical conductivity are discussed. The motion due to torsional oscillations of two infinite discs in an infinitely conducting viscous fluid is studied by Bhatnagar [5]. This analysis has been extended to include the effects of finite conductivity by Devanathan [6]. More recently Thornley [7] has considered non-torsional oscillations of a single disc and two parallel discs in a rotating fluid. The aim of the present investigation is to understand the effect of a uniform axial magnetic field in a motion induced by the non-torsional oscillations of a disc in its own plane. It is found that the resonant phenomenon prevail if the solutions are assumed to be of periodic nature. In deriving the linearized magneto-hydrodynamic equations it has been assumed that the electrical conductivity of the medium is infinitely large (*i.e.*, magnetic Reynolds number is large) and the induced magnetic field is not negligible. Debnath [8] has recently studied this problem for a medium of finite conductivity assuming that the induced magnetic field is negligibly small. In this case one can get periodic solutions satisfying all the physical requirements even for the resonant frequency, whereas in our case it is not possible to obtain a general periodic solution in the resonant case without an initial value formulation. Thus we have obtained the general solution using an initial value formulation. It is interesting to note that the periodic solution in the resonant case can be obtained without an intial value formulation by placing one more disc and a more general solution is obtained in this case also.

2. FORMULATION

The hydromagnetic flow set up by the non-torsional oscillations of a disc ($z = 0$) in its own plane bounding a semi-infinite expanse of an incompressible, viscous and infinitely conducting fluid is considered when the fluid and the disc are in solid body rotation with angular velocity Ω about the z-axis in cartesian coordinate system (x, y, z). The magnetic field H_0 is applied along the axis of rotation and the non-torsional oscillations of the disc are taken to be of the form

$$q = u + iv = ae^{i\omega t} + be^{-i\omega t}, \tag{2.1}$$

where a and b are complex constants, t is the time, ω is the frequency of oscillation of the disc, u and v are the velocity components in the x and y directions respectively.

Taking the physical quantities as functions of z and t only as in the ordinary Stokes' layers, the hydromagnetic equations in the rotating frame of reference (assuming no external pressure gradient) reduce to*

$$\frac{\partial u}{\partial t} - 2\Omega v = \frac{\mu H_0}{4\pi\rho}\frac{\partial H_x}{\partial z} + \nu\frac{\partial^2 u}{\partial z^2}, \tag{2.2}$$

$$\frac{\partial v}{\partial t} + 2\Omega u = \frac{\mu H_0}{4\pi\rho}\frac{\partial H_y}{\partial z} + \nu\frac{\partial^2 v}{\partial z^2}, \tag{2.3}$$

$$\frac{\partial H_x}{\partial t} = H_0 \frac{\partial u}{\partial z}, \tag{2.4}$$

$$\frac{\partial H_y}{\partial t} = H_0 \frac{\partial v}{\partial z}, \tag{2.5}$$

where H_x and H_y are the components of the induced magnetic field in x and y directions, μ is the magnetic permeability, ρ the density and ν the kinematic viscosity.

Writing

$$q = u + iv, \quad H = H_x + iH_y \tag{2.6}$$

and rendering the variables dimensionless by the following scheme:

$$z' = \frac{z}{L}, \quad q' = \frac{p}{\Omega L}, \quad t' = \Omega t, \ h = \frac{H}{H_0}, \tag{2.7}$$

where $L^2 = \nu/\Omega$, the equations (2.2) to (2.5) in dimensionless form reduce to (after dropping the dashes),

$$\frac{\partial q}{\partial t} + 2iq = \alpha \frac{\partial h}{\partial z} + \frac{\partial^2 q}{\partial z^2}, \tag{2.8}$$

$$\frac{\partial h}{\partial t} = \frac{\partial q}{\partial z}, \tag{2.9}$$

where $\alpha = \dfrac{\mu H_0^2}{4\pi\rho\Omega^2 L^2} = \dfrac{\mu H_0^2}{4\pi\rho\Omega\nu}$ is the magnetic interaction parameter.

