The First Eigenvalue Estimates of Warped Product Pseudo-Slant Submanifolds

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Abstract: The aim of this paper is to construct a sharp general inequality for warped product pseudo-slant submanifold of the type $M = M_\perp \times_f M_\theta$, in a nearly cosymplectic manifold, in terms of the warping function and the symmetric bilinear form $h$ which is known as the second fundamental form. The equality cases are also discussed. As its application, we establish a bound for the first non-zero eigenvalue of the warping function whose base manifold is compact.

Keywords: nearly cosymplectic manifold; warped products; pseudo-slant; inequality; eigenvalue

1. Introduction

The clue of warped product manifolds is related to the generalization of Riemannian products. The role of warped product submanifolds in studying Riemannian geometry was studied actively from the pioneering work of Chen [1]. The work of Chen is about the characterization of CR-warped products in Kaehler manifolds, and derives the inequality for the second fundamental form. In fact, distinct classes of warped product submanifolds of the different kinds of structures were studied by several geometers (see [1–14]). Recently, Ali et al. [15], established general inequalities for warped product pseudo-slant isometrically immersed in nearly Kenmotsu manifolds for mixed, totally geodesic submanifolds. Moreover, some results on the existence of the warped product pseudo-slant submanifolds in a nearly cosymplectic manifold in terms of endomorphisms were proved by Uddin in [14]. We have noticed that the warped product pseudo-slant submanifolds of the form $M_\perp \times_f M_\theta$, and $M_\theta \times_f M_\perp$, is a CR-warped product submanifold with slant angle $\theta = 0$. For contradict that warped product pseudo-slant submanifolds always not generalize CR-warped product submanifold which was show in [13]. However, some interesting inequalities have been obtained by many geometers (see [4,10,12,16–20]) for distinct warped product submanifolds in the different types of ambient manifolds. In [5], Al-Solamy derived the inequality for mixed, totally geodesic warped product pseudo-slant submanifolds of type $M = M_\theta \times_f M_\perp$, in a nearly cosymplectic manifold. On other hand, the warped product pseudo-slant submanifold in a nearly cosymplectic manifold of the type $M = M_\perp \times_f M_\theta$ was studied by Uddin et al. [14]. We consider the non-trivial warped product pseudo-slant submanifold $M = M_\perp \times_f M_\theta$, such that $M_\theta$ and $M_\perp$ are proper-slant and anti-invariant submanifolds, respectively. In this case, considering that $M$ is not mixed and totally geodesic, we announce our first result as follows.

Theorem 1. Assuming $\tilde{M}$ is a nearly cosymplectic manifold, let $M = M_\perp \times_f M_\theta$ be a warped product pseudo-slant submanifold of $\tilde{M}$. Then,
Theorem 2. Assuming provided that $\text{Ric}$ is the shape operator, respectively, for the submanifold of $M$, and $\Gamma$ is the Riemannian connection of $M$ and $\Gamma$. Let the Lie algebras of vector fields tangent and normal to a submanifold $M$. Then, we have:

\[ h(D^\perp, D^\perp) \subseteq \Gamma(qTM) \]

\[ \& \]

\[ h(D, D^\perp) \subseteq \Gamma(F(TM^\theta)) \& h(D^\perp, D^\perp) \subseteq \Gamma(qTM). \]

(ii) If the equality sign holds in (1), then $M_\perp$ is a totally geodesic submanifold with satisfying conditions:

\[ h(D^\perp, D^\perp) \subseteq \Gamma(qTM), \]

\[ \& \]

\[ h(D^\perp, D^\perp) \subseteq \Gamma(qTM). \]

As an application of Theorem 1, the next result comes from the idea of the eigenvalue comparison theorem of Cheng [21], which has proved that $M$ is complete and isometric to the standard unit sphere, provided that $\text{Ric}(M) \geq 1$ and $d(M) = \pi$ by using the first non-zero eigenvalue of the Laplacian operator. After that, Mihai [12] obtained the first eigenvalue for CR-warped products into the Sasakian space form. Therefore, we used the method of the maximum principle for the first non-zero eigenvalue $\lambda_1$ which is defined in [22], and made use of Theorem 1 to deduce the following.

