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Experiments on the Dynamic Response of a Flexible Strip to Moving Loads

Abstract: Experimental findings are reported on the dynamic response of a flexible strip to moving loads traveling at an oblique angle to its edges. The strip is wrapped under tension around a pair of supporting pressurized cylinder halves. The moving loads are applied to the flexible strip at the gap between the two cylinder halves. A capacitance displacement transducer measures the dynamic response of the strip, which is shown in isometric perspective for various boundary conditions. It is shown that waves on the strip created by the moving loads can be eliminated by providing a hydrodynamic air film support to the flexible strip in the vicinity of the moving loads. Experiments demonstrate that response to the loads along the edges of the strip differs from that near its center, which is to be expected because of the reflection of flexural waves from the boundaries of the strip.

Introduction

The general topic of moving loads on a beam, plate, or shell has gained considerable interest during the past decade. In the computer industry one specific interest has been the rotating-head, magnetic tape recording device. Here, the read/write heads become the moving loads against the magnetic tape, which is an open shell.

Elastohydrodynamic air films are used in magnetic recording to control the spacing between the head and the magnetic medium. This is important for consistency of signal and for minimizing wear on the head and the medium. Displacements of the medium, especially in front of a read/write transducer, can dominate the characteristics of the air film. Strip displacements due to moving loads, therefore, must be controlled if recording objectives are to be satisfied.

The work published so far has been entirely analytical. Kenney [1] analyzed the response of a moving load on a beam or an elastic foundation, including the effect of viscous damping. His study reveals that the character of the deflection profile depends strongly upon the speed ratio and the damping ratio. Without damping, the wavelength in front of the load and the wavelength behind the load are identical for subcritical speeds. For supercritical speeds the wavelength in front of the load is smaller than the wavelength behind it. When damping is introduced, different wavelengths in front of and behind the load are observed for all speed ratios. For a given speed ratio, the wavelength in front of the load is always smaller than that behind the load. Later, Reisman [2] analyzed the response of a moving load on an infinite plate strip and produced an identical set of results. Recently, Bogy et al. [3] analyzed the response of a moving load on a simply supported cylindrical shell. Again, they confirmed that at supercritical speeds the wavelengths in front of the load are shorter than those behind it.

Rather than establish an analytical model, this paper reports an experimental investigation on the dynamic response of a pair of moving loads on a flexible strip for several practical boundary constraints of that strip. Besides being experimental in nature, this study differs from published work in several areas. Kenney and others [1–3], for example, assume that the beam, plate, or shell is simply supported, while the strip in this study is supported by a pressurized air film. In addition, the present study involves a pair of moving loads rather than a single one, and they travel at an oblique angle rather than in the circumferential direction reported earlier [3].

Dynamic response characteristics at the edge of the strip are also investigated in this communication, and they show the effects of the reflection of flexural waves mentioned by Reisman [2]. The displacement phenomena are represented in isometric perspective.

Experimental configuration

The flexible strip used in our investigation is a coated mylar film 0.0038 cm thick and nearly 6.8 cm wide. This strip is wrapped in a helix around a pair of split cylinders, as shown in Fig. 1. One end of the strip is fixed and a uniform tension of 2.2 kg is applied to the other