The boundary conditions are

$$q = ae^{i\sigma t} + be^{-i\sigma t} \qquad \text{at} \quad z = 0, \tag{2.10}$$

$$q \to 0, \quad h \to 0 \qquad \text{as} \quad z \to \infty, \tag{2.11}$$

where $\sigma = \omega/\Omega$.

3. Periodic Solution

First we seek a periodic oscillatory solution of (2.8) and (2.9) of the form

$$q = q_1(z)\, e^{i\sigma t} + q_2(z)\, e^{-i\sigma t},$$
$$h = h_1(z)\, e^{i\sigma t} + h_2(z)\, e^{-i\sigma t}. \tag{3.1}$$

* In deriving these equations we have used the fact that $w \equiv 0$, $H_z \equiv 0$ in view of the equation of continuity and $\nabla \cdot \bar{H} = 0$.

These expressions for q and h are substituted in (2.8) and (2.9) and the resulting equations are solved for the functions q_1, q_2, h_1 and h_2 using (2.10) and (2.11) and q is obtained as

$$q = ae^{-k_1 z} e^{i\sigma t} + be^{-k_2 z} e^{-i\sigma t}, \tag{3.2}$$

where $k_1 = \left[-\frac{\sigma(2+\sigma)}{\alpha + i\sigma} \right]^{\frac{1}{2}}$,

$$k_2 = \left[\frac{\sigma(2-\sigma)}{\alpha + i\sigma} \right]^{\frac{1}{2}}, \tag{3.3}$$

whose real parts are greater than zero. It is noticed that k_1 and k_2 as functions of a single variable σ or α are continuous at the origin but they fail to be so when they are treated as functions of two variables σ and α. Also the process of taking limits $\alpha \to 0$, $\sigma \to 0$ does not give a unique limit, as seen below:

$$\underset{\alpha \to 0, \sigma \to 0}{\text{Limit}} \left[k_1, \ k_2 \right] = 0, \quad \underset{\sigma \to 0, \quad \alpha \to 0}{\text{Limit}} \left[k_1, \ k_2 \right] = \sqrt{2i}. \tag{3.4}$$

Hence the results for the case in which $\alpha = 0$, $\sigma = 0$ may not be obtainable as a particular case from the general results if we approach the origin of the $(\sigma - \alpha)$ plane along any arbitrary direction. However the second way of taking limits in (3.4) gives a correct solution to the equations and that is the only meaningful case to be considered in the neighbourhood of the origin in the $(\sigma - \alpha)$ plane.

The solution (3.2) represents a superposition of two waves whose amplitudes decay out with respect to the vertical distance from the disc. It satisfies all the boundary conditions except when $\sigma = 2$ which corresponds to the resonant frequency (*i.e.*, $\omega = 2\Omega$). In this case (3.2) reduces to

$$q = ae^{-k_0 z} e^{2it} + be^{-2it}, \tag{3.5}$$

where $k_0 = \dfrac{2\sqrt{2i}}{\sqrt{\alpha + 2i}}$.

The first term in (3.5) represents a type of Stokes' layer modified by the presence of magnetic field. This solution evidently does not satsfy the condition (2.11) unless $b = 0$. Hence there is no periodic soltuion in the resonant case for $b \neq 0$. On the other hand if we introduce another disc at $z = d$ which is at rest relative to the rotating frame of reference a periodic solution satisfying the condition (2.10) and that q=0 on $z = d$ can be obtained and it is given by

$$q = \frac{\sinh\,[k_1(d-z)]}{\sinh\,(k_1 d)}\, ae^{i\sigma t} + \frac{\sinh\,[k_2(d-z)]}{\sinh\,(k_2 d)}\, be^{-i\sigma t} \tag{3.6}$$

This again is a superposition of waves and is valid for all σ including the resonant case and the solution in this case is

$$q = \frac{\sinh\,[k_0\,(d - z)]}{\sinh\,(k_0 d)}\, a e^{2it} + (1 - z/d)\, b e^{-2it}\,. \qquad (3\cdot 7)$$

The first term in $(3\cdot 7)$ is still a wave and represents a modified Stokes' layer in which the effect of magnetic field is felt, while the second term representing a plane Couette flow is independent of the magnetic field.

