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Interaction of an axially moving band and surrounding fluid by boundary layer theory

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Abstract

The vibration characteristics of a submerged axially moving band are investigated. Where earlier studies used the ideal fluid assumption for modelling the effect of the surrounding air, the viscous flow of the air particles is included here by using an analytical model of a boundary layer on moving continuous flat surfaces. In order to use this theory to calculate boundary layer thicknesses, the shape of the boundary layer was assumed, so that the additional mass terms coming from the boundary layer flow could then be evaluated. Since the coefficients of the equation of motion for the submerged axially moving band changes as a function of the longitudinal coordinate, due to the change in the boundary layer, the equation is solved by the finite element method. The results show the difference between the present results and earlier ones to be significant, close to the critical velocity.
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Keywords: Axially moving material; Boundary layer; Momentum thickness; Displacement thickness; Structural dynamics; Fluid structure interaction

1. Introduction

There is a large class of industrial processes which involve the transport of bands and webs across spans. From the point of view of mechanics, the translating structural members must have special characteristics with regard to vibration and dynamic stability. The topic of axially moving material has been studied widely, and recent developments in research are reviewed by Chen (2005), Païdoussis and Li (1993), Wickert and Mote (1988) and Païdoussis (2004).

In paper making, for instance, the process often includes high-speed operations in which a thin, light web interacts strongly with the surrounding air flow, causing out-of-plane vibrations, or flutter. Theoretical and experimental results show that the effect of the surrounding air on the dynamic behaviour of a paper web is significant. According to the experimental results of Pramila (1986) the critical velocities and natural frequencies are only 15–30% of the values given by predictions that neglect the interaction between the paper sheet and the surrounding air.

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†*Note from the Editor*. Very sadly, this is a posthumous publication for Professor Antti Pramila. Readers can find a biographical sketch at the end of this paper.

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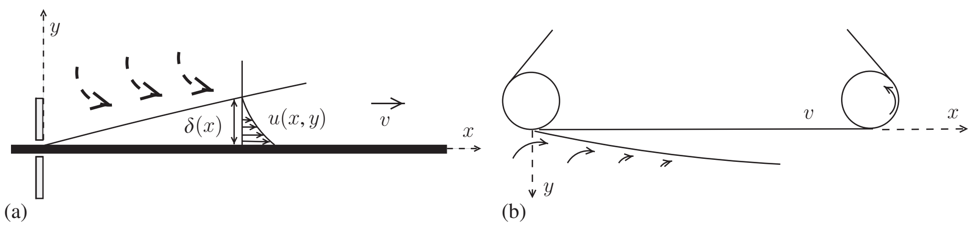


Fig. 1. Boundary layer behaviour on a moving continuous flat surface: (a) Sakiadis (1961b); (b) Arzate and Tanguy (2004).

The first analyses of the flutter of a moving web were performed by Pramila (1987) using analytical ‘‘travelling thread line’’ models that neglected the cross-direction variation in web motion by assuming that the entire web width deflects uniformly. The motion of the surrounding air was taken into account in the form of an ideal fluid by means of two models for added mass. In the first the added mass was incorporated in all three inertia terms of the axially moving string, assuming that the surrounding air field moves with the web, while in the second the added mass was included only in the inertia of transverse motion, assuming that the air particles move only in a plane perpendicular to the translation direction of the web.

The ‘‘threadline model’’ with surrounding potential flow was used again by Chang et al. (1991) to study the out-of-plane flutter of a moving web. They showed that each of the dynamic terms in the governing equation—namely the transverse inertia force, the Coriolis force and the centrifugal force—is affected differently by the air, depending on the air flow, and suggested that the inertia terms in the Coriolis and centrifugal forces are correspondingly dependent on the displacement thickness and momentum thickness of the boundary layer of the air flow dragged along with the web. Chang et al. (1991), however, noted that the boundary-layer thickness needed here cannot be predicted by flat-plate formulae, because the moving web does not have a leading edge.