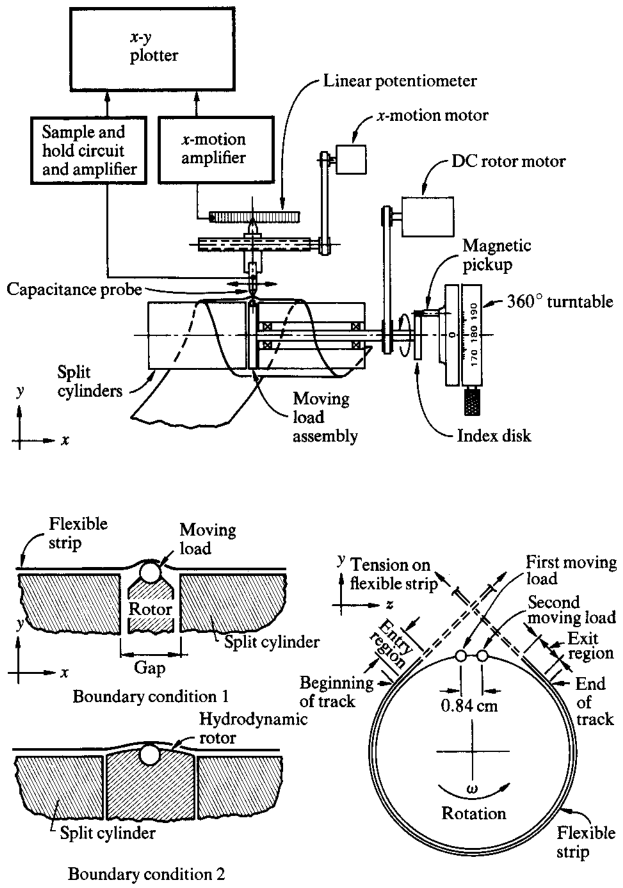


Figure 1 Basic configuration for flexible strip and moving load. Above, end view; below, side view.

Table 1 Effect of length of split cylinder gap on the number of distinguishable waves.

Gap (cm)	N_L	N_T
0.28	6	2
0.36	7	2
0.41	7	2
0.46	7	2
0.51	8	3
0.56	9	3

N_L and N_T, respectively, are the number of distinguishable waves in front of and behind the load.

end by means of a vacuum column. Orifices on the surfaces of the split cylinders generate an externally pressurized air bearing which floats the strip on the cylinders, thus avoiding large frictional forces due to the vast area of contact. To create the moving loads, two spherically shaped riders, spaced 0.85 cm apart and centered between the split cylinders, are displaced radially outward into the flexible strip and rotated about the axis of the cylinders with known angular velocity. The amount

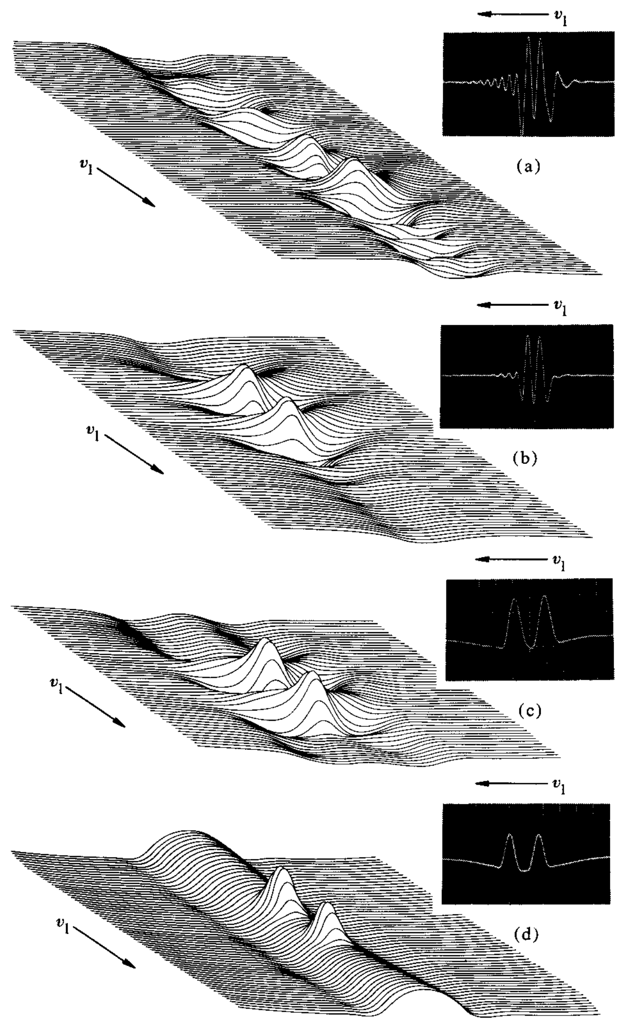


Figure 2 Flexible strip response to moving load for various strip restraint conditions. (a) Split cylinder, gap = 0.56 cm. (b) Split cylinder, gap = 0.28 cm. (c) Low-stiffness hydrodynamic rotor. (d) High-stiffness hydrodynamic rotor.

of radial displacement of the load into the strip is beyond the equilibrium position of the strip without the riders.