In the following section we pose an initial value problem to get a sensible solution at the resonant frequency by using Laplace transform technique.

4. The Initial Value Problem

Case (i). One disc problem:

We consider the same configuration as in §2 with the conditions (2.10) and (2.11) for $t > 0$ and the following initial conditions

$$q = 0, \quad h = 0 \quad \text{at} \quad t = 0 \quad \text{for all } z, \qquad (4.1)$$

Applying the Laplace transform defined by

$$\bar{q}\,(z,\; s) = \int_0^\infty e^{-st}\, q\,(z,\, t)\, dt, \qquad (4.2)$$

to $(2\cdot 8)$ and $2\cdot 9)$ and solving for $\bar{q}\ (z,\, s)$ subjected to the transformed boundary conditions, we get

$$\bar{q}\,(z, s) = \left(\frac{a}{s - i\sigma} + \frac{b}{s + i\sigma}\right) exp\,(-\,mz), \qquad (4.3)$$

where

$$m = \left[\frac{s\,(s + 2i)}{s + a}\right]^{1/2}, \text{ real part of } m > 0.$$

By the inversion formula $q\,(z, \mathrm{t})$ is given by

$$q\,(z,\, t) = \frac{1}{2\pi i} \int_{\gamma - i\infty}^{\gamma + i\infty} \left(\frac{a}{s - i\sigma} + \frac{b}{s + i\sigma}\right) \exp\,(st - mz)\, ds. \qquad (4.4)$$

The integral in (4.4) is evaluated by the method of residues. The integrand has two simple poles at $s = \pm\, i\sigma$ and branch points at $s = 0$,

$-2i$, $-a$. Choosing a contour Γ as shown in figure (1) and evaluating the integral in (4.4) (*see* Appendix), we get

$$q(z, t) = ae^{-k_1 z} e^{i\sigma t} + be^{-k_2 z} e^{-i\sigma t}$$

$$-\frac{1}{\Pi}\left[\int_0^a f(x)\,dx + \int_0^\infty f(x+2i)\,dx\right], \tag{4.5}$$

where

$$f(x) = \left(\frac{a}{x+i\sigma} + \frac{b}{x-i\sigma}\right)\sin\left(z\sqrt{\frac{x(x-2i)}{x-a}}\right)e^{-xt}.$$

It is evident that this solution includes the periodic solution. Incidentally the solution at the resonant frequency satisfying all the boundary conditions can be obtained from (4.5) by putting $\sigma = 2$. For any arbitrary a the integrals in (4.5) cannot be evaluated in a closed form whereas when $a = 0$, (4.5) reduces to

$$q(z, t) = a\exp\left[z\sqrt{i(2+\sigma)} + i\sigma t\right] + b\exp\left[z\sqrt{i(2-\sigma)} - i\sigma t\right]$$

$$+\frac{e^{-2it}}{2\sqrt{\pi t}}\int_0^\infty \left[ae^{-x\sqrt{i(2+\sigma)}} + be^{-x\sqrt{i(2-\sigma)}}\right]\left[e^{\frac{-(z+x)^2}{4t}} - e^{\frac{-(z-x)^2}{4t}}\right]dx \tag{4.6}$$

The integral in (4.6) can be evaluated exactly and $q(z,t)$ is given as,

$$q(z,t) = \tfrac{1}{2}ae^{i\sigma t}\left[\exp\left(-z\sqrt{i(2+\sigma)}\right)\operatorname{erfc}\left\{\frac{z}{2\sqrt{t}} - \sqrt{i(2+\sigma)t}\right\} + \right.$$

$$\left.\exp\left(z\sqrt{i(2+\sigma)}\right)\operatorname{erfc}\left\{\frac{z}{2\sqrt{t}} + \sqrt{i(2+\sigma)t}\right\}\right]$$

$$+\tfrac{1}{2}be^{i\sigma t}\left[\exp\left(-z\sqrt{i(2-\sigma)}\right)\operatorname{erfc}\left\{\frac{z}{2\sqrt{t}} - \sqrt{i(2-\sigma)t}\right\} + \right.$$

$$\left.\exp\left(z\sqrt{i(2-\sigma)}\right)\operatorname{erfc}\left\{\frac{z}{2\sqrt{t}} + \sqrt{i(2-\sigma)t}\right\}\right], \tag{4.7}$$

where $erfc(x)$ is the conplementary error function. Thus the solution (4.7) in the non-magnetic case coincides with the solution given by Thornley [7]. It is worthnoting that as $t \to \infty$, $f(x) \to 0$ and hence we get the periodic solution (3.2) as the steady solution.