The boundary layer flow on a moving web can be explained by analogy with the boundary layer on moving continuous flat surfaces as shown by Sakiadis (1961a,b) and Arzate and Tanguy (2004). Sakiadis (1961a,b) presents equations for the thicknesses of both a laminar and a turbulent boundary layer on a moving continuous flat surface. He considered the model of a long continuous sheet which issues from a slot and is taken up by a wind-up roll (Fig. 1(a)). Indeed, his results regarding boundary layer behaviour on moving continuous flat surfaces (Sakiadis, 1961b) do indeed show this to be significantly different from that observed with a moving flat plate of finite length.

Arzate and Tanguy (2004), investigating the air boundary layer behaviour at the surface of a moving web with experimental measurements made on the web loop system of a jet coating rig, as shown in a schemantic figure (Fig. 1(b)), and comparing their measurements with the theoretical values predicted by the Blasius (1908), Rayleigh (1911) and Sakiadis (1961b) solutions, showed the Blasius solution to be more appropriate for this flow configuration, while the Sakiadis (1961b) solution could be better applied to a two roll nip in which the web moves between the rolls, limiting the origin of the boundary layer.

The aim of this study was to improve the accuracy of earlier analytical results by considering the interaction between the moving band and the surrounding air in terms of boundary layer theory. The viscous flow of air particles is included by using an analytical model for boundary layers on moving continuous flat surfaces. In order to use this theory and calculate the boundary layer thicknesses, the shape of the boundary layer was assumed on the basis of numerical results, whereupon the added mass terms coming from the boundary layer flow could be evaluated. Since the boundary layer changes along the band, there is no analytical solution for the equation of motion, and the problem is solved by the finite element method (FEM).

2. Theoretical model

The band and the boundary layer of the surrounding fluid are modelled as a layered system, as shown in Fig. 2. The transverse displacement w is assumed be so small that it does not disturb the flow in the boundary layer, and therefore all the layers have identical transverse displacements. A direct consequence of this assumption is that the flow velocity u is also a function of the transverse coordinate y if the flow is viscous and the band is translating with a constant axial velocity $u(x, 0) = v$.

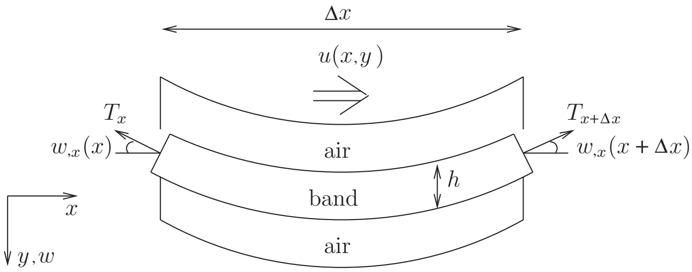


Fig. 2. Differential part of the system.

2.1. Equation of motion

Considering the equilibrium of a differential element and assuming constant tension T, the equation of motion for the "layered" system becomes

$$\int_{-\infty}^{\infty}[b\rho(y)(w_{,tt}+2u(y)w_{,xt}+u^2(y)w_{,xx})-T(y)w_{,xx}]\,\mathrm{d}y=0, \tag{1}$$

where b is the width of the band and ρ is the density of the system. The density ρ, the flow velocity u and the tension T are all piecewise continuous functions of the transverse coordinate y, and can be written

$$\rho(y)=\begin{cases}\rho_s, & -\frac{h}{2}\leqslant x\leqslant\frac{h}{2},\\ \rho_f & \text{otherwise;}\end{cases}\quad u(y)=\begin{cases}v, & -\frac{h}{2}\leqslant x\leqslant\frac{h}{2},\\ u_f(y) & \text{otherwise;}\end{cases}$$

$$T(y)=\begin{cases}\frac{P}{h}, & -\frac{h}{2}\leqslant x\leqslant\frac{h}{2},\\ 0 & \text{otherwise;}\end{cases} \tag{2}$$

where h is the thickness of the band, ρ_s is the density of the solid material, ρ_f is the density of fluid, v is the constant axial velocity of the band, u_f is the flow velocity of the fluid, and P is the constant tension of the band.