Dynamic response of the flexible strip in this configuration has been investigated for several boundary conditions around the moving loads. The gap distance between the pair of split cylinders was varied. Hydrodynamic platforms of different stiffness were provided around the moving loads. The pressure was varied to the externally pressurized air bearing on the split cylinder. Under these various restraints, the response of the strip to different velocities of the loads was also measured.

The instrumentation for this investigation utilizes a capacitive displacement transducer to detect the motion of the strip in the radial direction y.

The use of a mechanism to traverse the transducer parallel to the cylinder axis, a sample hold circuit, and a circumferentially adjustable index pulse provides a transducer output for isometric display on an x-y plotter. This permits three-dimensional visualization of the strip response for the various test conditions that no previously published work has shown.

Three display techniques show the response of the strip. In the oscilloscope trace in Fig. 2, the physical location of the displacement transducers is fixed, and its y-displacement output is displayed as a function of time. The time axis is proportional to the z axis in the same figure. The x, y, and z axes are of different scale.

An x-y plotter display is obtained by mounting the displacement transducer on a lead-screw slide and slowly scanning parallel to the axis of the split cylinder. The x-axis input to the plotter is from the output of a linear potentiometer on the lead-screw slide. To accomplish the y response of the strip at any position of the moving load in real time, two additional features in the instrumention are required. A thin strip of magnetic material is attached to the rotating shaft, so that a magnetic transducer can be used to generate an index pulse which is fixed with respect to the moving load. The index pulse is then used to trigger a sample-hold circuit to open up a 10 μs window to transmit the y-displacement output at a fixed circumferential location around the split cylinder.

The loft drawing in Fig. 4 is the result of multiple plots made by starting the lead-screw slide from a fixed position on each trace after incrementally changing the circumferential location of the index pulse. A magnetic sensor is mounted on a turntable which allows the timing between the index pulse and moving load to be constant, but the timing between the pulse and displacement transducer to be adjustable. Because there is no electronic delay, there is no loss in the z-axis accuracy due to the slight velocity variations in the moving load. A further extension is to display the multiple traces in an isometric manner to create a three-dimensional plot of the strip response, as shown in Fig. 2. This is accomplished by the same procedure as for the loft drawing except that the starting position of the pen on the x-y plotter is incremented a prescribed distance along the isometric axis z for each trace. Line crossings are eliminated to enhance clarity.

Discussion of results

The three-dimensional displays in Fig. 2 clearly show that the response of the flexible strip to moving loads is strongly dependent on the boundary conditions of the strip in the near vicinity of the load. These undulations, or waves, propagating forward and backward from the moving loads are of practical interest in several cases. If the moving load is generated by a defect or contaminant in a rotor, it could affect the stability of a rotor employing a foil bearing support [4]. If the moving load is a magnetic transducer, as in a helical scan video recording