Case (ii). Two disc problem:

Introducing one more disc at $z = d$ as a rigid boundary in the same configuration of case (i), the solution using Laplace transforms satisfying the additional boundary condition that $q = 0$ on $z = d$ is

$$q(z, t) = \frac{1}{2\pi i} \int_{\gamma - i\infty}^{\gamma + i\infty} \left(\frac{a}{s - i\sigma} + \frac{b}{s + i\sigma} \right) \frac{\sinh [m(d - z)]}{\sinh (md)} e^{st} ds \tag{4.8}$$

Eventhough m as a function of s has branch points at $s = 0$, $s = -2i$ and at $s = -\alpha$, they are regular points of the integrand. The only singularities of the integrand are the simple poles located at

$$s = \pm i\sigma, \ \xi_n^+ \ \xi_n^-, \ n = 1, 2, 3 \ldots.$$

where $\xi_n^{\pm} = \frac{1}{2}\{-(2i + n^2\pi^2 d^2) \pm [(2i + n^2\pi^2/d^2)^2 - 4n^2\pi^2\alpha/d^2]^{1/2}\}$. (4 9)
The integral in (4.8) is evaluated again by the method of residues and the solution is obtained as

$$q(z, t) = ae^{i\sigma t} \frac{\sinh [k_1(d - z)]}{\sinh (k_1 d)} + be^{-i\sigma t} \frac{\sinh [k_2(d - z)]}{\sinh (k_2 d)}$$

$$+ 4\pi^2 \sum_{n=1}^{\infty} \frac{n \sin (n\pi z/d \quad \left[e^{\xi_n^+ t} (\xi_n^+ + \alpha) \left(\frac{a}{\xi_n^+ - i\sigma} + \frac{b}{\xi_n^+ + i\sigma} \right) \right.}{\{n^4\pi^4 - 4n^2\pi^2 d^2\alpha - 4d^2 + 4id^2 n^2\pi^2\}^{1/2}}$$

$$\left. - e^{\xi_n^- t} (\xi_n^- + \alpha) \left(\frac{a}{\xi_n^- - i\sigma} + \frac{\xi_n^- + i\sigma}{b} \right) \right] \tag{4.10}$$

Each term in the infinite series represents propagation of damping waves along the positive and negative directions of z-axis and the solution as a whole represents a type of Stokes' layer. It can be easily seen that real parts of $\xi_n^{\pm}$ are negative and hence as $t \to \infty$ we get the oscillatory solution (3.6). The solution (4.10) is valid for all values of σ including the resonant frequency. For $\alpha = 0$ the present results in all cases reduce to the results of Thornley [7].

5. Uniform Motion of the Disc

We now discuss the flow induced by the uniform motion of the disc (which corresponds to $\sigma = 0$) in both the cases (i) and (ii).

Case (i): When $\sigma = 0$ the uniform velocity of the disc $z = 0$ is given by

$$q = a + b = c, \tag{5.1}$$

c being a complex constant, and the solution is

$$q(z,t) = c\left[1 - \frac{1}{\pi}\left\{\int_0^\alpha \frac{1}{x}\sin\left(z\sqrt{\frac{x(x-2i)}{x-\alpha}}\right)e^{-xt}\,dx\right.\right.$$

$$\left.\left. + e^{-2it}\int_0^\infty \frac{1}{x+2i}\sin\left(z\sqrt{\frac{x(x+2i)}{x+2i-\alpha}}\right)e^{-xt}\,dx\right\}\right] \tag{5.2}$$