By separating the lower and the upper boundary layers from the solid by dividing the integrals, and by taking note of Eqs. (2), we obtain the equation of motion (Frondelius and Pramila, 2003)

$$\begin{aligned}&b\left(\int_{-h/2}^{h/2}\rho_s\,\mathrm{d}y+\int_{-\infty}^{-h/2}\rho_f\,\mathrm{d}y+\int_{h/2}^{\infty}\rho_f\,\mathrm{d}y\right)w_{,tt}\\ &\quad+2b\left(\int_{-h/2}^{h/2}\rho_s\,\mathrm{d}y+\int_{-\infty}^{-h/2}\rho_f\frac{u_f(y)}{v}\,\mathrm{d}y+\int_{h/2}^{\infty}\rho_f\frac{u_f(y)}{v}\,\mathrm{d}y\right)vw_{,xt}\\ &\quad+b\left(\int_{-h/2}^{h/2}\rho_s\,\mathrm{d}y+\int_{-\infty}^{-h/2}\rho_f\frac{u_f^2(y)}{v^2}\,\mathrm{d}y+\int_{h/2}^{\infty}\rho_f\frac{u_f^2(y)}{v^2}\,\mathrm{d}y\right)v^2w_{,xx}-\int_{-h/2}^{h/2}\mathrm{d}y\frac{P}{h}w_{,xx}=0.\end{aligned} \tag{3}$$

If we assume that the density of the solid material is constant over the band, the first inertia term of each inertial force, the mass per unit length of the band, can be written as

$$m=\rho_s bh. \tag{4}$$

The other three components of each term are due to the inertia of the fluid and its motion, as explained by Chang et al. (1991). The added mass per unit length in the first force term is due to the transverse inertia of the fluid

$$m_a=b\int_{-\infty}^{-h/2}\rho_f\,\mathrm{d}y+b\int_{h/2}^{\infty}\rho_f\,\mathrm{d}y. \tag{5}$$

In the second term the inertia is due to the gyroscopic effect of the fluid flow, which depends on the displacement thicknesses of the boundary layer δ_l^* and δ_u^*, representing the lower and upper sides of the band, respectively,

$$m_{aG} = \frac{b\rho_f}{v}\int_{-\infty}^{-h/2} u_f(y)\,\mathrm{d}y + \frac{b\rho_f}{v}\int_{h/2}^{\infty} u_f(y)\,\mathrm{d}y = b\rho_f(\delta_l^* + \delta_u^*); \tag{6}$$

and in the last term it is due to the centrifugal effect of the fluid flow, which depends on the momentum thicknesses of the boundary layer θ_l and θ_u,

$$m_{aK} = \frac{b\rho_f}{v^2}\int_{-\infty}^{-h/2} u_f^2(y)\,\mathrm{d}y + \frac{b\rho_f}{v^2}\int_{h/2}^{\infty} u_f^2(y)\,\mathrm{d}y = b\rho_f(\theta_l + \theta_u). \tag{7}$$

Using Eqs. (4)–(7), the equation of motion can be rewritten in the form

$$(m + m_a)w_{,tt} + 2(m + m_{aG})vw_{,xt} + (m + m_{aK})v^2 w_{,xx} - Pw_{,xx} = 0, \tag{8}$$

where the first term is the traditional inertia term, the second is known as the gyroscopic inertia term and the third represents the centrifugal term. The boundary conditions for fixed ends are

$$w(0, t) = w(l, t) = 0, \tag{9}$$

where l is a free length of the band.

2.2. Added masses and boundary layer theory

Only two of the three inertia terms for the surrounding air depend on the boundary layer flow of the fluid, namely m_{aG} and m_{aK}, as the first, the transverse inertia term m_a, should be proportional to the transverse movement of the surrounding air. According to Pramila (1986), it can be written as

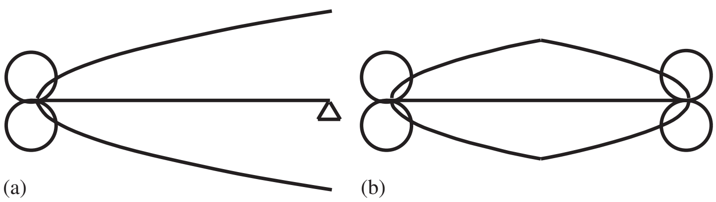
$$m_a = \beta\rho_f lb, \tag{10}$$

where β is constant, depending on the geometry of the band.