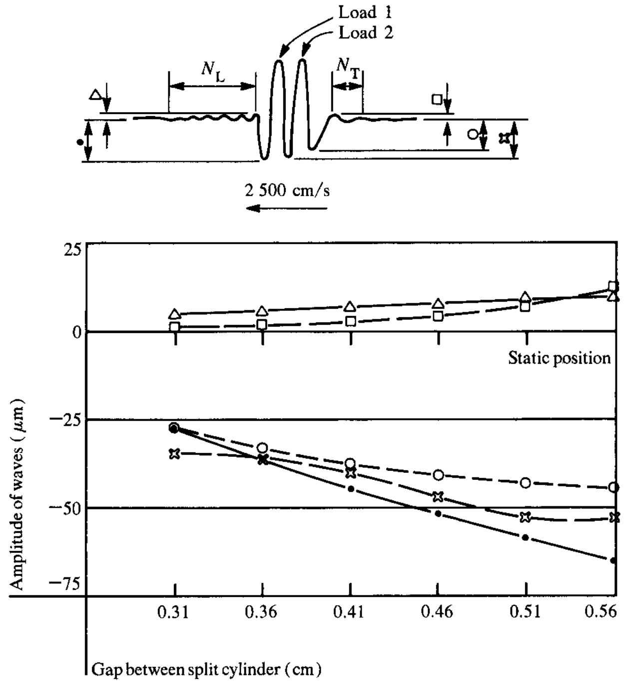
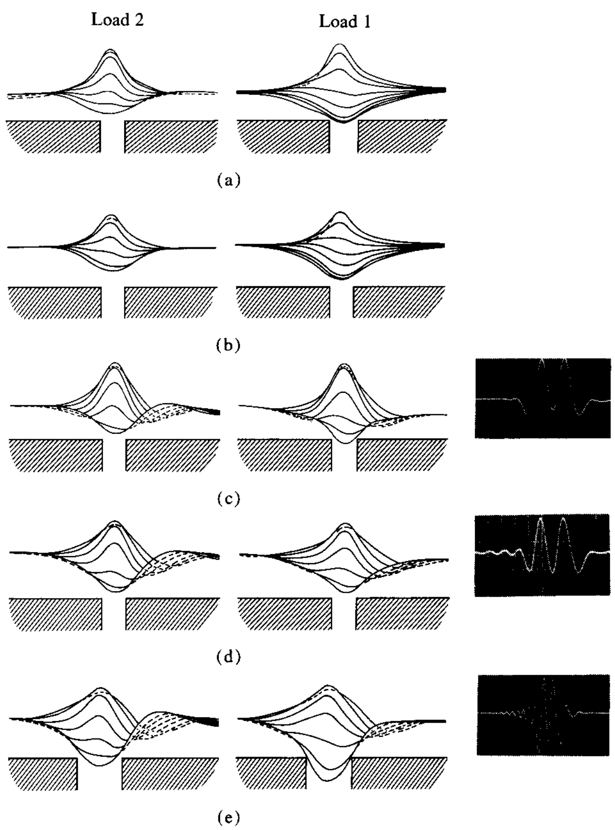


Figure 3 Variation of wave amplitude at various split-cylinder gaps. (See Table 1.)

Figure 4 Position of flexible strip with respect to split cylinder. (a) Gap = 0.28 cm; static, low-pressure in split cylinder. (b) Gap = 0.28 cm; static, high-pressure. (c) Gap = 0.28 cm; 2500 cm/s, low pressure. (d) Gap = 0.28 cm; 2500 cm/s, high pressure. (e) Gap = 0.56 cm; 2500 cm/s, high pressure.