When $\alpha = 0$, (non-magnetic case) the integral in (5.2) can be evaluated closely and q is given as

$$q(z,t) = \frac{c}{2}\left[2 + e^{\sqrt{2i}\,z}\, efrc\left(\sqrt{2it} + \frac{z}{2\sqrt{t}}\right)\right.$$

$$\left. - e^{-\sqrt{2i}\,z}\, erfc\left(\sqrt{2it} - \frac{z}{2\sqrt{t}}\right)\right] \tag{5.3}$$

The steady solution corresponding to this case is $q = c$ which does not satisfy either the equations or the boundary conditions. But if we let $\alpha \to 0$ first and then $\sigma \to 0$ we get Thornley's results for which steady solution is $q = ce^{-\sqrt{2i}\,z}$. Such non-unique limits in the solutions arise as a consequence of the observation made earlier (§2), namely, that the simultaneous approach of σ and α to zero along any arbitrary direction does not give a unique limit for k_1 and k_2.

Case (ii): Similar situations arise in this case also. The steady solution for $\sigma = 0$ (with $\alpha \neq 0$) is

$$q = c(1 - z/d) \tag{5.4}$$

which satisfies the boundary conditions but not the equations where as the steady motion corresponding to $\sigma = 0$ in the non-magnetic problem is

$$q = \frac{\sinh[\sqrt{2i}(d-z)]}{\sinh(\sqrt{2i}\,d)}\,. \tag{5.5}$$

This solution satisfies the equations and the boundary conditions and hence should be taken as the correct solution. Hence we arrive at the conclusion that the different processes of taking limits would give different results when discontinuous functions are involved.

The solution (3·2) is a superposition of two waves with same frequency σ propagating in the opposite directions with different velocities and amplitudes. The amplitudes and wavelengths of these waves are $|a|\exp[-k_{1r}z]$, $|b|\exp[-k_{2r}z]$ and $\frac{2\pi}{k_{1i}}$, $\frac{2\pi}{k_{2i}}$ respectively. Here suffix r and i denote real and imaginary parts respectively. A simple computation shows that the thickness of penetration of vorticity, which is the maximum of the wave-lengths of these waves, is given by

$$d_0 = \frac{2\sqrt{2}\,\pi\sqrt{\sigma^2+\alpha^2}}{[\alpha(2-\sigma)(\sqrt{\sigma^2+\alpha^2}-\alpha)]^{\frac{1}{2}}} \text{ for } \sigma < 2 \tag{5.6}$$

$$d_0 = \frac{2\sqrt{2}\,\pi\sqrt{\sigma^2+\alpha^2}}{[\sigma(\sigma-2)(\alpha+\sqrt{\sigma^2+\alpha^2})]^{\frac{1}{2}}} \text{ for } \sigma > 2 \tag{5.7}$$

From this expression one can see that in the case $\sigma < 2$ the depth of penetration d_0 is increased due to the presence of magnatic field. In the case $\sigma > 2$, d_0 is decreased from that of the non-magnetic case for $\alpha < \sigma$.

ACKNOWLEDGEMENT

The author is highly grateful to Dr. Rathna Devanathan and Dr. A. R. Rao for the fruitful discussions and guidance throughout the preparation of this paper. He thanks C.S.I.R., Government of India, for the financial support.

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APPENDIX

The integral in (4·4) is evaluated by choosing the contour as given in Fig. 1 with branch cuts denoted by the thick lines.

By the Cauchy's residue theorem, we have

$$\frac{1}{2\pi i}\int_{\Gamma} \exp(st - mz)\left(\frac{a}{s - i\sigma} + \frac{b}{s + i\sigma}\right) ds$$

$$= \text{Sum of the residues at } s = \pm i\sigma$$

It can be easily seen that the integral along the bigger circle of radius R and along the smaller circles of radius ϵ tend to zero as $R \to \infty$ and $\epsilon \to 0$ respectively. By choosing the values of s properly on the branch cuts we get in the limit as $R \to \infty$ and $\epsilon \to 0$,

$$\int_{AB} + \int_{CD} = \frac{e^{-2it}}{\pi}\int_0^{\infty}\left(\frac{a}{x + i(2+\sigma)} + \frac{b}{x + i(2-\sigma)}\right) e^{-xt} \sin\left(z\sqrt{\frac{x(x+2i)}{x + 2i - a}}\right) dx \qquad \text{(A.2)}$$

and

$$\int_{IJ} + \int_{KL} = \frac{1}{\pi}\int_0^{a}\left(\frac{a}{x + i\sigma} + \frac{b}{x + i\sigma}\right) e^{-xt} \times \sin\left(z\sqrt{\frac{x(x-2i)}{x-a}}\right) dx \qquad \text{(A.3)}$$