The model considered in this work is a two-roll nip, in which the web moves between the rolls with a constant axial velocity v, as shown in Fig. 3(a). The boundary layer flow grows partly due to the air flow through the nip and partly due to the sucking in of ambient air. If we neglect the flow disturbances created by the rolls and assume that a certain time has elapsed after the initiation of motion, such that steady-state conditions prevail, the model is very similar to that examined by Sakiadis (1961a), who considered a long, continuous sheet which issues from a slot and is taken up by wind-up roll, as shown in Fig. 1(a).

Sakiadis (1961a, 1961b) showed that, although the governing equations for the boundary layer of a laminar, steady, incompressible flow are the same for a moving continuous flat surface and a moving finite length surface, the boundary conditions are different. Therefore, the solutions to these two cases and the boundary layer thicknesses are different. The displacement thickness, which determines the pumping action of the moving continuous surface, is in this case according to Sakiadis (1961b),

$$\delta^* = \frac{1}{v}\int_0^{\infty} u_f\,\mathrm{d}y = 1.62\sqrt{\frac{\nu x}{v}}, \tag{11}$$



(a) (b)

Fig. 3. Schematic shape of the boundary layers: (a) increasing; (b) symmetric.

while the momentum thickness, which determines the drag on the moving continuous surface, is

$$\theta = \frac{1}{v^2}\int_0^\infty u_f^2\,\mathrm{d}y = 0.887\sqrt{\frac{\nu x}{v}}, \tag{12}$$

where ν is the kinematic viscosity of the fluid.

Sakiadis (1961b) determined the boundary layer thicknesses for turbulent flow by using empirical relations for the velocity profile in the boundary layer. The displacement thickness is (Sakiadis, 1961b)

$$\delta^* = 1.01x\left(\frac{vx}{\nu}\right)^{-1/5}, \tag{13}$$

and the momentum thickness is

$$\theta = \frac{1}{v^2}\int_0^\infty u_f^2\,\mathrm{d}y = \int_0^1 [1-\hat{\eta}^{1/7}]^2\delta\,\mathrm{d}\hat{\eta} = \frac{1}{36}\delta^*. \tag{14}$$

2.3. Shape of the boundary layer

According to Sakiadis (1961a), the essential physical characteristic of a boundary layer on a continuous surface is that the origin and termination of the boundary layer around such a surface are identified by the boundaries of the system. In Sakiadis' model these boundaries are the slot at the origin and the wind-up roll at the termination point.

The system shown here in Fig. 3(b) is slightly different, because we have a web moving over a span between two roll nips. The origin of the boundary layer is almost the same, however, if the flow disturbances created by the rolls are neglected. The other end differs because of an extra roll, and this should somehow be taken into account at the termination of the boundary layer. For a short span, the shape of the boundary layer shown in Fig. 3(b) is good approximation of the results of Karasek (2003), who analysed the dynamics of a web moving over a span between two roll nips with a fluid-structure interaction finite element model; he showed the thickness of the boundary layer to decrease towards the downstream end, as in Fig. 3(b).

3. FEM model

The discrete equations of motion are derived in the same way as in Niemi and Pramila (1987), Laukkanen (2002), Lumijärvi (2006), and can be written as

$$\mathbf{M}\ddot{\mathbf{w}} + \mathbf{G}\dot{\mathbf{w}} + \mathbf{K}\mathbf{w} = \mathbf{0}, \tag{15}$$

using the trial expression

$$w(x) = \mathbf{N}\mathbf{w}. \tag{16}$$

The mass matrix is

$$\mathbf{M} = \int_0^l (m + m_a)\mathbf{N}^{\mathrm{T}}\mathbf{N}\,\mathrm{d}x, \tag{17}$$

the skew symmetric gyroscopic inertia matrix is

$$\mathbf{G} = \int_0^l (m + m_{aG}(x))v[\mathbf{N}^{\mathrm{T}}\mathbf{N}_{,x} - \mathbf{N}_{,x}^{\mathrm{T}}\mathbf{N}]\,\mathrm{d}x, \tag{18}$$

and the stiffness matrix is

$$\mathbf{K} = \int_0^l [P - (m + m_{aK}(x))v^2]\mathbf{N}_{,x}^{\mathrm{T}}\mathbf{N}_{,x}\,\mathrm{d}x. \tag{19}$$