Theorem 2. Assuming $\tilde{M}$ is a nearly cosymplectic manifold, let $M = M_\perp \times_f M^\theta$ be a warped product pseudo-slant submanifold of $\tilde{M}$, such that $M_\perp$ is a compact submanifold of $\tilde{M}$. Then, we have:

\[ \lambda_1 \leq \left( \frac{9 \text{sec}^2 \theta \int_{M_\perp} \|h\|^2 dV}{d_1 \int_{M_\perp} (\ln f)^2 dV} \right), \]

where $\lambda_1$ is a first non-zero eigenvalue of the warping function $\ln f$. The dimensions are defined in Theorem 1 (ii).

2. Preliminaries

An odd $(2n + 1)$-dimensional Riemannian manifold $(\tilde{M}, g)$ is called a nearly cosymplectic manifold, if it consists of an endomorphism $\varphi$ of its tangent bundle $T\tilde{M}$, a structure vector field $\xi$, and a 1-form $\eta$, which satisfies the following:

\[ \varphi^2 = -I + \eta \otimes \xi, \quad \eta(\xi) = 1, \quad \eta \circ \varphi = 0, \quad \& \quad \varphi(\xi) = 0, \]

\[ g(\varphi U, \varphi V) = g(U, V) - \eta(U)\eta(V), \]

\[ (\tilde{\nabla}_U \varphi) V + (\tilde{\nabla}_V \varphi) U = 0, \]

for any vector field $U, V$ on $\tilde{M}$ such that $\tilde{\nabla}$ denotes the Riemannian connection with respect to the Riemannian metric $g$ (see [14]). Furthermore, the fundamental 2-form denoted by $\Phi$, i.e., $\Phi(U, V) = g(\varphi U, V)$.

Let the Lie algebras of vector fields tangent and normal to a submanifold $M$ be denoted as $\Gamma(TM)$ and $\Gamma(T^\perp M)$. Moreover, the induced connection on $T^\perp M$ is denoted $\nabla^\perp$, and $\nabla$ is the Levi-Civita connection of $M$. Thus, the Gauss and Weingarten formulas are defined as:

\[ \tilde{\nabla}_U V = \nabla_U V + h(U, V), \]

\[ \tilde{\nabla}_U N = -A_N U + \nabla^\perp_U N, \]

for each $U, V \in \Gamma(TM)$ and $N \in \Gamma(T^\perp M)$, where $h$ and $A_N$ are the second fundamental form and the shape operator, respectively, for the submanifold of $M$ into $\tilde{M}$, which are related as:
we consider the warped product pseudo-slant submanifold of the form $M = \tilde{M} \times \tilde{N}$, where $\tilde{N}$ is a cosymplectic manifold, $\tilde{M}$ is the Riemannian product $M_1 \times M_2$, and $N$ is a pseudo-slant submanifold of an almost-contact manifold. For deeper classifications of pseudo-slant submanifolds, we refer to [7]. First, we give the definition of a pseudo-slant submanifold:

\[ g(h(U, V), N) = g(A_N U, V). \] (10)

For any $U \in \Gamma(TM)$, we have:

\[ \varphi U = PU + FU, \] (11)

where $PU$ and $FU$ are the tangential and normal components of $\varphi U$, respectively. Similarly, for any $N \in \Gamma(T^\perp M)$, we have:

\[ \varphi N = tN + fN, \] (12)

where $tN$ (resp. $fN$) are tangential (resp. normal) components of $\varphi N$. If $h(U, V) = 0$, then $M$ is totally umbilical. We shall use Theorem 2.1 [5] in our subsequent proof as a characterization of the slant submanifold.

In this sequel, by using the slant distribution given in [23, 24], we shall give the definition of pseudo-slant submanifolds of almost-contact manifolds. For deeper classifications of pseudo-slant submanifolds, we refer to [7]. First, we give the definition of a pseudo-slant submanifold:

**Definition 1.** If the tangent bundle $TM$ of submanifold $M$ in an almost-contact manifold is decomposed as $TM = D^\theta \oplus D^\perp < \xi >$, where $D^\theta$ and $D^\perp$ are slant and anti-invariant distributions such that $PD^\theta \subseteq D^\theta$ and $\varphi D^\perp \subseteq T^\perp M$, respectively—in this case, where $< \xi >$ is a one-dimensional distribution spanned by the structure field $\xi$, then $M$ is called pseudo-slant submanifold.

If $\mu$ is an invariant subspace of $T^\perp M$, then for the pseudo-slant case, the normal bundle $T^\perp M$ can be decomposed as: $T^\perp M = \varphi D^\perp \oplus PD^\theta \oplus \mu$.