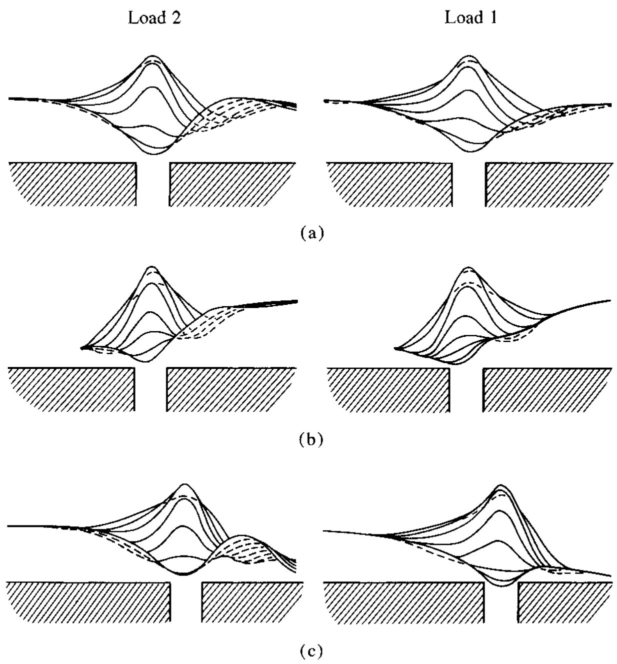
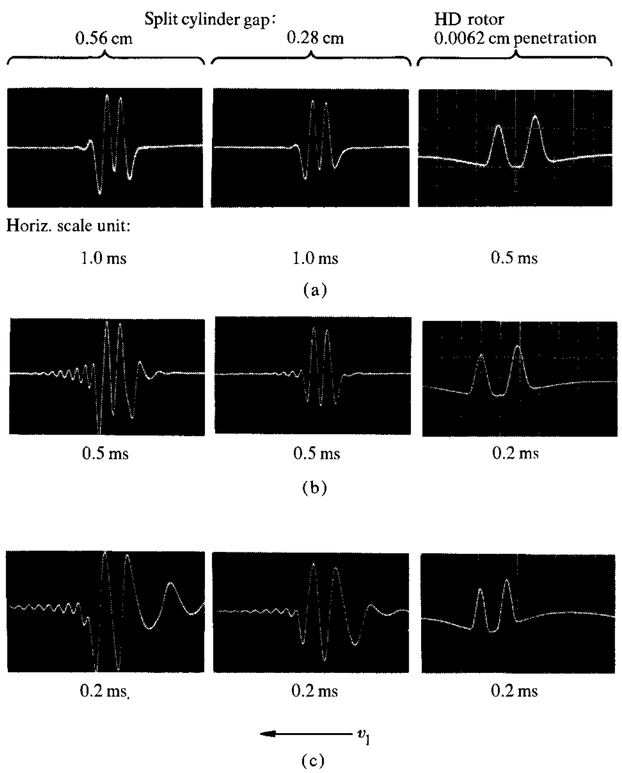


Figure 5 Position of flexible strip along edges with respect to split cylinder. Gap = 0.28 cm. Load velocity = 2500 cm/s. (a) Center of track on strip. (b) Track location at entry. (c) Track location at exit.

Figure 6 Response of flexible strip vs moving load velocity. Load velocities: (a) 1250 cm/s; (b) 2500 cm/s; (c) 3750 cm/s. Vertical scale: 25.4 μm/main division.



device, the strip displacement in front of the transducer would affect the elastohydrodynamic film characteristics between transducer and magnetic medium.

The strip response to changing gap distance between the supporting cylinders is emphasized by the isometric representation in Figs. 2(a) and 2(b). Figure 3 shows the effect of gap distance on the amplitude and frequency of waves. Table 1 indicates the effect of gap length on the number of waves.

As the gap increases, the amplitude of the waves and propagation distance from the load increases. The wavelength of the leading waves appears unaffected by gap separation; however, that for the trailing waves increases with increased gap distance. As the separation between the flexible strip and the cylinder is reduced by lowering the external pressure to the cylinder bearings, the waves become less severe. This change is attributed to a significant change in the restraint conditions for the flexible strip as the waves now appear to contact the split cylinder, which in turn inhibits their propagation (Fig. 4).

Figure 5 is included to show that the displacements in front of the moving loads vary as a function of the position of the moving loads with respect to the edges of the strip. Within 1.4 cm of the entrance and exit points of the strip, the response to the moving loads is distinctly different from that for the remainder of the strip, illustrated in Fig. 5. In these regions the severity of the waves increases and their direction of propagation deviates from the norm. In addition to the fact that strip restraint conditions are obviously different in these regions, the theory has been proposed that the response of plates to traveling loads is complicated by the reflection of flexure waves from the boundaries of the plates.