Linear shape functions of an element of length l_e,

$$\mathbf{N} = \left[1 - \frac{x}{l_e}\;\; \frac{x}{l_e}\right], \tag{20}$$

are used at the element level. The added masses as a function of the coordinate x are approximated in a similar manner, i.e.

$$m_{aG}(x) = \mathbf{N}\left[m_{aG_1} \ \ m_{aG_2}\right]^{\mathrm{T}}, \quad m_{aK}(x) = \mathbf{N}\left[m_{aK_1} \ \ m_{aK_2}\right]^{\mathrm{T}}. \tag{21}$$

The nodal values m_{aG_i} and m_{aK_i} are calculated from analytical boundary layer theory Eqs. (11) and (12), respectively, for laminar flow and from (13) and (14), for turbulent flow.

The eigenvalue problem is obtained by substituting a trial function $\mathbf{w} = \mathbf{X}e^{\lambda t}$ in the equation of motion (15), as is done by Meirovitch (1980),

$$(\mathbf{K} + \lambda\mathbf{G} + \lambda^2\mathbf{M})\mathbf{X} = 0, \tag{22}$$

where λ is an eigenvalue and $\mathbf{X}$ is the corresponding eigenvector. Thus, the natural angular frequency and the eigenfrequency are

$$\omega = \sqrt{\operatorname{Im}\lambda}, \quad f = \frac{\omega}{2\pi}. \tag{23}$$

4. Results

Numerical examples are included here to compare the present results with the earlier analytical and experimental ones, to illustrate the analysis, and to demonstrate the effect of the surrounding fluid flow.

First we compare the results of the current model with the experimental measurements of Pramila (1986) and the results of the earlier ideal fluid idealization of Pramila (1987) shown in Fig. 4. Pramila (1986) measured the fundamental frequencies of a narrow paper web using a pilot coater with a web of length 2.4 m, width 0.47 m, weight per unit length 17 g/m and constant β 0.3275.

The dashed and chain-dotted lines represent the analytical solutions of Pramila (1987). In the first equation (chain-dotted, line), the added mass due to the transverse inertia is incorporated into all three inertia terms of the axially moving string, assuming that the surrounding air field moves with the web motion. In the second (dashed line), the added mass is included only in the inertia of the transverse motion, assuming that the air particles move only in a plane perpendicular to the direction of translation of the web.

The results of the current model are calculated on the assumption that the boundary layer flow is turbulent and the shape of the boundary layer conforms to the increasing pattern shown in Fig. 3(a). The number of elements is chosen to be 60. For the sake of clarity, the results are shown in nondimensional form in terms of frequency, axial velocity and

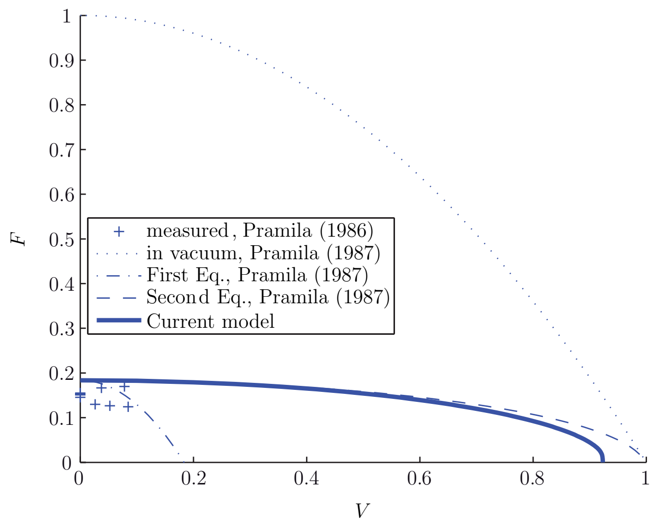


Fig. 4. Dimensionless lowest eigenfrequencies F as a function of dimensionless velocity V.