**3. Warped Product Submanifolds of the Form $M_1 \times f M_\theta$**

Let $(M_1, g_1)$ and $(M_2, g_2)$ be two Riemannian manifolds. Then, the warped product of $M_1$ and $M_2$ is the Riemannian product $M_1 \times_f M_2 = (M_1 \times_f M_2, g)$ with the metric $g = g_1 + f^2 g_2$ and $f$ being a positive differential function defined on $M_1$. Then, from Lemma 7.3 [25], we have:

\[ \nabla_U W = \nabla_W U = U(\text{ln} f) W, \] (13)

for any vector fields $U$ and $W$ tangent to $M_1$ and $M_2$, respectively, where $\nabla$ denote the Levi-Civitas connection on $M$ (see [25]). If the warping function $f$ is constant, then a warped product manifold $M = M_1 \times_f M_2$ is called a simply Riemannian product or a trivial warped product manifold. Now, we consider the warped product pseudo-slant submanifold of the form $M = M_1 \times_f M_\theta$, such that $\xi \in \Gamma(TM_\perp)$ and other cases is leaved because they were studied by Al-Solamy [5], and then we obtain some lemmas for use in our main result.

**Lemma 1.** Let $M = M_1 \times_f M_\theta$ be a warped product pseudo-slant submanifold of a nearly cosymplectic manifold, $\tilde{M}$. Then:

\[ 2\varepsilon(h(U, W), PU U) = (W \text{ln} f) \cos^2 \theta ||U||^2 + g(h(U, PU), \varphi W) + g(h(W, PU), FU), \]

for any $U \in \Gamma(TM_\theta)$ and $W \in \Gamma(TM_\perp)$.

**Proof.** Suppose that $M = M_1 \times_f M_\theta$ is a warped product pseudo-slant submanifold of a nearly cosymplectic manifold $\tilde{M}$; then, from (8), we find that:
\[ g(h(U, W), FPU) = g(\tilde{\nabla}_W U, FPU). \]

Thus, from (11) and from Theorem 2.1 in [5], we obtain:
\[ g(h(U, W), FPU) = -g(\varphi \tilde{\nabla}_W U, PU) + \cos^2 \theta g(\nabla_W U, U). \]

Then, using (13), we can derive:
\[ g(h(U, W), FPU) = g((\tilde{\nabla}_W \varphi) U, PW) - g(\tilde{\nabla}_W \varphi U, PU) + \cos^2 \theta (W \ln f)||U||^2. \]

Using (7) and (11), the above equation then becomes:
\[ g(h(U, W), FPU) = -g((\tilde{\nabla}_U \varphi) W, PU) - g(\nabla_W PU, PU) - g(\tilde{\nabla}_W PU, PU) + \cos^2 \theta (W \ln f)||W||^2. \]

By using (13), (9), and from (Equation (2.12) in [5]), we derive the following:
\[ g(h(U, W), FPU) = -g((\tilde{\nabla}_U \varphi) W, PU) - g(\tilde{\nabla}_U W, \varphi PU) - \cos^2 \theta (W \ln f)||U||^2 + g(h(W, PU), FPU) + \cos^2 \theta (W \ln f)||U||^2. \]

From (9), (11), and Theorem 2.1 [5] for the slant submanifold, it is not hard to come by the following:
\[ g(h(U, W), FPU) = g(A_{\varphi W} U, PU) + \cos^2 \theta g(\nabla_U W, U) - g(\tilde{\nabla}_U W, FPU) + g(h(W, PU), FPU). \]

Finally, (8) and (13) implies that:
\[ 2g(h(U, W), FPU) = (W \ln f) \cos^2 \theta ||U||^2 + g(h(U, PU), \varphi W) + g(h(W, PU), FPU), \]

which gives our assertion. \(\square\)

**Lemma 2.** Assume that \(M = M_\perp \times f M_\theta\) is a warped product pseudo-slant submanifold of a nearly cosymplectic manifold \(\tilde{M}\). Then:
\[ g(h(U, W), FPU) = 2g(h(U, PU), \varphi W) - g(h(W, PU), FPU), \]

for any \(U \in \Gamma(TM_\theta)\) and \(W \in \Gamma(TM_\perp)\).