The integrals along GH and MN cancel each other and the integral along EF tends to the required integral in (4·4) as $R \to \infty$. From (A.1), (A.2) and (A.3) the result (4.5) follows.

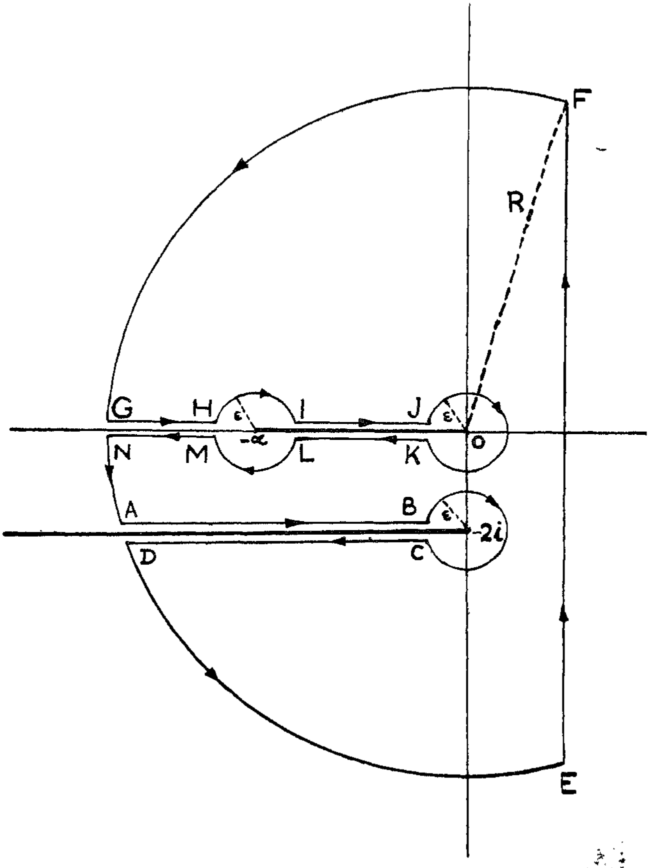

FIG. 1. Contour Γ.

Calendar of events: Conferences/Symposia at the Indian Institute of Science Campus

Sl. No.	Name of the School	Period	Sponsoring Department of the Institute
1.	Summer Institute in Molecular Structures	1–24 May 1975	Molecular Biophysics
2.	Indian National Science Academy	16–17 May 1975	Physics
3.	Intensive Course on High Voltage Technique	25 May to 8 June 1975	High Voltage Engineering
4.	Ferrous Foundry Technology	11–28 June 1975	Mechanical Engineering
5.	Molecular Biology of Bacteria and Bacterial Viruses	16 June to 12 July 1975	Microbiology and Pharmacol Laboratory
6.	Microwave and Millimeter Wave Communication	30 June to 12 July 1975	Electrical Communication Engineering
7.	All India Symposium on Biomedical Engineering	22–25 July 1975	Electrical Engineering
8.	Geo-physical Fluid Dynamic Workshop	7–20 July 1975	Centre for Theoretical Studie
9.	Organization of UNESCO Conference	1–15 September 1975	Mechanical Engineering
10.	Intensive Course on Fluid Engineering	20 October to 2 November 1975	School of Automation
11.	Lecture Course on Cavitation	Nov. to Dec. 1975	Chemical Engineering
12.	Crystal Chemistry for College Teachers	December 1975	Inorganic and Physical Chemistry

On the basis of the information received by the Editorial Office on 15th July 1975.

5307/75. Published by T. K. S. Iyengar, Executive Editor, Indian Institute of Science, Bangalore-560012 and Printed at the Bangalore Press, Bangalore-560018.