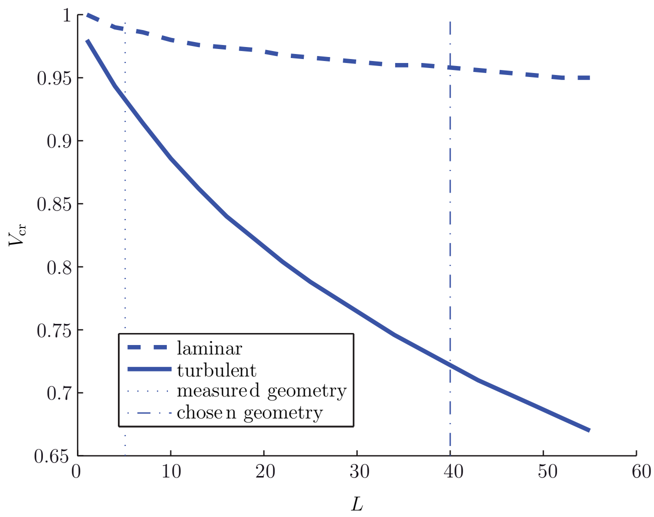


Fig. 5. Dimensionless critical speed V_{cr} as a function of dimensionless length L.

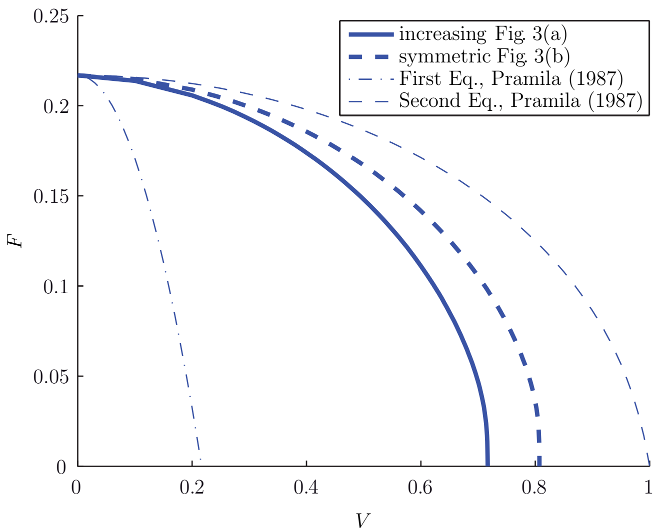


Fig. 6. Dimensionless lowest eigenfrequencies F as a function of dimensionless velocity V for chosen geometry.

length, are defined as follows:

$$F = f \cdot 2l\sqrt{\frac{m}{P}}, \quad V = v\sqrt{\frac{m}{P}}, \quad L = \frac{l}{b}. \tag{24}$$

The same nondimensional presentation is used for all the following analyses.

The ideal fluid analyses presented by Pramila (1987) form the upper and lower approximations for the boundary layer model, and the current results should be between these two. The effect of the boundary layer flow for the lowest eigenfrequency grows as the axial velocity increases and the maximum is reached at the critical velocity. The effects at lower velocities are quite small, because the practical example used has quite a short span, and therefore the boundary layers do not become very thick at low axial velocities. The effect of viscous flow is more significant with longer spans, as can be seen in Fig. 5, where the critical velocity is presented as a function of the span length for both turbulent and laminar flows. It can also be seen in the same figure that the turbulent flow has a significantly larger influence on dynamic behaviour than does the laminar flow.

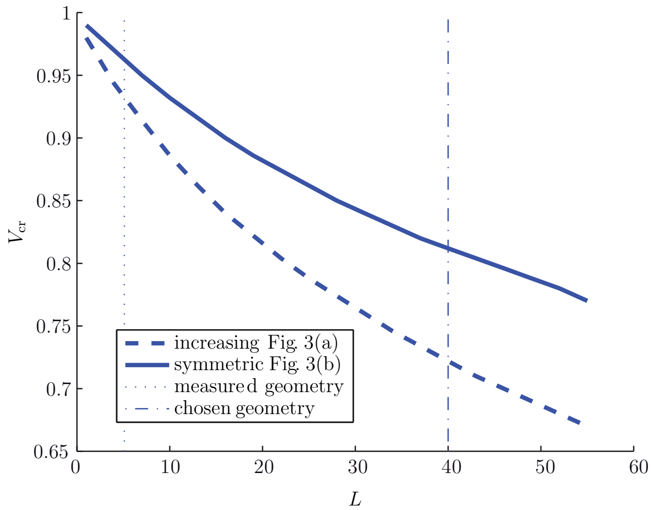


Fig. 7. Dimensionless critical speed V_{cr} as a function of dimensionless length L for both different shapes from Fig. 3.