**Proof.** From (8) and (11), we have:
\[ g(h(W, PU), FPU) = -g(\varphi \tilde{\nabla}_W PU, U) - g(\tilde{\nabla}_W PU, PU), \]

for \(U \in \Gamma(TM_\theta)\) and \(W \in \Gamma(TM_\perp)\). Then, the covariant derivative of \(\varphi\) and (13), and from (Equation (2.12) in [5]), we modified as:
\[ g(h(W, PU), FPU) = g((\tilde{\nabla}_W \varphi) PU, U) - g(\tilde{\nabla}_W \varphi PU, U) - \cos^2 \theta (W \ln f)||U||^2. \]

Taking into account (7) for the nearly cosymplectic manifold, the virtues of (8), (11), and Theorem 2.1 in [5], it follows that:
\[ g(h(W, PU), FPU) = g(h(U, W), FPU) - \cos^2 \theta (W \ln f)||U||^2 - g((\tilde{\nabla}_PU \varphi) W, X) + \cos^2 \theta g(\nabla_W U, U). \]

Using (13), one can obtain:
\[ g(h(W, PU), FPU) = g(h(U, W), FPU) - g(\tilde{\nabla}_PU \varphi W, U) - g(\tilde{\nabla}_PU W, \varphi U). \]
Then, from (9) and (11), it is clear that:
\[ 2g(h(W, PU), FU) = g(h(U, W), FPU) + g(h(U, Pu), \varphi W) - g(\tilde{\nabla}_UW, PU). \]

Again, from (13) and (Equation (2.12) in [5]), the last equation reduces the new form:
\[ 2g(h(W, PU), FU) = g(h(U, W), FPU) - (W \ln f) \cos^2 \theta ||U||^2 + g(h(U, PU), \varphi W). \]  

(14)

Now, rearrange \( X \) by \( PX \) in (14) and Theorem 2.1 from [5], and it will give us:
\[ -2 \cos^2 \theta g(h(U, Z), FPU) = - (W \ln f) \cos^4 ||U||^2 - \cos^2 \theta g(h(W, PU), FU) \]
\[ - \cos^2 \theta g(h(PU, U), \varphi W). \]

which implies:
\[ 2g(h(U, W), FPU) = (W \ln f) \cos^2 ||U||^2 + g(h(W, PU), FU) + g(h(PU, U), \varphi W). \]  

(15)

From (14) and (15), it concludes that:
\[ g(h(W, PU), FU) = 2g(h(U, PU), \varphi W) - g(h(U, W), FPU), \]

which completes the proof of lemma. \( \square \)

**Lemma 3.** On a warped product pseudo-slant submanifold, \( M = M_\perp \times \mathcal{M}_\theta \) of a nearly cosymplectic manifold \( \tilde{M} \). Then:
\[ g(h(PU, U), \varphi W) = g(h(U, W), FPU) - \frac{1}{3} \cos^2 \theta (W \ln f)||U||^2, \]

for any \( U \in \Gamma(TM_\theta) \) and \( W \in \Gamma(TM_\perp) \).

**Proof.** From Lemmas 1 and 2, we can derive the proof of Lemma 3. \( \square \)

**Lemma 4.** On a warped product pseudo-slant submanifold, \( M = M_\perp \times \mathcal{M}_\theta \) of a nearly cosymplectic manifold \( \tilde{M} \). Then:
(i) \( g(h(W, W), FU) = g(h(U, W), \varphi W), \)
(ii) \( g(h(W, W), FPU) = g(h(W, PU), \varphi W), \)

for any \( U \in \Gamma(TM_\theta) \) and \( W \in \Gamma(TM_\perp) \).

**Proof.** From (8) and (11), we obtain:
\[ g(h(W, W), FU) = g(\tilde{\nabla}_W W, \varphi U) - g(\tilde{\nabla}_W W, PU), \]

for \( U \in \Gamma(TM_\theta) \) and \( W \in \Gamma(TM_\perp) \). It can be extended further by the fact that \( W \) and \( PU \) are orthogonal, i.e.,
\[ g(h(W, W), FU) = -g(\varphi \tilde{\nabla}_W W, U) + g(\tilde{\nabla}_W PU, W). \]

We also derived from the covariant derivative of \( \varphi \) and (8), that is:
\[ g(h(W, W), FU) = g((\tilde{\nabla}_W \varphi) W, U) - g(\tilde{\nabla}_W \varphi W, U) + g(\tilde{\nabla}_W PU, W). \]
Then, from (7) and (13), we obtained:

\[ g(h(W, W), FU) = g(A_{\varphi W}W, U) + (W \ln f)g(\varphi(U), W), \]

which implies:

\[ g(h(W, W), FU) = g(A_{\varphi W}W, U). \]  \hspace{1cm} (16)