The strip response to boundary condition 2 (Fig. 1) is shown in Figs. 2(c) and 2(d). With a low stiffness (low-penetration hydrodynamic rotor and moving load velocity less than 2500 cm/s), waves propagating in the direction of the moving load are eliminated and those propagating along the axis of the split cylinder are reduced when compared to the results obtained with boundary condition 1. With a high stiffness (i.e., high-penetration hydrodynamic rotor), all waves, both those traveling in the direction of the moving load and those propagating axially, are eliminated for load velocities less than 3800 cm/s. The increase in stiffness on the hydrodynamic rotor because of higher penetration is based on the nonlinear stiffness characteristics of the hydrodynamic air film.

Wave elimination is believed to be achieved through three mechanisms:

1. The previously unsupported region of the tape in the gap between the split cylinders is now supported and is

under greater tension because of the penetration of the rotor which will in turn increase the critical velocity.

2. A significant elastic foundation reaction modulus for the strip in the near region of the moving load is now present because of the hydrodynamic film between the rotor and strip, thereby further increasing the critical velocity of the system [1].
3. The existence of the hydrodynamic film permits damping via a squeeze film effect.

The existence of the self-generated hydrodynamic film between the flexible strip and the rotor was measured by recording the static displacement of the strip along the axis of the cylinder and comparing it to the same trace with the rotor at velocity. Its existence is explainable by flexible foil bearing theory [4, 5]. The measurements show that the spacing varies both in the transverse and circumferential directions and is smaller than that predicted from theory. This discrepancy is believed to be due to two deviations. The first is the two-dimensional effect, i.e., side flow; the rotor is of finite width and the theory assumes a wide foil with no side flow. The second deviation is the displacement normal force and tension variation effect that is the result of the rotor radial penetration beyond the radial equilibrium value of the strip around the split cylinder.

The velocity of the moving load was varied for the several different support conditions of the flexible strip. The results are shown in Fig. 6. As the moving load velocity increases, the number and amplitude of the waves increase and the wavelengths of the leading and trailing waves decrease and increase, respectively, for boundary condition 1. The phenomenon is more pronounced in the split cylinders with a wide gap than in those with a narrow gap. With the high-penetration hydrodynamic rotor, no wave was observed up to 3800 cm/s.

Concluding remarks

The technique used for the isometric study of the dynamic response of moving loads on flexible strips has revealed many interesting characteristics.

Results obtained in Figs. 3 and 6 support the findings of Kenney [1], Reisman [2], and Bogy et al. [3], i.e., the character of the deflection profile depends strongly on the speed ratio. In the velocity range investigated (1250 to 3800 cm/s), the results shown in Fig. 6 confirm that different wavelengths occur in front of and behind the load, as if damping exists. For a given speed ratio the wavelength in front of the load is always smaller than the wavelength behind the load. This difference is demonstrated in Fig. 6 to increase substantially with an increase in the speed ratio. Also, our testing shows that the pressure profile at the interface between the load and the flexible strip due to the formation of a hydrodynamic air bearing does not influence the deflection profile characteristics of the flexible strip.

As for differences, Reisman [2] observed that the deflection amplification is greater behind the load than in front of the load in the case of supercritical speed. Figure 3 in our study shows the opposite trend. That is, the wave amplitude in front of the load is higher than the wave amplitude behind the load. Kenney, Reisman, and Bogy et al. also showed that the deflection under the load is zero in the supercritical speed region. In our study the deflection under the load is always maximum. The two significant differences between the analytical models and our experimental models should be noted. We have two moving loads instead of one; moreover, the moving loads in our experiment are constant displacements, while the analytical models assume constant forces.

Greater insight has been developed for those design parameters that affect the magnetic transducer in helical-scan recording devices. The importance of boundary conditions has been clearly demonstrated. The response of the strip to increasing velocity of the load at those boundary conditions has been measured. Because the moving load travels at an oblique angle, the resulting waves are asymmetrical, and the effects of the reflection of flexural waves from the boundaries of the strip are also shown. If the strip must be unsupported in the region of the moving load the separation between cylinders should be minimized to control the dynamic response of the strip. It is significant that waves created by the moving loads can be eliminated by providing a hydrodynamic air film to the flexible strip in the vicinity of the moving loads.

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Received August 12, 1976; revised December 7, 1976

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