The above results are calculated on the assumption that the boundary layer is of the increasing shape, as used by Sakiadis (1961a). In Figs. 6 and 7, however, the results are also calculated using the shape proposed in the current work, as shown in Fig. 3(b) for a moving band of length 18.8 m, width 0.47 m, mass per unit length 17 g/m and constant β 0.0296. Fig. 6 presents the lowest eigenfrequency as a function of axial velocity, and Fig. 7 the critical velocity as a function of the nondimensional span length. The results suggest that the influence of the shape depends on the axial velocity of the web and the length of the span, and that the shape is obviously significant at high axial velocities and large span lengths.

5. Concluding remarks

The vibration characteristics of a submerged axially moving band were investigated by means of analytical boundary layer theory in order to include the viscous effect of the surrounding fluid flow. The shape of the boundary layer was assumed according to the numerical results, and the boundary layer thicknesses were calculated according to the model presented by Sakiadis (1961b) for the boundary layer on moving continuous flat surfaces. The inertia of the flow was then included in the equation of motion for an axially moving web in the form of added mass terms. Because of boundary layer changes along the band, the eigenvalue problem was solved by the finite element method.

The greatest influence exerted by the surrounding flow on the dynamics of the axially moving web comes from the first term, the transverse inertia m_a, which is proportional to the transverse movement of the surrounding air. The drop in the lowest eigenfrequency can be about 80%, as shown in earlier studies. The viscous boundary layer flow has a considerably smaller effect, particularly at low axial velocity. Its influence grows as the axial velocity increases, however, and the drop in the critical speed of the system can be significant due to turbulent flow if the span length of the system is high. It should also be noted, that the influence of the laminar flow is considerably smaller. The shape of the boundary layer also has some influence on the natural vibration of the band, particularly at high axial velocities. The proposed shape for the boundary layer in the system considered here gives changes in the critical velocity that are one third smaller than that proposed by Sakiadis.

Acknowledgements

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In memoriam of Professor Antti Pramila

Antti Pramila, a prominent and much-honoured member of the Finnish engineering mechanics community and professor at the Department of Mechanical Engineering, University of Oulu, passed away suddenly on December 20, 2005, at the age of 54.

Antti became a student at Helsinki University of Technology in 1970, enrolling in the Faculty of Mechanical Engineering. He graduated with distinction in Naval Architecture (the Ship Laboratory) in 1975, and received his doctorate from the same university five years later, in 1980. He immediately accepted the position of assistant professor at the Department of Mechanical Engineering, University of Oulu. In 1984 he was appointed professor in the Department of Mechanical Engineering at Tampere University of Technology and a year later he was elected head of the Institute of Engineering Mechanics. He was invited to the professorship in the Department of Mechanical Engineering at the University of Oulu in 1988 and served as head of that department from 1993 to 1999 and as vice-dean of the Faculty of Technology from 1994 to 1997.

Antti's research, for which he was renowned, was concerned with of vibrations in axially moving materials, composite mechanics and the design and optimization of ship hull forms. His publication list encompasses more than 140 articles, and he contributed to many edited volumes.

Professor Antti Pramila was also an excellent teacher and mentor. He taught courses in mechanics and supervised numerous doctoral dissertations. Most of his doctoral students continued their research work with him. He also participated in many international conferences over the years and chaired various sessions in these. He was especially closely involved in initiating and building up close relations between Nordic, Baltic and Finno-Ugric researchers in engineering mechanics.

The Editor of JFS, on behalf of the whole of the FSI and Mechanics communities, expresses his deep sorrow for the untimely passing of this prominent member of both these communities; he will be missed.

Some of the most important representative papers by Professor Pramila

Pramila, A. 1998. Coupling term makes temperature fields unsymmetric in laminated composite plates. Computers & Structures 66(5), 509–512.

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