That is, the first part of the proof of lemma ends up and part (ii) can be constructed by rearranging \( X \) by \( PX \) in (16). \( \square \)

**Lemma 5.** Let \( \tilde{M} \) be a nearly cosymplectic manifold and \( M = M_\perp \times_f M_\theta \) be a warped product pseudo-slant submanifold in \( \tilde{M} \). Thus,

(i) \( g(h(U, U), \varphi W) = g(h(W, U), FU); \)

(ii) \( g(h(PU, PU), \varphi W) = g(h(W, PU), FPU); \)

for any \( U \in \Gamma(TM_\theta) \) and \( W \in \Gamma(TM_\perp) \)

**Proof.** Assuming \( U \in \Gamma(TM_\theta) \) and \( W \in \Gamma(TM_\perp) \), we have:

\[ g(h(U, U), \varphi W) = g(\tilde{\nabla}_U U, \varphi W) = -g(\varphi \tilde{\nabla}_U U, W) \]

From the covariant derivative of the tensor field \( \varphi \), it follows that:

\[ g(h(U, U), \varphi W) = g(\tilde{\nabla}_U \varphi(U), W) - g(\tilde{\nabla}_U \varphi(U), W). \]

Taking into account (7) and (8), we have:

\[ g(h(U, U), \varphi W) = g(\tilde{\nabla}_U W, PU) - g(\tilde{\nabla}_U FU, W). \]

Thus, from (13) and (9), it can easily be found that:

\[ g(h(U, U), \varphi W) = (W \ln f)g(U, PU) + g(A_{\tilde{\varphi}_U}U, W). \]

Since \( U \) and \( PU \) are orthogonal and (10), we arrive at:

\[ g(h(U, U), \varphi W) = g(h(U, W), FU), \]  \hspace{1cm} (17)

which is the first part of the lemma. Then, by switching \( X \) by \( PX \) in (17), we were able to find the proof of the second part of the lemma. \( \square \)

4. Main Proof of Inequality for Warped Product of the form \( M_\perp \times_f M_\theta \)

In this section, we establish a geometric inequality for warped product pseudo-slant submanifolds in terms of the symmetric bilinear form and warping functions with included immersion.

4.1. Proof of Theorem 1

Let \( M = M_\perp \times_f M_\theta \) be an \( (m + 1) \)-dimensional warped product pseudo-slant submanifold of a nearly cosymplectic manifold \( \tilde{M} \), such that \( M_\theta \) of dimension \( d_\theta = 2\beta \) and \( M_\perp \) of dimension \( d_\perp = (\alpha + 1) \). We chose the orthonormal frames \( \{e_1, e_2, \cdots, e_\alpha, e_\alpha+1 = \hat{\xi}_r\} \) and \( \{e_{\alpha+2} = e_1^r, \cdots, e_{\alpha+\beta+1} = e_\beta^r\} \) of \( TM_\perp \) and \( TM_\theta \), respectively. Thus, the orthonormal frames of the normal subbundles \( \varphi(TM_\perp), F(TM_\theta) \), and \( \mu \) are denoted by \( \{e_{m+1} = \hat{\xi}_1 = \varphi\hat{e}_1, \cdots, e_{m+\alpha} = \hat{\xi}_\alpha = \varphi\hat{e}_\alpha\} \), \( \{e_{m+\alpha+1} = \hat{\xi}_{\alpha+1} = \hat{\xi}_1 = \csc\varphi\hat{e}_1^r, \cdots, e_{m+\alpha+\beta} = \hat{\xi}_{\alpha+\beta} = \hat{\xi}_\beta = \csc\varphi\hat{e}_\beta^r\} \), and \( \{e_{m+\alpha+\beta+1} = \hat{\xi}_{\alpha+\beta+1} = \hat{\xi}_1 = \csc\varphi\hat{e}_1^r, \cdots, e_{m+2\beta} = \hat{\xi}_{2\beta} = \csc\varphi\hat{e}_{\beta+2}^r\} \) of \( TM_\perp \) and \( TM_\theta \), respectively.
\[
\csc \theta \mathbf{F}_e^{s+n+\alpha} = \mathbf{e}_{m+\alpha+\beta+1} = \mathbf{e}_{\beta+1} = \mathbf{e}_m\csc \theta \mathbf{F}_e^{s+n+\alpha} \mathbf{e}_{m+\alpha+\beta} = \mathbf{e}_{\alpha+2\beta} = \mathbf{csc} \theta \mathbf{F}_e^{s+n+\alpha},
\]
and \{\mathbf{e}_{2m-1} = \mathbf{e}_{m}, \ldots, \mathbf{e}_{2n+1} = \mathbf{e}_{2(n-m+1)}\}, respectively. From the definition of the second fundamental form, we have:
\[
||h||^2 = ||h(D^\theta, D^\phi)||^2 + ||h(D^\phi, D^\theta)||^2 + 2||h(D^\theta, D^\phi)||^2.
\] (18)

After missing the second term of the above equation, we get:
\[
||h||^2 \geq ||h(D^\theta, D^\phi)||^2 + 2||h(D^\theta, D^\phi)||^2.
\]

Thus, changes in the above equation into a new form by using the definition of \(h\) lead to:
\[
||h||^2 \geq \sum_{l=m+1}^{2n+1} \sum_{l=1}^{2\beta} \sum_{r=1}^{a+1} g(h(e_r^s, e_s^s), e_l^s)^2 + 2 \sum_{l=m+1}^{2n+1} \sum_{l=1}^{2\beta} \sum_{r=1}^{a+1} g(h(e_r^s, e_s^s), e_l^s)^2.
\] (19)

If we put \(h(U, \xi) = 0\) in the second term in the components of \(\varphi D^\phi, F D^\theta, \) and \(u\), the proceeding equation can be expressed as:
\[
||h||^2 \geq \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2 + 2 \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2
\] + \(2 \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2 + \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2.
\]

Considering only the first, second, and fourth terms, they then imply that:
\[
||h||^2 \geq \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2 + 2 \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2 + \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2.
\]

Then, using the components of the adapted frame for \(F D^\theta, \) we derive:
\[
||h||^2 \geq 2 \csc^2 \theta \sum_{s=1}^{\beta} \sum_{l=1}^{a} g(h(e_r^s, e_s^s), F e_l^s)^2 + 2 \csc^2 \theta \sec^4 \theta \sum_{s=1}^{\beta} \sum_{l=1}^{a} g(h(e_r^s, e_s^s), F e_l^s)^2
\] + \(2 \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2 + 2 \sec^2 \theta \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2 + \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2.
\]

After taking into account Lemmas 4 and 5, the above equation then takes the form:
\[
||h||^2 \geq 2 \csc^2 \theta \sum_{s=1}^{\beta} \sum_{l=1}^{a} g(h(e_r^s, e_s^s), \varphi e_s)^2 + 2 \csc^2 \theta \sec^4 \theta \sum_{s=1}^{\beta} \sum_{l=1}^{a} g(h(e_r^s, e_s^s), \varphi e_s)^2
\] + \(2 \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), F e_l^s)^2 + 2 \sec^2 \theta \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), F e_l^s)^2 + \sum_{l=1}^{a} \sum_{r=1}^{\beta} g(h(e_r^s, e_s^s), e_l^s)^2.
\] (20)
Now, if we just consider the last part and the rest of the parts are left, then we have:

$$||h||^2 \geq \sum_{l=1}^{\alpha} \sum_{r,\beta=1}^{2} g(h(e^*_r, e^*_\beta), \xi_l)^2.$$ 

Again, using the components of $D^{\phi}$, we finish at:

$$||h||^2 \geq \sum_{l=1}^{\alpha} \sum_{r,\beta=1}^{2} g(h(e^*_r, e^*_\beta), \xi_l)^2 + \sec^2 \theta \sum_{l=1}^{\alpha} \sum_{r,\beta=1}^{2} g(h(Pe^*_r, e^*_\beta), \xi_l)^2$$

$$+ \sec^2 \theta \sum_{l=1}^{\alpha} \sum_{r,\beta=1}^{2} g(h(e^*_r, Pe^*_\beta), \xi_l)^2 + \sec^4 \theta \sum_{l=1}^{\alpha} \sum_{r,\beta=1}^{2} g(h(Pe^*_r, Pe^*_\beta), \xi_l)^2. \quad (21)$$

If we leave the first and last terms of the right-hand side in (21) and just add the remaining terms, then we obtain:

$$||h||^2 \geq 2 \sec^2 \sum_{l=1}^{\alpha} \sum_{r,\beta=1}^{2} g(h(Pe^*_r, e^*_\beta), \xi_l)^2.$$ 

With the help of Lemma 3 in the above inequality, we get:

$$||h||^2 \geq \frac{2}{9} \cos^2 \theta \sum_{l=1}^{\alpha} \sum_{r,\beta=1}^{2} (\xi_l \ln f)^2 g(e^*_r, e^*_\beta)^2 + 2 \sum_{l=1}^{\alpha} \sum_{r,\beta=1}^{2} g(h(e^*_r, e^*_\beta), FPe^*_\beta)^2$$

$$- \frac{4}{3} \sum_{l=1}^{\alpha} \sum_{r,\beta=1}^{2} (\xi_l \ln f)g(h(e^*_r, e^*_\beta), FPe^*_\beta). \quad (22)$$

Now, we can add and subtract the term $\xi \ln f$ in the first part of (22), and we have

$$||h||^2 \geq \frac{2}{9} \cos^2 \theta \sum_{s=1}^{\alpha+1} \sum_{l=1}^{\beta} (\xi_s \ln f)^2 g(e^*_l, e^*_s)^2 - \frac{2}{9} \cos^2 \theta \sum_{l=1}^{\beta} (\xi \ln f)^2 g(e^*_l, e^*_l)^2.$$ 

It is known that $\xi \ln f = 0$ for a nearly cosymplectic manifold (see [14]). Thus, the above inequality reduces to:

$$||h||^2 \geq \frac{d_1}{9} \cos^2 \theta ||\nabla \ln f||^2. \quad (23)$$

If (23) holds, then from the missing terms in (22), we obtain some conditions from the second and third terms, i.e., $(\xi_l \ln f)g(h(D^{\perp}, D^{\phi}), FD^{\phi}) = 0$. This implies that either $\xi_l \ln f = 0$ or $g(h(D^{\perp}, D^{\phi}), FD^{\phi}) = 0$. If we take $\xi_l \ln f = 0$, it means that $f$ is a constant function on $M$, which is a contradiction for the non-trivial warped product pseudo-slant submanifold. Hence, we get $g(h(D^{\perp}, D^{\phi}), FD^{\phi}) = 0$, and also from the third term of (19), we derive:

$$h(D^{\perp}, D^{\phi}) \subseteq \Gamma(\varphi TM_{\perp}), \quad (24)$$

which is (2). Because of the terms which were left in (18), $M_{\perp}$ is a totally geodesic submanifold in $\bar{M}$. On the other hand, leaving the terms in (19), (20), and (21) implies that:

$$g(h(D^{\phi}, D^{\phi}), \varphi D^{\perp}) = 0, \quad g(h(D^{\phi}, D^{\phi}), \mu) = 0,$$

&

$$g(h(D^{\perp}, D^{\phi}), FD^{\phi}) = 0, \quad g(h(D^{\perp}, D^{\perp}), \mu) = 0,$$
which means that:

\[ h(D^\perp, D^\perp) \subseteq \Gamma(F(TM_\theta)) \quad \& \quad h(D^\theta, D^\theta) \subseteq \Gamma(\varphi TM_\perp). \quad (25) \]

From this, we get the required condition (3). Thus, the equality cases are verified.

4.2. Proof of Theorem 2

Let us assume that \( f \) is a non-constant warping function. From the minimum principle on the first eigenvalue \( \lambda_1 \), one obtains: (p. 186 in [22]).

\[ \lambda_1 \int_{M^\nu} (\ln f)^2 dV \leq \int_{M^\nu} \|\nabla \ln f\|^2 dV. \quad (26) \]

with equality holding if, and only if \( \Delta \ln f = \lambda_1 \ln f \). On the other hand, taking the integration of Equation (1) along the volume element \( dV \), we have:

\[ \int_{M_\perp} \|h\|^2 dV \geq \frac{2\beta}{9} \cos^2 \theta \int_{M_\perp} \|\nabla \ln f\|^2 dV. \quad (27) \]

Thus, (26) and (27) implies that:

\[ \int_{M_\perp} \|h\|^2 dV \geq \frac{2\beta}{9} \cos^2 \theta \lambda_1 \int_{M_\perp} (\ln f)^2 dV \]

The above implies Equation (4). This completes the proof of the Theorem.

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